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**Central and Arctic Region**

# Biophysical and Ecological Overview of the North Water and Adjacent Areas

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## Foreword

This series documents the scientific basis for the evaluation of aquatic resources and ecosystems in Canada. As such, it addresses the issues of the day in the time frames required and the documents it contains are not intended as definitive statements on the subjects addressed but rather as progress reports on ongoing investigations.

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# ABSTRACT

The North Water region is located in the High Arctic, geographically situated between Canada and Greenland. It is a remote region highly influenced by ocean currents and wind conditions, which interact with the unique local geography and coastline. The North Water polynya, also known as *Sarvarjuaq* by the Qikiqtani Inuit and *Pikialasorsuaq* ("great upwelling") by Greenland, is a recurring area of anomalously thin sea ice and/or open water surrounded by thicker sea ice. Predominantly a latent heat polynya, the North Water forms southward of a recurrent ice bridge (or arch) across Nares Strait, and is maintained by strong winds, currents, and an upwelling of warm water carried from the Atlantic by the West Greenland Current. For millennia, Inuit have regarded the North Water as a place of great cultural and spiritual significance, and rely on the sea ice/ice edge environment as an important hunting ground and transportation corridor. The North Water is considered to be one of the largest (80,000 $km^2$) polynyas in the Arctic, and is well known for its early and reliable productivity, and high biodiversity of species. This region is home to an estimated 60 million birds, including the endangered Ivory Gull and the largest aggregation of Dovekies/Little Auks on earth. The open water, and productive coastal and ice edge environments, provide critical habitat in all seasons for many marine mammal species, such as Atlantic Walrus, Beluga and Bowhead Whales, Narwhal, Ringed Seal, Bearded Seal, and Polar Bear. Due to its ecological, socioeconomic, and cultural importance, this area has been evaluated as unique through several international processes. In recent decades, there have been changes to the physical, biological and chemical processes of the North Water. However, observations and science programs have not been systematic and/or sustained, and there remain uncertainties and knowledge gaps regarding the actual degree of change that is occurring. In order to establish a baseline for ongoing collaborations related to the North Water region, a comprehensive literature review was developed, highlighting important physical, biological, and ecological features, and seasonally important areas for key species within the region, including the polynya and adjacent areas. This review also summarizes data uncertainties, knowledge gaps, and stressors that have the potential to affect this dynamic marine ecosystem.

# 1. INTRODUCTION

Fisheries and Oceans Canada (DFO), under the authority of the *Oceans Act*, and with Indigenous partners is working to establish a national system of marine protected areas (MPAs) to conserve and protect Canada's marine areas and to maintain their ecological integrity. Ecological integrity is a characteristic of ecosystems that are minimally disturbed by human activity such that natural processes are intact and self-sustaining, ecosystems evolve naturally and biodiversity and resilience are maintained. In March 2019, the Prime Minister of Canada, Justin Trudeau, released a joint statement with Canadian Inuit leaders that committed to working in partnership with the Governments of Denmark and Greenland, to advance the sustainable marine management and environmental protection for the North Water region. Subsequent to the release of that statement, DFO, on behalf of the Government of Canada, has been actively engaged with the Kingdom of Denmark through government officials within relevant ministries in Greenland and Denmark, in work towards joint, ecosystem based management and monitoring for the region. In the past year, the Qikiqtani Inuit Association (QIA) of Canada has further committed to working with the Government of Canada to ensure protection of the North Water within Canada, and to work as part of a team with Greenland and Denmark to support international protection for this unique area of global importance (QIA 2020).

For millennia, Inuit communities in Canada and Greenland have relied on the North Water as an important hunting ground, providing food and resources for tools and clothing (ICCC 2017, QIA 2018). It was the open water early in the summer and abundance of marine mammals that also made this area attractive to 19th century whalers and explorers (Bell and Brown 2018). Today, *Sarvarjuaq* is the name Qikiqtani (Baffin region) Inuit give to an area of year-round open water surrounded by ice. *Pikialasorsuaq* ("great upwelling") is the west Greenland name more commonly used by international organizations, such as World Wildlife Fund (WWF) and the Inuit Circumpolar Council, to describe the North Water polynya and surrounding bi-national region (ICCC 2017, QIA 2020). The scientific community defines a polynya as a recurrent area of thin ice and open water that occurs in winter at a location where nearby ice is appreciably thicker (Smith et al. 1990, Martin 2001). Polynyas can either be maintained by the action of oceanic upwelling of warm water (sensible heat polynya) or by that of prevailing winds that blow ice out of the area as it forms (latent heat polynya). The North Water is predominantly a latent heat polynya that forms southward of an ice bridge (or arch) across Nares Strait/Kane Basin in winter and spring. The polynya is maintained mostly by wind, with additional impetus from currents and upwelling of water brought north by the West Greenland Current (WGC). The distinct oceanographic features and water masses that converge in this region influence the high benthic diversity, primary production, and support many unique and diverse species (Ardyna et al. 2011, Kenchington et al. 2011, Bell and Brown 2018).

The North Water is critical habitat for many migratory and resident species, such as Beluga Whales (*Delphinapterus leucas*), Narwhals (*Monodon monoceros*), Bowhead Whales (*Balaena mysticetus*), and several pinniped (seal) species, such as Ringed (*Pusa hispida*), Bearded (*Erignathus barbatus*), Hooded (*Cystophora cristata*), and Harp Seals (*Pagophilus groenlandicus*) (DFO 2015a, QIA 2018, Barber et al. 2019). Atlantic Walrus (*Odobenus rosmarus*) use the North Water as a migratory route between Greenland and Canada, and the region provides several important winter and summer haul-out sites (DFO 2011a, 2015a, QIA 2018). Polar Bears (*Ursus maritimus*), from at least two subpopulations, depend on the fast ice adjacent to the polynya during winter and spring for feeding. Several large colonies of seabirds, including an estimated 80% of the world's population of Dovekie/Little Auk (*Alle alle*) and most of the Canadian population of the endangered Ivory Gull (*Pagophila eburnea*), nest within or adjacent to the North Water in Canada and/or Greenland, and feed extensively within its waters (Boertmann and Mosbech 1998, DFO 2011a, 2015a, QIA 2018). Thick-billed Murre (*Uria lomvia*), Black Guillemot (*Cepphus grylle)*, Black-legged Kittiwake (*Rissa tridactyla*), Glaucous Gull (*Larus hyperboreus*), and Northern Fulmar (*Fulmarus glacialis*) also nest and/or stage in the North Water.

The North Water and surrounding area has been evaluated through many international processes led by Canada, Greenland, and Denmark, emphasizing its unique binational, cultural, biophysical, and ecological value. The North Water Ecologically and Biologically Significant Area (EBSA) was identified by DFO in 2011, meeting both the aggregation and fitness consequences criteria required by DFO for EBSA designation for multiple trophic levels (DFO 2015a). During this assessment, the polynya was ranked as one of the largest (maximum of 80,000 km$^2$) and most biologically productive polynyas in the Arctic (Barber and Massom 2007, DFO 2011a, 2015a). In the same year, Aarhus University and the Greenland Institute of Natural Resources ranked the North Water as the most ecologically significant and vulnerable of all Greenlandic Marine Areas using the IMO Particular Sensitive Sea Areas Criteria (Christensen et al. 2012). In another strategic effort to enhance area-based protection of Greenlandic biodiversity, an overview of areas of ecological and biological significance in West and South-East Greenland was prepared using the EBSA and other international criteria, to identify important areas in Greenland (the report identifies 23 areas, including three within the North Water; see Christensen et al. 2016). Further, the International Union for Conservation of Nature and Natural Resources (IUCN) and the UNESCO's World Heritage Centre identified the North Water Polynya and Adjacent Areas as one of seven potential candidate areas in the Arctic for Outstanding Universal Value (OUV).

Inuit communities surrounding the North Water and researchers have described the North Water as an ecosystem currently in a state of rapid change, primarily due to climatic influences (Mosbech and Kyhn 2019). It is expected that there will be increases in pollutants and other anthropogenic impacts to the system, contributed by localized shipping, mining activity, oil and gas exploration, and commercial development (ICCC 2017). As such, there is fear that climate change and future anthropogenic disturbances could result in a reduction or displacement of valued subsistence species and resources. Due to the remote location of the North Water, the sporadic nature of research projects, the high degree of connectivity and complexity within the system, and jurisdictional challenges, many uncertainties and knowledge gaps exist. These include the future reliability of the polynya (i.e., formation, duration, and stability), actual magnitude, extent and timing of productivity, and overall biodiversity within the region. The consequences of many changes to the overall ecosystem, including climatic shifts, are unknown, and present challenges when trying to predict long-term trends for the region. The last large-scale ecosystem project within the North Water was completed in the late 1990s. This was the International North Water Polynya Study (NOW), conducted from 1997 through 1999, with emphasis in 1998, which combined icebreaker and ice-camp endeavors to document physical and biological processes (Deming et al. 2002, Barber et al. 2010). Much of our knowledge on phytoplankton blooms, community size and structure, and ice algae in the North Water is based upon data collected during these three cruises. Since then, few coordinated research projects have been dedicated to understanding the whole North Water ecosystem.

## 2. ASSESSMENT OF THE NORTH WATER AND ADJACENT AREAS

To further the Government of Canada's commitment to advancing environmental protection of the North Water, DFO Strategic Policy and Marine Conservation and Planning (formally Oceans Management) requested a bi-national Canadian Science Advisory Secretariat (CSAS) meeting, to summarize and review the state of knowledge of the North Water and surrounding area. It was also necessary to improve our understanding of the current and future impacts that this region faces in a time of rapid change. This report provided the foundation for this meeting, and presents the most current and comprehensive review of scientific knowledge for the region. It was prepared from an extensive literature review of published scientific documents, reports and peer-reviewed journals, as well as any documented Inuit Qaujimajatuqangit (IQ), and local hunter/user knowledge for the region. People of the North Water region are interconnected with the marine environment, and the recognition of Inuit as an integral part of the North Water system was a key driver in the establishment of the Pikialasorsuaq Commission, as well as subsequent consultations between Canada and Greenland from 2016–2017, and the report *"People of the Ice Bridge: The Future of Pikialasorsuaq"* (ICCC 2017). As a result of this and other processes, important IQ has been documented for the region in workshops (e.g., Nunavut Tunngavik Inc. 2005), coastal inventories (e.g., Government of Nunavut 2012), commissioned reports (e.g., Remnant and Thomas 1992, QIA 2018), spatial tools, atlases (e.g., Pikialasorsuaq Commission 2017), books (e.g., Gearheard et al. 2013), and peer-reviewed journals (e.g., Dowsley 2007). We cite these works within this document when relevant; however, it is important to note that much of the IQ and local/hunter knowledge specifically pertaining to the North Water remains with local knowledge holders and has yet to be documented or published.

This document has the following sections:

**Section 3. Environmental and Ecological Information** – This section describes and maps the North Water's biological and ecological attributes and identifies, where possible, the special features of the North Water and adjacent areas. It is based on a literature review compiled by North/South Consultants Inc. (2017). This section is divided into five core themes:

Section 3.1. The physical system (climate, sea ice, ocean, and atmosphere);

Section 3.2. Lower trophic levels (productivity, biogeochemistry, benthic community, and zooplankton);

Section 3.3. Marine fishes;

Section 3.4. Marine mammals; and

Section 3.5. Birds.

Each theme concludes with a general summary, highlighting where knowledge/data are lacking, uncertain, or incomplete, and summarizes the possible future impacts of climate change. Note: this report focuses on the interactions and influences to the marine environment and reviews neither interactions between the North Water and the terrestrial system (i.e., anadromous fishes), nor the socio-economic potential of the ecosystem to the Canadian/Greenland economy.

**Section 4. Seasonally Important Areas** – This section uses maps from the Danish North Water Report (Christensen et al. 2017), and summarizes core biodiversity areas and particularly sensitive areas within the North Water; based on our current knowledge of different species and ecosystem components. The maps include information on seasonal productivity (algal blooms), and abundance and distributions of key seabirds and marine mammals.

**Section 5. Anthropogenic Stressors** – This section identifies trans-boundary stressors to the North Water ecosystem and potential future impacts related to local resource extraction and development.

## 2.1. GEOGRAPHIC SCOPE AND TERMINOLOGY

The North Water is geographically situated between Ellesmere Island (Canada) and northwest Greenland in northern Baffin Bay, connected to Tallurutiup Imanga (Lancaster Sound) and Jones Sound in the west, to Kane Basin and the Lincoln Sea in the north, and to central Baffin Bay and Davis Strait in the south (Figures 1 and 2). The landmasses surrounding the North Water are a part of the Precambrian (or Canadian) Shield, featuring eroded mountainous peaks with summits reaching 1,500 m (Bostock 1970, Maclean 1990). The coastline surrounding the North Water is irregularly incised by fiords and sounds, and much of the high land is covered by permanent ice (Martec 1982). A number of glaciers in northwestern Greenland and the Ellesmere Island terminate in the vicinity of the North Water. The polynya is loosely defined as the area of anomalously thin ice and open water in winter, bordered by much thicker coastal landfast sea ice along Ellesmere Island and Greenland; it extends north into Smith Sound/Kane Basin and south into Jones Sound; in most years it stretches from the east coast of Devon Island to Cape York (Figure 2).

The ecological and cultural footprint of the North Water is much larger than the bounds of the polynya itself. The people in the region view the North Water as a culturally continuous region, connecting people and resources across international borders. The ice bridge that forms across Nares Strait/Smith Sound in winter traditionally provided a transportation route between Canada and Greenland, connecting Umimmaat Nunaat (Ellesmere Island) and Avanersuaq (Northwest Greenland) (ICCC 2017). International border restrictions preventing travel between Ellesmere Island and Greenland coincided with changing environmental and sea ice conditions rendering the crossing too dangerous to undertake with confidence (Gearheard et al. 2013). Although local people no longer travel freely between Canada and Greenland, the region remains important to the communities of Aujuittuq (Grise Fiord), Siorapaluk, Qaanaaq, and Pituffik. While not directly in the vicinity of the North Water, the communities of Qausuittuq (Resolute Bay), Ikpiarjuk (Arctic Bay), Mittimatalik (Pond Inlet), Qikiqtarjuaq, Savissivik, and Kullorsuaq are ecologically, culturally, economically, and politically connected to the North Water (QIA 2020), specifically harvesting wildlife that moves between Tallurutiup Imanga and the North Water seasonally (Figure 1).

We acknowledge there is a larger cultural zone (including social, political, and economic elements) outside the ‘typical’ extent of the polynya, however the geographic scope of this review (Figures 1 and 2) is generally focused upon the oceanographic features of the North Water, including the physical and biological connectivity within the study area. This is a complex area with dynamic boundaries; even drawing the extent of the polynya can present challenges. The polynya moves (sometimes never forms), can have varied extent and duration, and has connections extending into other water bodies (i.e., influences directly from the Lincoln Sea and remotely from the Bering Sea and North Atlantic). As such, adjacent areas are mentioned in this assessment where relevant. In addition, Figure 1 does not include management lines, as the North Water system was assessed by experts from both countries as a whole, without international boundaries. In past and current literature, the scientific community often uses the acronym NOW (North Open Water) when describing the polynya. Although this is a common acronym, it is important to recognize that the region is not only open water and is a system characterized by many important ice features. As such, within this report we will just be referring to the region as ‘the North Water’ or ‘North Water region’, with no abbreviation. When describing the polynya, as a winter phenomenon, we will use terminology the ‘North Water polynya’ or just ‘the polynya’.

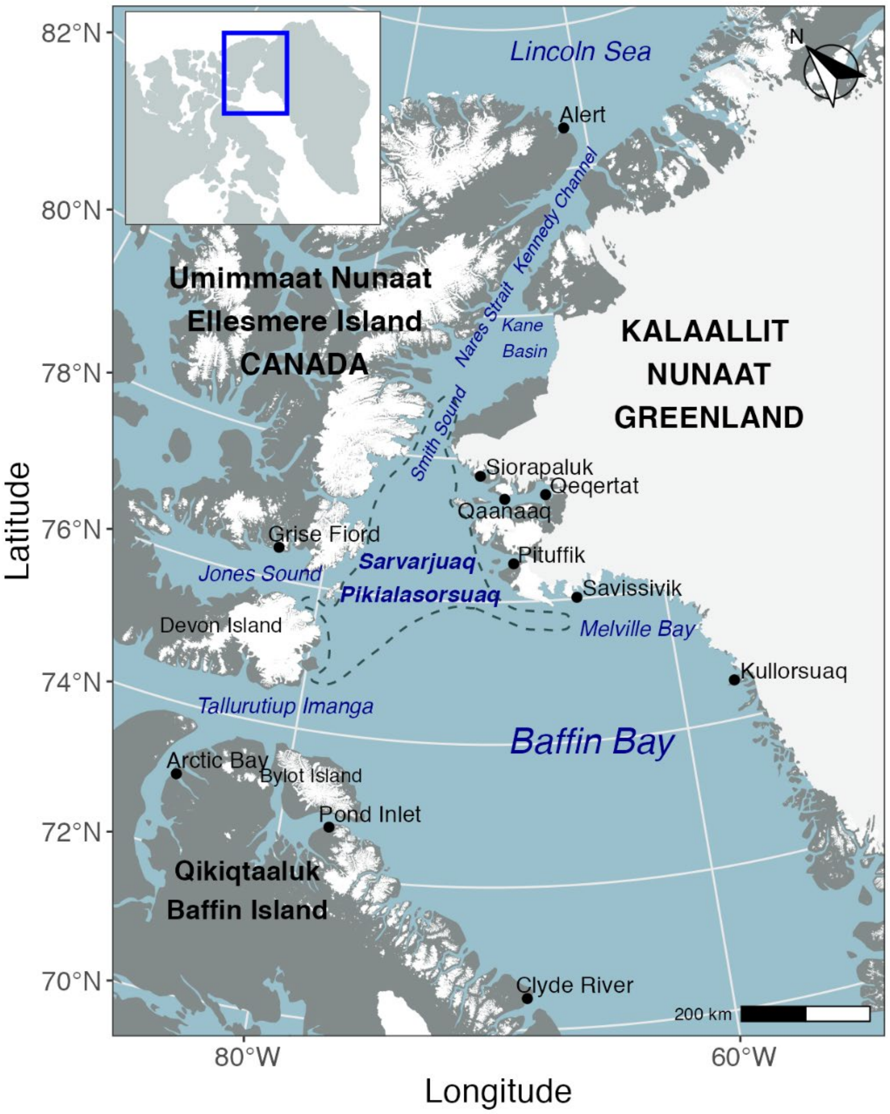

*Figure 1. The North Water (Sarvarjuaq/Pikialasorsuaq) region, including adjacent water bodies connected to the study area, and connected coastal communities mentioned in this report. A notional polynya boundary (dashed green line) is shown, representing the May monthly mean extent, adapted from Dunbar (1969).*

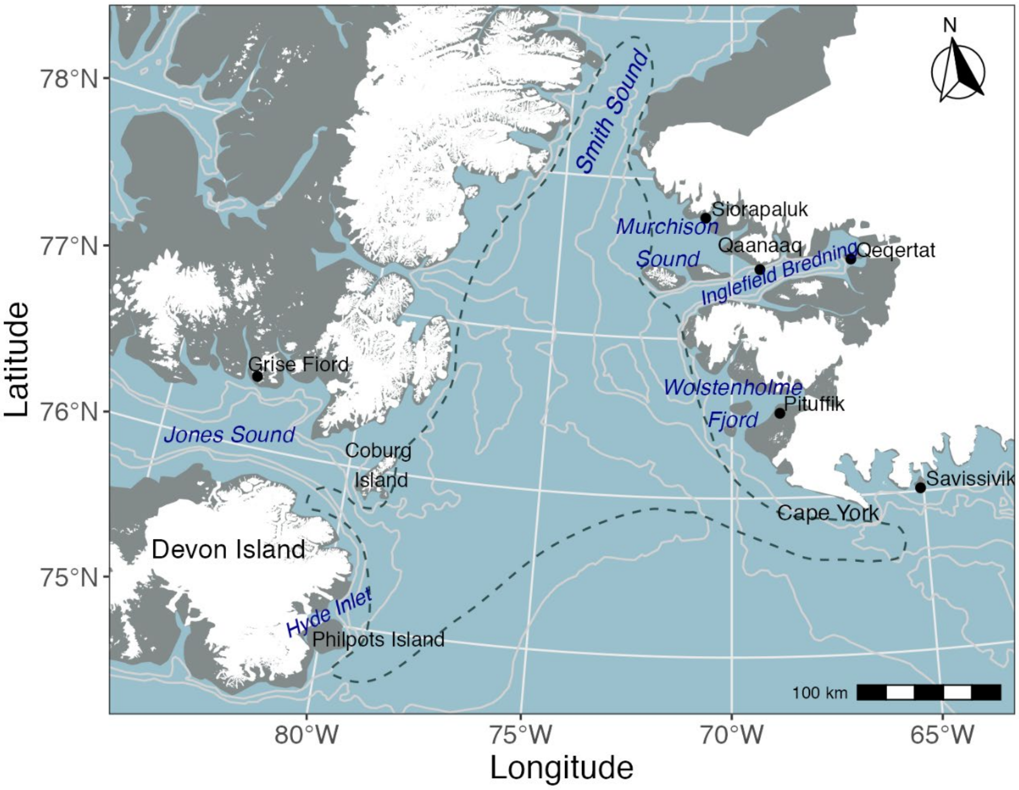

*Figure 2. A close up of the North Water (Sarvarjuaq/Pikialasorsuaq), including 200–500 m bathymetry contour lines (source: Natural Resources Canada), and important coastal fiords, islands, and water bodies mentioned in this report.*

## 2.2. CONNECTIVITY AND ECOSYSTEM LINKAGES

The Canadian Arctic Ocean is best understood as a holistic ecosystem, in which each component creates and adds to the dynamic habitats of all biota. As such, it is important to view the North Water with this context in mind; a general picture of Arctic food web dynamics can be a useful tool to this end (Figure 3). In some cases, general ecosystem processes in the North Water can be inferred from other Arctic regions; however it is important to remember that despite similar species assemblages, the structure and function of ecosystems are not uniform across the Arctic (Niemi et al. 2019). For instance, the connections species have with each other and their physical environments can vary spatially (e.g., by region, Yurkowski et al. 2016a, and by habitat type, Loseto et al. 2009) and temporally (e.g., seasonally, Matthews and Ferguson 2015, and inter-annually, Yurkowski et al. 2016b), and these can be modified as species respond to changing habitats and prey availability (e.g., Case Studies 6 and 7 in Niemi et al. 2019). Additionally, some key species can rely on multiple food webs (e.g., Greenland Halibut, Giraldo et al. 2018, and Polar Bears, Brown et al. 2018).

The North Water is unique because its high productivity and interconnectivity is physically supported by the presence of a polynya, ice bridges, and surrounding coastal regions and landfast ice, which are key habitats and migration corridors for many important Arctic species. However, like many ecosystems across the Arctic, many details about the structure of the food web in the North Water remain largely unknown. A better understanding of ecosystem dynamics in the North Water will be critical for managing this region at a species and ecosystem level into the future. Within this report we aim to document the important ecosystem linkages when information is available, and highlight key knowledge gaps in each theme/subtheme.

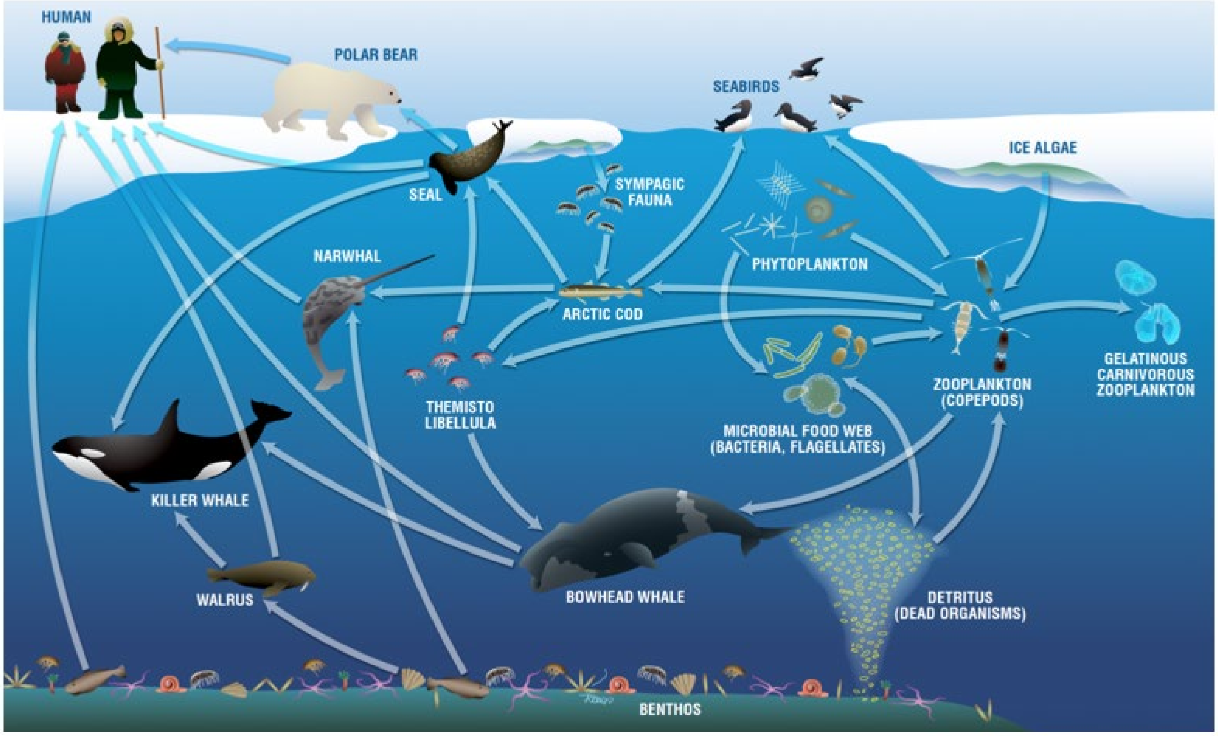

*Figure 3. An example of a food web showing the feeding relationships among organisms in a typical Canadian Arctic marine ecosystem. Energy is transferred through key species, such as Calanus copepods and Arctic Cod, through the ecosystem up to top predators (source: Darnis et al. 2012).*

## 2.3. SEASONALITY

This review discusses in detail the biophysical, ecological, and oceanographic processes which define the North Water system, each being highly influenced by the change in seasons and availability of light. Defining seasonality in the Arctic can be complicated, since it often can be described differently for physical (e.g., ice breakup, period of open water, etc.) and biological (e.g., breeding season, timing of productivity) events, or in the context of human interaction with the environment. For coastal communities, seasonality of the Arctic Ocean is integral to daily life and deeply rooted in Inuit culture and history (see 4.5, Niemi et al. 2019). Most scientific literature will make reference to the four typical seasons (winter, spring, summer and fall), which are loosely correlated with the seasons in the Gregorian calendar, but may vary from year-to-year. Since the North has long winters and short summers, the Inuit calendar is organized according to six main seasons: early fall, fall, winter, early spring, spring and summer. The change in seasons reflects environmental conditions, such as daylight and darkness periods, ice conditions, and the types of food that can be found (Figure 4) (QIA 2018). The seasons are often described in relation to the harvest of animals and the conditions associated with the use and accessibility of certain hunting grounds. In the high Arctic, the hunting platform is dependent on the presence or absence of sea ice, as a great majority of harvested species' life cycles are directly linked to it (Gearheard et al. 2013). The seasonal calendar specifically links the knowledge of animal species with the climate. The spelling of each season varies by each Qikiqtaaluk community, for example, in Grise Fiord they are: Ukiuq (winter), Upirngaaq (early spring), Upirngu (late spring), Auja (summer), Ukiaksaaq (early fall), and Ukiaq (fall/early winter) (QIA 2018). In this report, we discuss seasons and seasonality in a variety of settings, however, we attempt to provide clarity and context by providing approximate months when available.

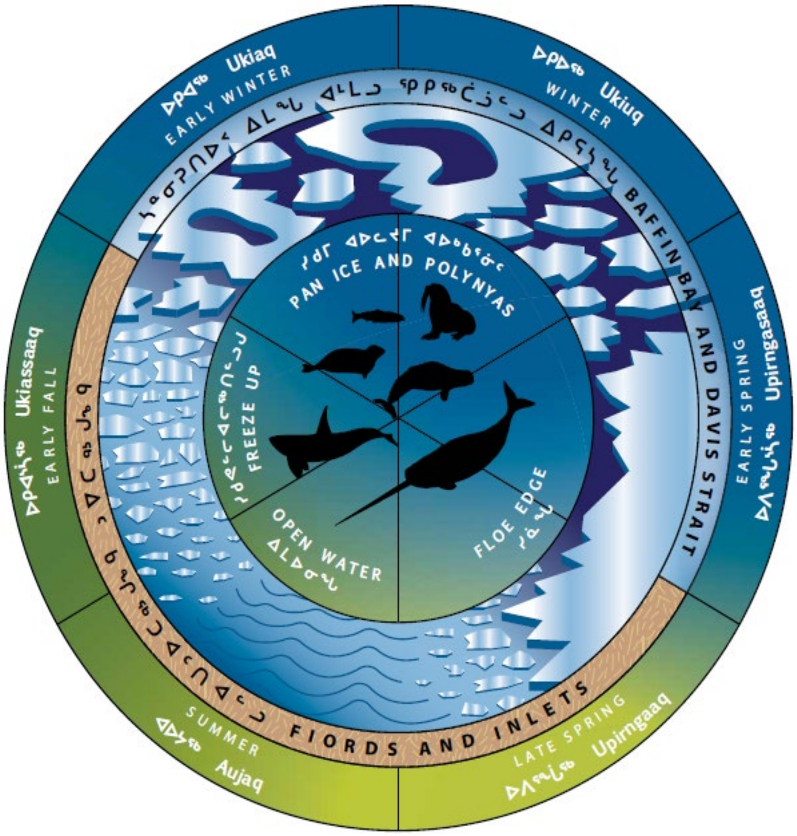

*Figure 4. The Inuit marine species seasonal calendar (Source: QIA 2018).*

# 3. ENVIRONMENTAL AND ECOLOGICAL INFORMATION

## 3.1. PHYSICAL SYSTEM (CLIMATE, SEA ICE, OCEAN AND ATMOSPHERE)

### 3.1.1. Climate Overview

Polynyas are known to have an effect on the regional climate. The presence of open water increases the amount and variation of moisture flux from the ocean to the atmosphere (Barber et al. 2001a). Moisture flux, in turn, can affect the sustainability of Arctic sea ice as large moisture fluxes can increase cloud cover and change the surface energy budget (Boisvert et al. 2012, Boisvert 2013). Being a large polynya, the North Water generates its own weather from evaporation, fog, low cloud, and enhanced snowfall over adjacent elevated terrain. It is also a site for cyclogenesis (storm development by virtue of terrain and heating from the sea surface) and is known as a place where storms ‘go to die’. Precipitation is notoriously hard to measure in the Arctic. Measurements of solid precipitation (snow and hail) are subject to many systematic errors (Goodison et al. 1998) and measurements can be affected by high-speed wind. Precipitation patterns are also incredibly localized and heavily influenced by topography and areas of open water. Due to this, there is a limited understanding about precipitation over the North Water.

Weather and climate regimes within the North Water region depend on a number of features that are related to global atmospheric circulation patterns. These patterns represent standing or slowly evolving oscillations influencing the Arctic on seasonal to decadal time scales. These large-scale circulation patterns can impact how ice is transported around and out of the Arctic

(Rigor et al. 2002). In addition, these circulation patterns can influence the number of storms that reach the North Water region (Rogers 1990, Clark et al. 1999). The Lincoln Sea, located where Nares Strait meets the Arctic Ocean, is often called a ‘switch gate’ (Falkner et al. 2005) , as large-scale atmospheric patterns either transport thick multiyear ice (MYI) to the coastline of northern Greenland, or out of the Arctic via Fram Strait, influencing the ice types found in Nares Strait.

There is strong agreement between many observational and modeling studies that the driving mechanism for formation of the North Water is the rapid wind-forced advection of sea ice southward from northern Baffin Bay (Melling et al. 2001, Barber et al. 2001, Biggs and Willmott, 2001, Yao and Tang, 2003, Moore and Vage 2018, Heinemann 2018). Formation is further aided by the narrowing of landmasses upwind towards Smith Sound, and the often-present ice bridge across the sound. The North Water is unusually windy, even for an offshore area. Throughout the year, the winds flow mainly from the north, converging into Nares Strait from the Lincoln Sea and increasing in speed through the narrow strait (Samelson and Barbour 2008, Heinemann, 2018). The wind speed and direction in Smith Sound are strongly constrained by the steep topography of Greenland and Ellesmere Island, with the winds blowing parallel to Nares Strait (Ito 1982, Ingram et al. 2002). The surrounding high terrain and the low level ‘Arctic inversion’ (increase in air temperature with elevation) strongly enhance wind speed within Nares Strait, and also within Lady Ann Strait and Lancaster Sound.

The characteristics of the sea ice in this region are of course linked to the seasonal variation in air temperature. However, the high terrain of Greenland and Ellesmere Island, and the reduced ice cover of the polynya, causes the weather and climate of the North Water to differ appreciably from that of nearby inland stations (i.e., Grise Fiord and Thule Air Base). Therefore, these stations can only provide an approximation to the North Water’s monthly mean air temperatures, as shown in Figure 5. Mean monthly temperatures for Grise Fiord and Thule Air Base (1985–2015) have ranged from -31° and -25°C, respectively, in February to +4° to +6°C, respectively, in July (Figure 5).

Like the rest of the Arctic, the North Water is undergoing rapid change. Annual mean surface air temperatures at nearby inland stations have increased by approximately 1°C per decade since the 1990s (AMAP 2018; note in the next paragraph that other studies support smaller increases). Spatially, the recent warming appeared to be at a maximum over the eastern Canadian Arctic, and seasonally, warming was greatest in the fall and early winter (AMAP 2018).

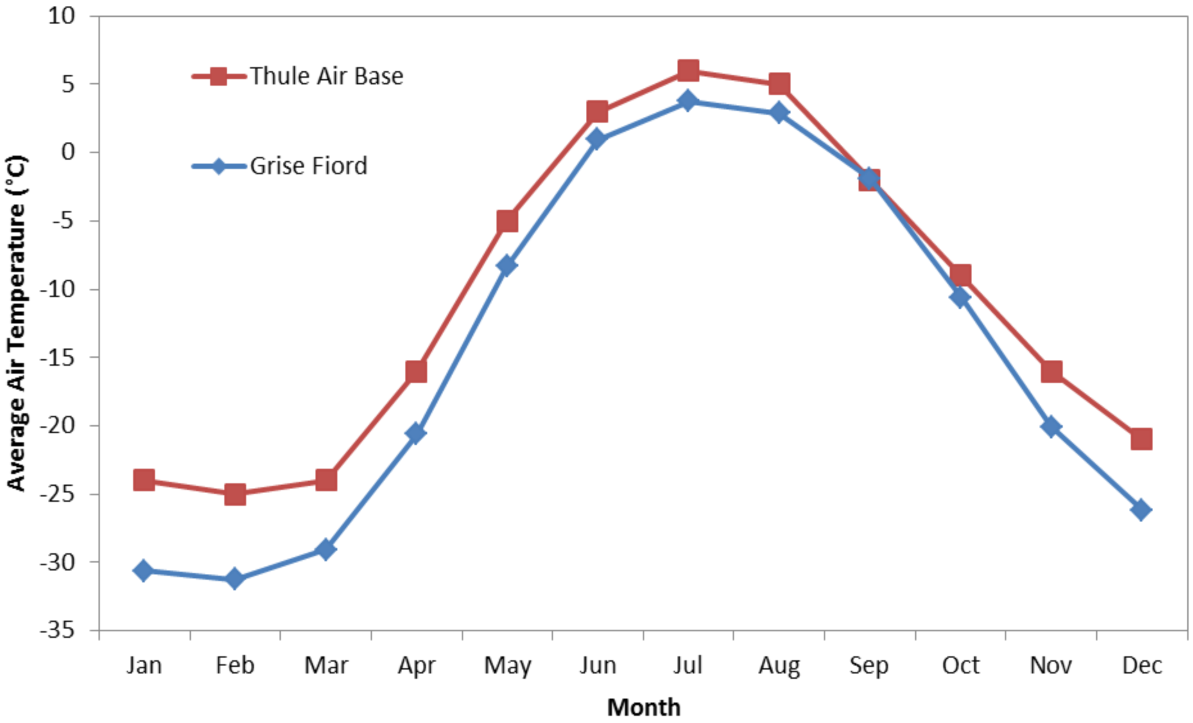

*Figure 5. Average monthly air temperature per year (1985–2015) collected from the meteorological station located at Thule Air Force Base (Thule Air Base 1 from CustomWeather, © 2019, Thule Air Base 2 from World Meteorological Organization (WMO). Environment Canada meteorological station located at Grise Fiord, NU). Note: Due to some missing data, mean monthly data at Grise Fiord is based on 24–29 out of 31 years of record.*

Systematic, regular, and standardized measurements of weather in the Canadian Arctic have been collected since the 1940s by Environment and Climate Change Canada (ECCC). However, sporadic weather observations and measurements in Canada date back to the Hudson Bay Company (e.g., Middleton 1735, Wilson 1982). The available weather data have been compiled and studied to examine changes over the past ~ 70 years, partially as a tool to assist in the projection of future trends in climate change. Some of the available assessments of recent change that are relevant to the North Water are presented here. Prowse et al. (2009) examined temperature and precipitation in four regions of Canada's north from 1948 to 2005 and came up with the following summations for the Arctic Mountains and Fiords region, part of which forms the western boundary of the North Water. Over the period of record, annual and winter temperatures increased by 0.8°C and 0.4°C, respectively. In addition, annual precipitation increased by 16% for the Arctic Mountains and Fiords region (Prowse et al. 2009). Similar trends have been noted for wind speed. Based on data from Alert and Clyde River, wind speed increased significantly over the 1954–2011 period for the Baffin Bay area (Steiner et al. 2013). At Alert, the increase is +0.33 m/s/decade and at Clyde River the increase is +0.58 m/s/decade (Steiner et al. 2013).

Zhang et al. (2011) examined data from existing weather stations in Canada to identify patterns in temperature and precipitation from 1950 to 2007. At the Eureka station, which is nearest to the North Water, there was a significant 1.5–3°C increase in mean daily air temperature over the sampling period. Resolute, Alert, and Clyde River all showed smaller increases of 0.5–1.5°C, but the change was only statistically significant at Resolute. Seasonally, changes were smallest in summer and largest in spring and fall. For precipitation, Eureka and Resolute showed significant increases of > 40%, while Clyde River showed a similar, but non-significant increase. No precipitation data were available for Alert. Seasonal increases in precipitation were largest in spring and winter. A study of multiple climate datasets for the 1950–2010 period showed a similar trend towards increasing temperatures and precipitation throughout the Canadian Arctic (Rapaić et al. 2015).

Changes have been observed by those that live in the region. Inuit elders from communities across Nunavut, including Grise Fiord, Clyde River, and Pond Inlet, have stated that the winds throughout Baffin Bay are now stronger, more erratic, and less predictable than they have been in the past (Nunavut Tunngavik Inc. 2001, Government of Nunavut 2012). Community members and hunters from Grise Fiord and Qaanaaq have both noted a number of observed environmental changes in the region. Importantly, they indicated that the ice-free season is now longer, with sea ice melting sooner and breaking up faster, and that the sea ice is less stable and there is less summer ice (Government of Nunavut 2012, Hastrup 2018). They are also observing glaciers melting and receding quickly. Additionally, wind and rain appear to be increasing, and storms in the spring and fall are now larger (L. Audlaluk, Hamlet of Grise Fiord, pers. comm.). In the remote communities surrounding the North Water polynya, sea ice is inextricably linked to travel, well-being, and ultimately freedom (Gearheard et al. 2013). With changes to the safety and presence of sea ice comes the loss of traditional travel routes, connectivity and hunting grounds. As Qaerngaaq Nielsen from Savissivik recounts in the 1980's, Inughuit from Savissivik were able to travel to Uummannaq, Morriussaq, and Qaanaaq across the sea ice, with only polynyas to avoid. Now, travel to other communities is unavailable by sea ice and has to occur via land, over a glacier (Gearheard et al. 2013) – a much more arduous journey for both humans and dogs. This is one of many stories describing rapid changes through the eyes of locals.

### 3.1.2. Sea Ice

#### 3.1.2.1. Formation of sea ice

The process of seawater freezing is no different in northern Baffin Bay than in other polar marine areas: heat is lost to the atmosphere and to space during the cold season. Seawater freezes at temperatures as low as -1.9˚C, depending on its salinity. During its early stage of development, wave action prevents an organized aggregation of ice crystals. This results in a granular crystal structure within the first 10–20 cm of ice grown, which traps as much as 30% of the salt from the seawater (Kawamura et al. 2001). A regular columnar crystal structure is established when ice becomes thick enough to damp out wind waves. This structure incorporates vertical crystal faces which facilitate drainage of brine, so that only about 10% of the salt is retained throughout much of the thickness of first-year ice (Nakawo and Sinha 1981).

In places where wide leads are opened by wind in relatively thick sea ice, waves can create floating beds of frazil ice (essentially slush) later in winter. The frazil is swept downwind towards the pre-existing thicker ice (Figure 6). If it remains in the lead, it develops into new ice in the usual manner. However, if it is carried beneath the adjacent thicker ice by current, it forms layers of saline granular ice at depth within the ice sheet. Such layers are well documented in marginal ice zones (ice fields bounded by open ocean) found at mid latitudes (Greenland Sea, Labrador Sea, and Southern Ocean). Kawamura et al. (2001) documented its occurrence in first-year ice in northern Baffin Bay in 1998, both near the shore of Ellesmere Island and at the floe edge near the North Water. Sea ice develops through the following stages: 1) new ice; 2) nilas; 3) young ice; 4) first-year ice (FYI); 5) old or multi-year ice (MYI) (Sater 1971, Canadian Ice Service 2005, Shokr and Sinha 2015).

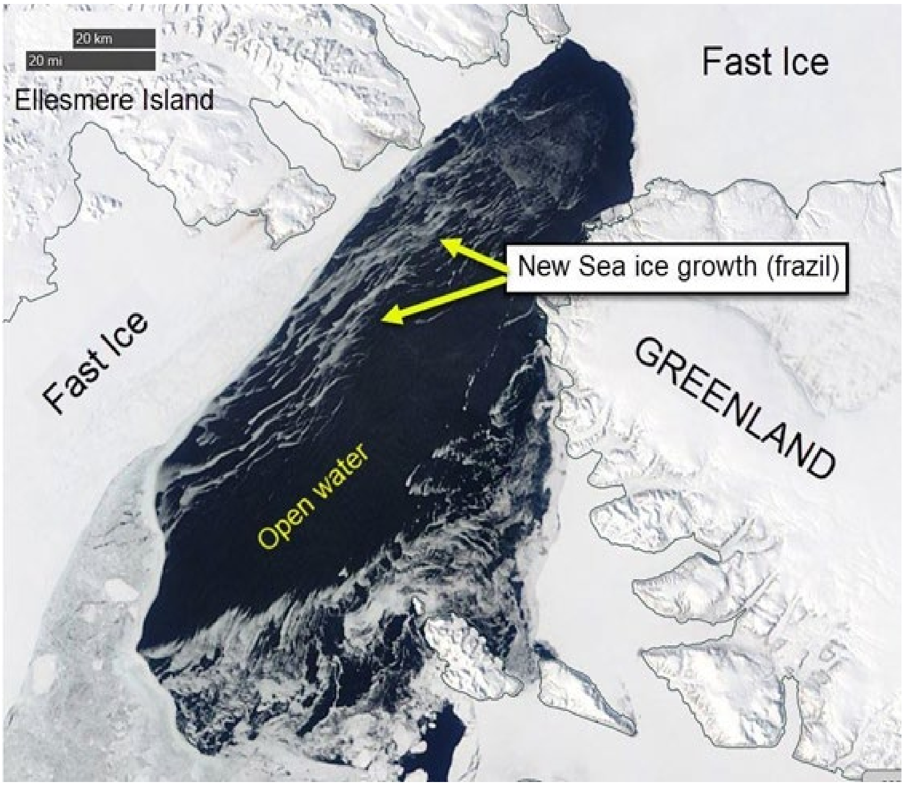

*Figure 6. The North Water on May 14, 2018, showing north-east winds pushing sea ice away from the fast ice, as well as new sea ice being generated (Source: Mark Brandon 2018, map image from NASA Worldview).*

New ice is a thin collection of randomly oriented ice crystals that are not completely frozen together. Nilas is a crust of ice up to 10 cm thick that is flexible and moves with waves. Young ice is the next stage of transition to FYI, with sub-stages of grey ice (10–15 cm thick) and grey-white ice (15–30 cm thick). Inughuit in northwest Greenland call this newly frozen ice *quasaq* (Gearheard et al. 2013). First year ice may be thin (30–70 cm), medium (70–120 cm) or thick (> 120 cm) but is a maximum of one year old. This classification is based on the thickness (a surrogate for age) of level sheets of ice. However, first-year ice only forms vast, level sheets in sheltered locations such as small bays and channels. Elsewhere it fractures in response to forces generated by wind and current, and the fragments are heaped into a network of sinuous mounds (ice ridges) separated by relatively small (less than a kilometre) floes of uniform level ice. Floes that survive transformations in form and structure (via partial melting and subsequent re-freezing) for at least two summers are termed old or multi-year ice (Markham 1878, Canadian Ice Service, Shokr and Sinha 2015). Multi-year ice is less saline, less dense and stronger than first-year ice, and presents an icescape of hollows and hummocks that is often heavily drifted with snow in winter.

Sea ice is also categorized by its state of motion. Sea ice begins life as pack ice – a mix of ice of various ages, level floes and ridges – that is free to drift in response to wind and current. Close to shore, in shallow water (less than 30 m) or where constrained by coastlines, the pack ice may stop moving in winter as its weakest ice thickens and strengthens. Movement stops when the strength of the ice cover as a whole is sufficient to resist the motive forces of wind and current. It is then known as fast ice. Ice immobilized by the grounding of ridge keels is simply fast ice; ice immobilized in very shallow water (less than a few metres), where it is grounded everywhere, is bottom-fast ice; ice immobilized by coastal confinement is known as landfast ice.

Inuit have a deep understanding of sea ice, and use a vast vocabulary of detailed terminology to describe the various states and motion of sea ice, as well as its relation to snow and human activities. Sea ice terminology from Inughuit in Qaanaaq is included in *The Meaning of Ice: People and sea ice in three Arctic Communities* by Gearheard et al. (2013) and should be referred to for a deeper understanding of the characteristics, variability and significance of sea ice. The book contains illustrations, created by Qaanaaq resident Toku Oshima, which display an astonishing depth of knowledge and detail. Single words can encompass an entire set of observations and experiences, such as *qaleriigginneq*; "when pieces of ice are pushed together and layered on top of each other; may be deceiving from the surface, e.g., one may try to make a hole through the ice and realize it is two pieces on top of each other" (p. 335; Gearheard et al. 2013). We recognize that Inuit Qaujimajatuqangit and local Inuit observations encompass a timeless and rich knowledge base of intimate sea ice observations. They are not presented in this report, but should be acknowledged as critical components within knowledge base of the sea ice environment in the North Water region.

#### 3.1.2.2. Movement of sea ice in northern Baffin Bay

Baffin Bay is connected to the Arctic Ocean in the north via Nares Strait. This relatively narrow (40 km) and long (550 km) strait through high mountainous terrain forms a pathway for the movement of air, ice and seawater between the larger water bodies. The general movement of all three elements is southward. Prevailing winds blow from the north because there is high air pressure over the Arctic on average and low pressure in Baffin Bay. Normally the Earth's rotation causes wind to blow around atmospheric highs and lows rather than between them. However, the high terrain bordering Nares Strait prevents this, so the wind blows down (or up) the strait rather than across it. Because the air is channelled by the strait, the wind can be extremely strong (Samelson and Barbour, 2008). Winds are fastest at the openings to wider parts of the strait, in northern Kane Basin and in northern Baffin Bay.

The principal driving mechanism for ice drift in Nares Strait is the wind (Samelson et al. 2006), with a secondary impetus provided by ocean current. Water would flow southward ("down-hill") through Nares Strait even without wind, because the Arctic sea level is higher than that in Baffin Bay. The water flowing out of the Arctic has low density relative to Baffin Bay and therefore, because of Earth's rotation hugs the Canadian side of Nares Strait; there is a weak northward flow on the Greenlandic side. The prevailing wind from the north augments the force of current on ice on the Canadian side and weakens it on Greenlandic, so there is an overall drift of ice into Baffin Bay from the north, with quantities fluctuating annually (Kwok et al. 2010).

Baffin Bay is wide enough to allow wind to circulate around the low air pressure that exists there on average. That circulation is counter-clockwise, northward on the Greenlandic side and southward on the Canadian; the circulation of the ocean and its ice cover in northern Baffin Bay reflect this. The ice moving up the Greenlandic coast follows the westward tending curve of Melville Bay to merge with the ice stream from Nares Strait drifting south from Smith Sound. Here again, southward ice movement is faster on the Canadian side because of terrain-amplified wind in Smith Sound and the complementary effects of wind and current. Southward ice drift as fast as 69 km/day has been documented (Ito and Muller 1982, Lewis et al. 1996, Vincent et al. 2001, Wilson et al. 2001).

Effects of passing weather patterns and tides are superimposed over shorter time intervals (days to seasons). Tidal current is sufficiently strong to reverse ice movement every 6 hours, except during the strongest winds (Dunphy et al. 2005). Moreover, when low-pressure systems move into the Arctic, the pressure drop towards Baffin Bay may be reversed and strong winds from the south may dominate Nares Strait, retarding or, particularly on the Greenlandic side reversing the southward drift of ice.

#### 3.1.2.3. Bridges of fast ice across Nares Strait

Much of the ice covering channels between the islands of the Canadian Arctic Archipelago becomes land-fast at some point during the winter, commonly by early December. This ice remains fast until appreciably weakened by thermal deterioration, typically by early August. In a channel, the boundary between fast ice and pack ice takes the shape of an arch that supports a bridge. Therefore, these boundaries in ice fields are commonly known as ice bridges. The outline of the arch delineates a curve in the ice cover where stress is compressive, which is the type of loading where materials display their greatest strength.

Any arch loses strength if the material forming it deteriorates, if it is unevenly loaded, or if its shape is disrupted. In ice fields, deterioration is linked to warming, softening, and melting of the ice in summer (Timco and Johnston 2002). Uneven loading may result from stronger current on one side of the arch than the other, and shape disruption may occur if the arch is loaded from the concave side so that it is under tensile stress, or if the ice melts away at the coastal points of contact, so that the compressive stress cannot be transferred to the land. Reversed loading can happen at any time with a strong reversal of wind, which has an effect analogous to removing a keystone from a masonry arch. Loss of coastal contact occurs annually in early summer with the progression of snow-melt on land.

Nares Strait is prone to frequent and very strong wind, in both directions (Samelson et al. 2006, Samelson and Barbour 2008, Melling 2011, Heineman 2018). Therefore, the location of bridge formation, and the timing of bridge formation and collapse, vary more from year to year than in other channels on the Canadian Polar Shelf (Lancaster Sound is the second most variable). Bridge formation is a stochastic process because sea ice is a granular material (the granules are strong floes in a matrix of weaker ice). This means that despite favourable conditions of loading, a bridge forms only if, by chance, a string of strong and appropriately shaped/oriented floes span the strait such that each need only resist compression (these floes are the analogue of the wedge shaped keystones of a masonry bridge). The ice bridge across Nares Strait forms most commonly across the opening from Kane Basin into Smith Sound. The loading of this bridge by wind from its convex side (the north side) quickly becomes evident in satellite images as the ice to the south of the bridge continues to drift south with that wind, to (briefly) expose a warm, ice-free sea surface (appearing dark in thermal-band satellite images). The Inuit of local communities are unable to travel on the sea ice and utilize the region for hunting if the ice bridge is not in place (Larry Audlaluk, Hamlet of Grise Fiord, pers. comm.).

Vincent (2019) examined the development and timing of the ice bridge across Nares Strait using Canadian Regional Ice Charts for 1968–1979 (with a sparse charting interval during winter) and using Advanced Very High Resolution Radiometry (AVHRR) from 1979 to 2019. Based on these observations it has been documented that ice bridges can form as far north as Robeson Channel and the Lincoln Sea (Kozo, 1991, Vincent 2019). This ice bridge is usually established by February, but seldom before December. It persists until June, July or early August (Kwok, 2005, Vincent, 2019). In recent years, the bridge's formation has tended to be later and its breakup earlier (Vincent 2019). The year 2007 was the first winter since observations began in the late 1960s that an arch failed to form across Nares Strait (Figure 7, Figure 8) (Vincent 2019, 2020). In the absence of an ice bridge nothing blocks ice drift from the Arctic Ocean, resulting in additional annual ice loss from the Arctic Basin in the order of 20,000 to 30,000 km$^2$, most of which is multiyear ice (Kwok et al. 2008, Moore et al. 2017, 2019). Several authors have suggested that an ice bridge across Smith Sound is a necessary condition for polynya formation (Barber et al. 2001a, Yao and Tang 2003, Dumont 2019, Mosbech and Kyhn 2019). However, Vincent (2019, 2020) showed that since 2007, there have been four springs with no ice bridge in Smith Sound (2009, 2010, 2017, 2019), but a bridge instead at the northern end of Nares Strait still allowed the polynya to form (Figure 8). In each of these years, Nares Strait was blocked for an average of 71 days each year by northern ice arches, appreciably less time than the 173-day average from 1979 to 2019 when the ice bridge was in Smith Sound (Vincent 2020). The average position of the ice bridge in Smith Sound has been further north since 2007, resulting in the eastern edge being further from land and perhaps more susceptible to collapse (Figure 7) (Vincent 2020).

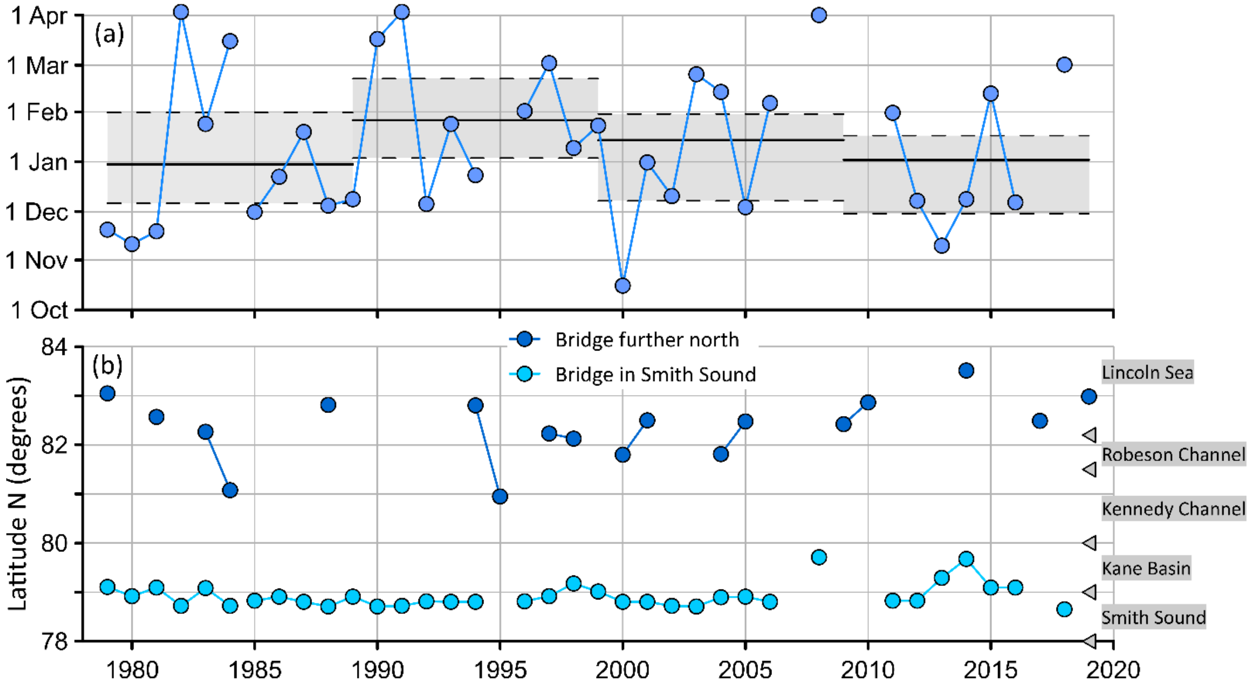

*Figure 7. Annual variation of the ice bridge across Nares Strait during winters since 1978–1979, at the start of the satellite era: (a) Date on which the ice bridge stabilized in the vicinity of Smith Sound during winters when it did so; the horizontal lines mark decadal means with shading representing the 95% confidence limits; (b) Latitude of the northernmost point of ice bridges that formed in Smith Sound and at locations further north. Ice-bridging dynamics clearly favour Smith Sound, but the northern widening of Nares Strait into the Lincoln Sea also seems to provide favourable conditions. The data are from Vincent (2019); values are plotted against the ending year of each winter.*

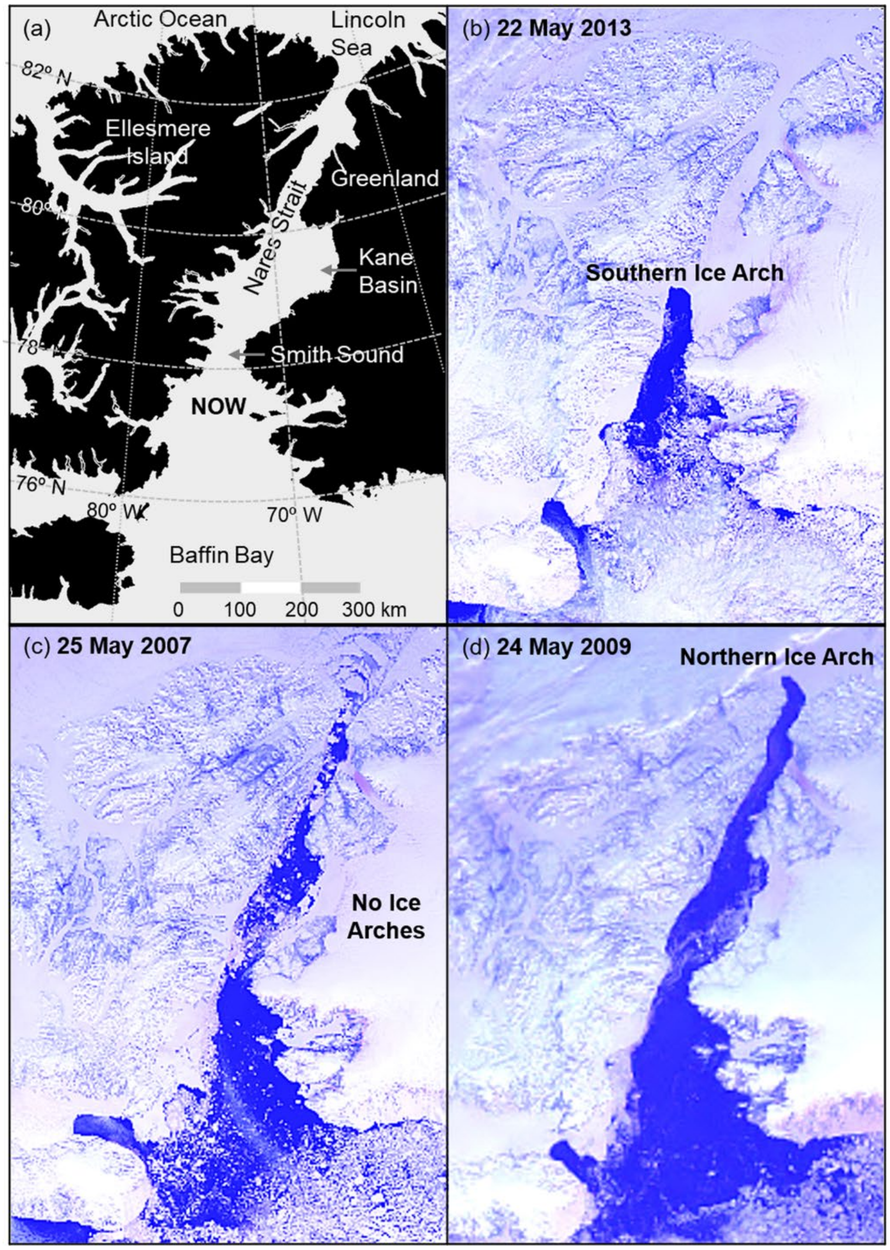

*Figure 8. (a) The North Water region. (b) An ice arch (or bridge) at the narrow head of Smith Sound which historically defines the northern boundary of the polynya, creating the iconic shape of the polynya. (c) In 2007, the Smith Sound ice arch failed to consolidate for the first time on record. (d) In 2009, the Smith Sound ice arch again failed to form, but an anomalous ice arch at the northern point of Nares Strait dominated the region (Source: Vincent 2019).*

### 3.1.2.4. Formation of the North Water in northern Baffin Bay

The North Water is delimited by landfast ice along the coasts of Ellesmere Island to the west and Greenland to the east. It opens into Smith Sound (in the north-west), but this opening is commonly bridged by fast ice during at least a part of most winters. The southern edge of the North Water is diffuse because the thickness of ice in the polynya increases with distance southward (Dunbar 1969, Steffen 1986, Smith et al. 1990). The polynya reaches its maximum extent (estimated at 80,000 km$^2$) in early summer (May–June), just before its expansion from the north merges with an expansion of open water from the south-east along the Greenland coast. At this time it occupies the length of Smith Sound and the northern part of Baffin Bay, and can extend as far south as Bylot Island in the west and to Melville Bay in the east (see Figure 1 and Figure 2) (Dunbar 1969, Steffen 1985, 1986, Barber et al. 2001a). After that time the surrounding ice disappears and the polynya ceases to exist by definition.

Observational and modeling studies (Barber et al. 2001, Melling et al. 2001, Biggs and Willmott 2001, Yao and Tang 2003, Moore and Vage 2018, Heinemann 2018) have demonstrated convincingly that the North Water is the consequence of rapid wind-forced movement of sea ice southward from the narrow northern end of Baffin Bay. This drift leaves the sea surface open for some distance, despite rapid re-freezing under cold wintertime conditions at this latitude. As previously stated, the strong prevailing north wind results from the drop in air pressure between the Arctic Ocean and Baffin Bay. The speed of the wind is amplified by channelling of airflow from the Arctic into Nares Strait and by the omnipresent polar inversion, which strengthens the channelling and reduces slowing of the wind by friction at the surface.

The common presence of an ice bridge across Smith Sound in the winter helps to maintain light ice cover by eliminating ice influx to the North Water. However, it is not a key element, since bridges forming further north play a similar role. The influx of old ice from the north does not resume until the bridge(s) breakup in early August (Kwok 2005, Kwok et al. 2010). New ice forming on wind-opened water in the north drifts steadily southward at 20–30 km/d, thickening with time by freezing and ridging as it travels (Ito 1982, Barber et al. 2001a, Melling et al. 2001, Wilson et al. 2001, Pikialasorsuaq Commission 2017, Langen et al. 2018). In general terms, one should expect the ice types to be arranged in bands according to age with distance to the south. Indeed, early studies by Ito (1985) reported higher concentrations of open water, nilas, and grey ice within Smith Sound than further south. Nonetheless, covers of young ice are dynamic and easily disrupted, so appreciable new ice is expected in leads found far to the south of Smith Sound, as shown by Steffen (1986). Thick first-year ice is not usually found within the North Water until March, the coldest part of winter (Steffen and Ohmura 1985). Multi-year ice does drift into northwestern Baffin Bay during late summer and autumn (Dey 1980, Mundy and Barber 2001), but is usually absent north of Baffin Island by winter (Agnew 1998, Environment Canada 2010, Tivy et al. 2011). While the majority of ice moves southward, there is some ice that drifts northward along the Greenland coast (Wilson et al. 2001).

#### 3.1.2.5. Seasonal Patterns

The North Water is a seasonal feature of the ice cover in northern Baffin Bay. As such, its variation over the course of each year reflects the variation in the factors controlling the character of sea ice in the area, namely:

- Influx of old ice from the north in late summer
- Freezing beginning in the autumn and continuing into May
- General southward drift of both old and new ice
- Possible stoppage of ice influx by fast-ice bridging in the north during winter
- Melting with the return of 24-hour insolation in May
- Renewal of ice influx with the collapse of northern ice bridges in July or August

All of Baffin Bay is largely ice-free during summer (late July through early September), so that, by definition, the polynya does not exist (Dunbar and Dunbar 1972, Barber et al. 2001a).Between November and February, more than 50% of the North Water is ice-free or covered only by nilas and young ice (Steffen and Ohmura 1985). The young ice is largely grey-white, measuring 15–30 cm thick (Steffen and Ohmura 1985). Mundy (2000) and Mundy and Barber (2001) described the distribution of different types of ice in the North Water during winter, spring, and fall of 1998. In the winter, they identified four distinct ice type assemblages: 1) areas with thick FYI along all coasts; 2) rubble, MYI, and FYI ice north of Smith Sound and along the western side of the North Water; 3) young, thin and medium FYI, and some open water east in Smith Sound; 4) thin FYI in the southern half of the North Water. Ice concentration within the North Water reaches a maximum in January (Barber et al. 2001a), with a mix of MYI and FYI that form a complete ice cover throughout the area, save for leads that are typical in drifting ice (Steffen, 1986). Older data reveal ice is generally thinner on the Greenland side by about 30–50 cm (Steffen and Ohmura 1985, Barber et al. 2001a, Tang et al. 2004). Landy et al. (2017) estimated a smaller difference, about 20 cm, for the winters of 2003–2016.

The area of the polynya varies during winter depending on how fast new ice drifts downwind from the ice bridge (primarily controlled by wind speed) and how rapidly new ice forms on open areas (primarily controlled by air temperature and upwelling). If an ice bridge is in place as winter transitions to spring, new ice formation slows and then stops, so that the polynya expands as older ice continues to drift southward. Most of the North Water is covered by young and thin FYI and open water at this time.

The appearance of extensive ice-free areas in the North Water coincides with the return of daylight, and is accelerated by solar warming of the upper ocean in areas that are free of ice (Yackel et al. 2001). Melting starts earlier in the south-east corner of the North Water and progresses northwest, with extensive open water appearing in the first half of May (Müller et al. 1975, Dey et al. 1979, Barber et al. 2001a, Barber and Massom 2007). The Greenland coast clears faster because of the relative warmth of the West Greenland Current and the warmer spring climate associated with it (Barber et al. 2001a, Yackel et al. 2001, Barber and Massom 2007, Environment Canada 2010). Kawamura et al. (2001) documented some decrease in ice thickness within Smith Sound between April and May; the area can quickly become ice-free as large floes break from the fast ice of the bridge (Vincent et al. 2001).

By the third week of June, open water generally extends from Smith Sound to Devon Island (Markham 1981); the polynya reaches its maximum extent by late June or early July (Dunbar 1969, Barber et al. 2001a). The North Water continues to expand until it eventually merges with open water expanding northward from Davis Strait, thereby creating a largely open ocean by August (Barber et al. 2001a, Environment Canada 2010, Preußer et al. 2015). Eventual collapse of the ice bridge across Smith Sound re-establishes the drift of heavy ice into the North Water, where it tends to stream down the eastern coast of Ellesmere Island. Meanwhile ice remains plentiful in Nares Strait throughout the summer because of its continual replenishment from the Lincoln Sea (Tivy et al. 2011).

## 3.1.3. Glaciers, Ice Caps, and Icebergs

### 3.1.3.1. Glacier-Ocean Interactions

The Eastern Canadian Arctic contains over a third of the world's Arctic glaciers and ice caps, and the last remaining ice shelves in the Northern Hemisphere (Copland et al. 2018). These features not only contribute diversity to the landscape of Nunavut and provide unique habitat for life living under extreme conditions (Copland et al. 2018), but also act as sentinels of climate change. Today, glaciers are extensive in northwestern Greenland and the Queen Elizabeth Islands, with many marine-terminating glaciers in the vicinity of the North Water. IQ identifies the glacier near Qaanaaq as a "glacier that produces enormous icebergs" (Pikialasorsuaq Commission 2018). Since the 2000s, glacial retreat rates have sharply increased across the Greenland ice sheet (Murray et al. 2015; Figure 9A) and along Ellesmere Island (Gardner et al.

2011, Cook et al. 2019, Figure 9B). Local observations on glacial retreat are often tied to the inability to use old land travel routes due to lack of snow and ice cover in recent years compared to historically (Gearheard et al. 2013).

Melt rates of marine-terminating glaciers on the Greenlandic side are largely controlled by oceanic forcing causing submarine melt (Holland et al. 2008, Chauché et al. 2014, Rignot et al. 2016), though they are also highly influenced by subglacial discharge rates regulated by atmospheric conditions (Straneo and Canedese 2015). Subglacial discharge enters the fiord waters through a complex network of subglacial channels at the base of the glacier's front (Chu 2014). This creates buoyant plumes which entrain ambient water, bringing it in contact with the glacier, further driving submarine melt (Fried et al. 2015, Straneo and Canedese 2015). Ocean currents across the continental shelf and over the sills of fiords are also important in determining melt rates (Straneo and Canedese 2015, Willis et al. 2018). In contrast, retreat rates on the Canadian side are primarily controlled by the atmospheric conditions causing surface melt, ocean forcing is less important (Copland et al. 2018, Cook et al. 2019). This difference between Greenland and Canada in oceanic influence on glacial melting reflects the cyclonic circulation of seawater in Baffin Bay, whereby relatively warm, saline water from the Atlantic flows northward along the west coast of Greenland while cold water from the Arctic flows southward along the eastern coasts of Ellesmere Island and Baffin Island (Münchow et al. 2015). Additionally, most glaciers on the Canadian side terminate in relatively shallow water (< 300 m) and are less affected by intrusion of warm water which is generally found only at greater depth. Glaciers in Greenland are thicker, extending to depths of 600 m or more, well into the Atlantic layer (Cook et al. 2019). That said, ocean forcing of mass loss may be important for individual deep terminating Canadian glaciers (e.g., Trinity and Wykeham Glaciers, Ellesmere Island), although this has yet to be established definitively (Wychen et al. 2016, Harcourt et al. 2020, A. Hamilton, University of Alberta, pers. comm.).

The discharge of meltwater at the grounding line has a different impact on nearby ocean stratification and circulation than surface meltwater discharge. Submarine meltwater and subglacial discharge rise as plumes near the glacier front, entraining ambient water, until they reach their level of neutral buoyancy, possibly the surface, and drift away from the ice-front (Straneo and Canedese 2015). While literature on glacier-ocean interactions from the Canadian side is limited, there have been studies on glacial fiord dynamics in Greenland. The depth of the glacier front appears to play a significant role in determining the impact of a glacier on its surrounding water, with deeper glaciers causing more vigorous entrainment of warm subsurface waters and thus having a greater effect on surrounding fiord waters (Hopwood et al. 2018, Willis et al. 2018). For instance, Willis et al. (2018) found that the Tracy Glacier, which terminates in Inglefield Gulf, modifies downstream fiord waters to a much greater extent than the nearby, shallower, Heilprin Glacier, despite the larger subglacial discharge from the latter.

Iceberg plume events (defined as "a mixture of freshly calved glacier ice and the ice mélange in front of the glacier terminus that are produced when icebergs are calved") vary in frequency and magnitude and are controlled by glacier velocity, terminus retreat rates, and the presence of adjacent sea ice (Dalton et al. 2019). As such, iceberg productivity is more heavily influenced by submarine melting on the Greenlandic side (Rignot et al. 2010, Dalton et al. 2019). Plume-driven melting also contributes to the erosion and undercutting of glacier termini, thus enhancing calving rates (Fried et al. 2015, Rignot et al. 2015). Additionally, glacial meltwater from Greenland and Ellesmere Island has significantly increased in recent decades, resulting in a strong freshening of the surrounding waters (Bamber et al. 2012). This may further stratify the surface waters within the North Water region, inhibiting vertical heat- and nutrient-transfer from deeper waters.

In calving, glaciers produce icebergs and tabular ice islands which drift southward from Nares Strait into Baffin Bay, or northward with the West Greenland Current to cross the North Water and join the southward flow on the Canadian side. The presence of sea ice at the terminus of marine-terminating glaciers is a major control on the seasonal timing of iceberg calving for glaciers on both the Canadian (Dalton et al. 2019) and Greenlandic side (Carr et al. 2013). Calving events are expected to increase as the climate warms (van den Broeke et al. 2009, Gardner et al. 2011, Nick et al. 2013), resulting in more icebergs and ice islands moving through Nares Strait.

Large ice features, if grounded, can slow down ice drift and promote consolidation of pack ice. They may also influence the timing and location of ice-bridge formation (Kubat et al. 2006). Indeed, an ice-island (WH-5; 20 km by 9 km) came up against Hans Island in Nares Strait and lodged there in mid-February 1963 (Nutt 1966). In this position the ice island formed an effective barrier to the southward movement of sea-ice from the Arctic Ocean. A polynya quickly appeared south of the obstruction because of continued southward sea ice drift there. The ice island remained in place until July 22, maintaining this polynya until it shifted and broke into 3 main fragments. They were observed in Kane Basin by the end of July and in Baffin Bay by the end of September.

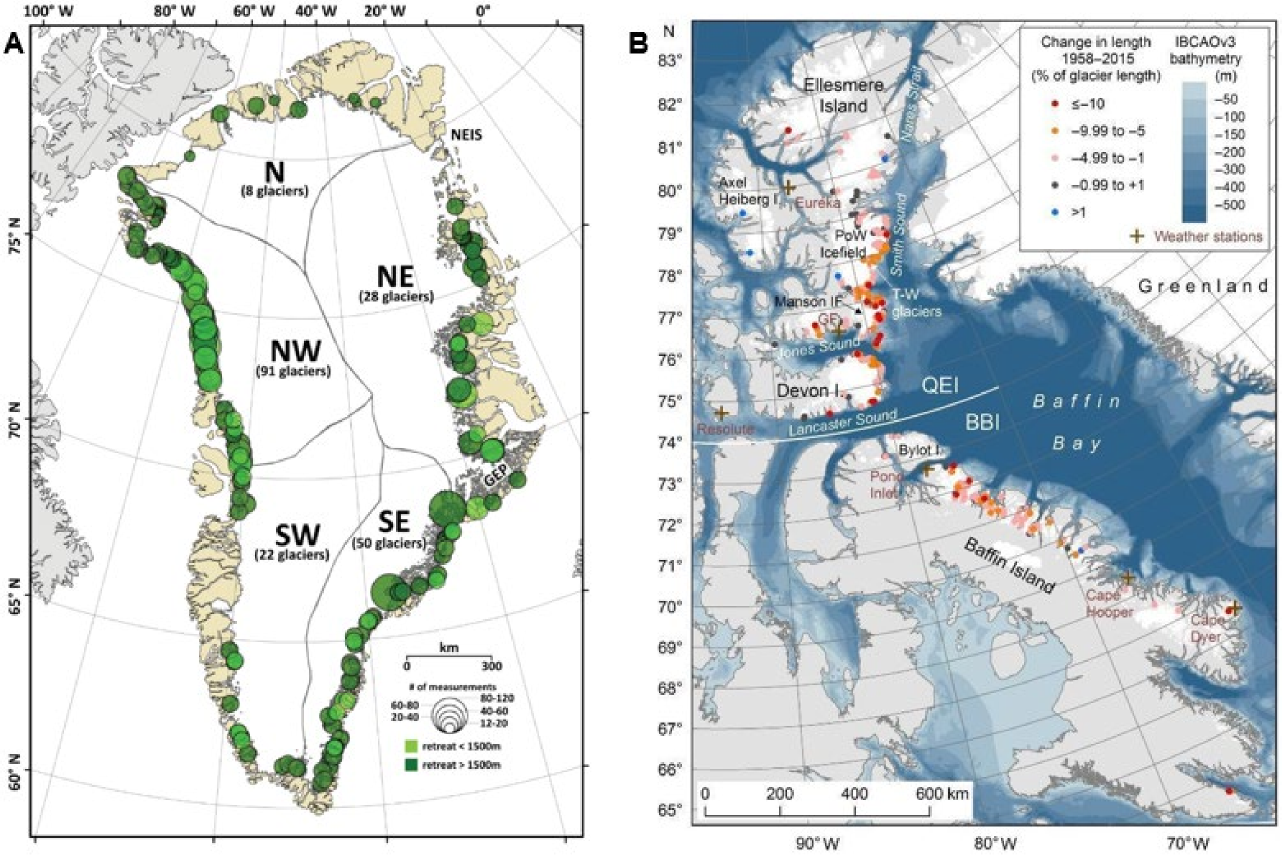

*Figure 9. A) Location of the glaciers on Greenland ice sheet, the circle size indicates the number of measurements between 2000 and 2010. Dark green indicates glaciers with more than 1500 m retreat. Numbers are the total number of glaciers in each region of the ice sheet, GEP is the Geikie Plateau region, and NEIS is North-East Greenland (Source: Murray et al. 2015). B) Spatial patterns of marine-terminating glacier front change from 1958/1959 to 2015 (as the percentage of glacier length in 2000). Grise Fiord (GF) weather station; PoW Icefield, Prince of Wales Icefield; Manson IF, Manson Icefield; T-W glaciers, Trinity and Wykeham glaciers (Source: Cook et al. 2019).*

#### 3.1.3.2. Freshwater Fluxes from Glaciers and Ice Sheets

The flux of fresh water carried in the ocean through the North Water and into northern Baffin Bay is a combination of fresh water diluting the Canadian Arctic through-flow (Arctic Surface Water and Pacific Water components), direct precipitation, ice meltwater, runoff from the Canadian Arctic Archipelago and runoff from surrounding glaciers and ice caps (Mernild et al. 2012). Based on year-round observations between 2003 and 2009, Muenchow (2016) estimated movement of seawater and freshwater through Nares Strait; yearly mean fluxes ranged from 0.71 to 1.03 ± 0.1 million $m^3$/s for volume and from 32 to 54 ± 10 thousand $m^3$/s for oceanic freshwater relative to a salinity of 34.8 (1000–1700 $km^3$/y) . Advection of ice adds another 8 ± 2 thousand $m^3$/s or 260 $km^3$/y to the freshwater export. Flux values are larger when the sea ice is mobile all year (Muenchow 2016).

This freshwater is delivered to the Arctic Ocean by rivers, inflow of Pacific water and precipitation less evaporation. The largest component (38%) is river discharge (Dyurgerov and Carter 2004, Serreze et al. 2006). However, most of this discharge originates at mid-latitudes in Eurasia and North America. The islands and land masses near the North Water are arid and their rivers are small and frozen most of the year (McLaren 1981, Woo et al. 2000, McLaughlin et al. 2004, Carmack and Wassman 2006). Therefore, direct river inflow is likely only a small fraction of the freshwater input in the North Water, although no local discharge data are available.

Locally, glaciers and ice caps likely contribute more freshwater than rivers. The Greenland Ice Sheet is the largest reservoir of freshwater in the Northern Hemisphere and its size is decreasing (Bamber et al. 2001, Ettema et al. 2009, Hofer et al. 2017). Some of its meltwater reaches the North Water. The Petermann Glacier in northwest Greenland melts in Nares Strait (Munchow et al. 2014). Along the west coast of Greenland where tide-water glaciers are rapidly retreating, freshwater enters the north-flowing coastal current. Run-off from Greenland's ice sheet has increased since 1990, and represents roughly half of the recent ice sheet mass loss (Hanna et al. 2008, van den Broeke 2009, Mernild et al. 2012). Records indicate that mass loss of Greenland's ice sheet in northwest Greenland, an area adjacent to the North Water, has increased since 2006 (Khan et al. 2010, Rignot et al. 2011).

Mernild et al. (2012) modeled runoff magnitudes in Greenland and their changes over time. The model suggested that the total freshwater runoff from Greenland increased 30% from 1960–2010, averaging 481 ± 85 $km^3$ $y^{-1}$. Specifically, runoff to Smith Sound, Baffin Bay, Davis Strait, and the Labrador Sea was predicted to be 237 $km^3$ $y^{-1}$, or 49% of the total Greenland runoff. Meanwhile, Bamber et al. (2018) suggested the up-to-present cumulative anomaly of melt from Greenland into Baffin Bay, compared to the 1960–1990 mean, was 1,864 $km^3$. The mass loss rate from land ice in the Canadian Arctic Archipelago has more than doubled from 11.9 $km^3$ $y^{-1}$ (pre-1996) to 28.2 $km^3$ $y^{-1}$ (Noël et al. 2018). The total delivery of land-ice meltwater to the Baffin region is therefore about 265.2 $km^3$ $y^{-1}$. In oceanographic terms, this is equivalent to about 8.4 thousand $m^3$/s, still a small fraction of the estimated freshwater transport by the Baffin Island Current, 187 thousand $m^3$/s (Munchow et al. 2015).

### 3.1.4. Physical Oceanography

#### 3.1.4.1. Bathymetry

Precambrian igneous and metamorphic rocks dominate the bedrock on the Canadian and Greenlandic sides of the North Water (Maclean et al. 1990). Baffin Bay is a sedimentary basin with deposits as thick as 14 km (Maclean et al. 1990). The surficial marine sediments are of glaciomarine origin, predominantly gravelly, sandy mud with clayey silts in the deep trenches around the Carey Islands (Blake et al. 1996).

The North Water region is characterized by a fairly deep, centrally located channel that extends from Kane Basin southward into Baffin Bay (Figure 10). This channel reaches a depth of 700 m (Bâcle 2000) and was excavated by a south-flowing ice stream during the Ice Age (Blake et al. 1996). The channel has a fairly uniform U-shape with steep sides. In northern Baffin Bay the main channel is located much closer to the Greenland coast than to Ellesmere Island. It is flanked on both sides by waters less than 500 m deep that are more extensive towards the west (Figure 10). Another deep channel (> 500 m for most of its length) extends from the Greenland coast west through Inglefield Bredning and then south towards the Carey Islands (Figure 10). A similar 500-m deep channel extends east from Talbot Inlet on Ellesmere Island. South of 75°N, average depths of 500 m gradually increase to the 2,400-m deep basin in Baffin Bay (Bâcle 2000).

Knowledge of water depths in the near-shore region along the coasts of Ellesmere Island and Devon Island is scarce, with large gaps in coverage. Existing charts are based, in part, on unreliable spot soundings from early explorers. Since seabed topography is so critical to all aspects of oceanography, this lack of data constrains our present understanding. Enhanced hydrographic survey effort on the Canadian side of the North Water is strongly recommended for future work in the region. Bathymetry on the Greenland side is better defined thanks to surveying conditions that are less impeded by sea ice (Morlighem et al. 2017, Fenty et al. 2016).

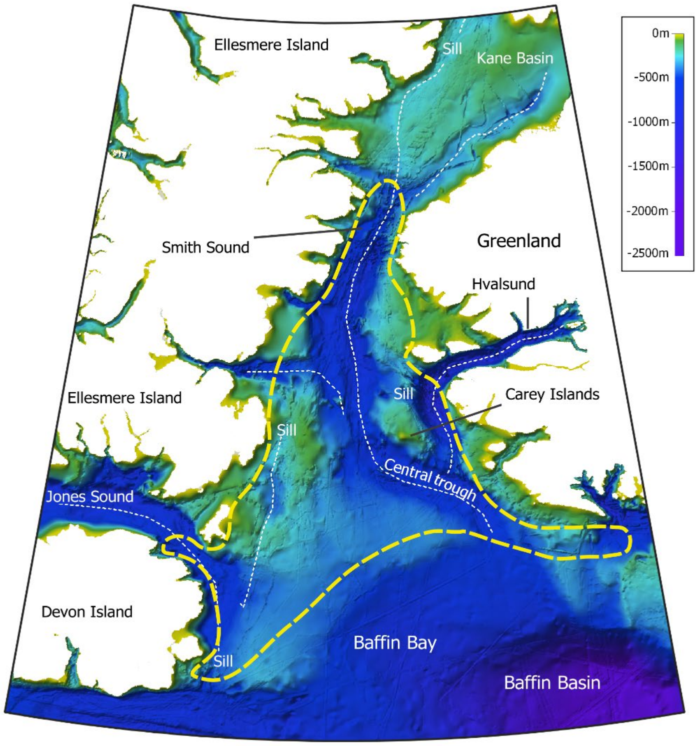

*Figure 10. Seabed topography (in meters) of the North Water region. The yellow dashed line represents the May monthly mean extent of the polynya, adapted from Dunbar (1969). The deep troughs are marked with white dashed lines and the locations of sills are indicated (data from [International Bathymetric Chart of the Arctic Ocean (IBCAO) ver. 4]).*

Northern Baffin Bay is linked to Lancaster and Jones Sound in the west, and to Nares Strait via Smith Sound in the north. However, shallow constrictions (sills) partially impede the free flow of seawater to northern Baffin Bay via these pathways. Inflow from the north is impeded by a 220 m deep sill in Kane Basin (Birch et al. 1983, Addison 1987). Sills no deeper than 125 m exist to the west and north-west of Lancaster Sound and the deepest path into Jones Sound from the west is 180 m. A sill at about the same depth obstructs flow from Jones Sound into Baffin Bay east of Coburg Island (Addison 1987). A 640 m deep sill in Davis Strait separates the deep waters of Baffin Bay from the Labrador Sea (Bâcle 2000). Ice movement is restricted by the width of these pathways, with Kennedy Channel having a minimum width of 25 km, Lancaster Sound a minimum width of 65 km, and Davis Strait a minimum width of 320 km (Munchow et al. 2015).

#### 3.1.4.2. General Circulation

The net flow of seawater through the Canadian Arctic Archipelago is from the northwest towards the southeast following a downward slope of the sea surface from the North Pacific Ocean to the North Atlantic Ocean. This slope exists because upper waters of the Pacific are less salty and lighter than those of the Atlantic (Stigebrandt 1984, Kliem and Greenberg 2003, McLaughlin et al. 2004). The elevation difference between the Pacific and Atlantic Oceans is estimated to be about 65 cm, with a drop of about 50 cm through Bering Strait and the remainder (15 cm) through the straits of the Canadian Arctic Archipelago (Muench 1970, Stiegbrandt 1984, Melling 2000). The sea-surface elevation of the Arctic's Canada Basin appears to have increased over the last two decades, driven by increasing air pressure over the northern Beaufort Sea and the consequent accumulation of low salinity seawater in the Beaufort gyre (Steele and Ermold 2007, Rabe et al. 2014, Armitage et al. 2016, 2018). Such spin-up of the Beaufort gyre draws down sea level around its perimeter and reduces the flow of water towards Baffin Bay (Peterson et al. 2012). Freshening of Baffin Bay, especially from enhanced Greenland melt and lifting of sea level in that basin, may also be reducing the gradient and flow of water through the archipelago (e.g., Castro de la Guardia et al. 2015, Grivault et al. 2017).

The flow through the Canadian Arctic Archipelago has two components, one of relatively low salinity moving south-eastwards from the central Arctic, and a weaker one of higher salinity moving north-westwards from Baffin Bay towards the central Arctic (Melling 2000). Earth's rotation causes each flow to hug the coastline to the right of its direction of flow; the difference in salinity keeps the core of the north-westward flow at a greater depth. This flow towards the central Arctic has been detected almost to the margin of the Arctic Basin via Nares Strait (Münchow et al. 2008, Gillard et al. 2020), Lancaster Sound, and other key pathways, although its properties become less distinctive with increasing distance from Baffin Bay (Münchow et al. 2007). This occurs because the counter flows mix as they slide past each other.

Water enters the North Water via the Canadian Arctic Outflow (CAT) from the north through Smith Sound and via the West Greenland Current coming north from Davis Strait along the eastern side of Baffin Bay; additional Arctic outflows via Jones and Lancaster Sounds on the western side of Baffin Bay are too far south to have much effect on the North Water (Muench 1970, Tang et al. 2004) (Figure 11). Most of the water reaching Baffin Bay via the Arctic Ocean originates in the North Pacific via Bering Strait (Jones et al. 2003, Münchow et al. 2007, Hu and Myers 2013). Arctic Surface Water – a strong mixture of terrestrial run-off with Pacific Water – also reaches Baffin Bay at an appreciable rate. A weak mixture of Atlantic-derived water with Pacific Water contributes only marginally because sills (submerged ridges) across contributing straits block passage of such saline (dense) water. The 15 cm sea-level drop from the Arctic to Baffin Bay is the primary driver of flow from the Arctic into Baffin Bay (Münchow et al. 2008). However terrain-channelled and intensified surface winds accelerate the flow into the North Water via Nares Strait (Samelson et al. 2008, Barber et al. 2019) and to lesser extent via Jones and Lancaster Sounds.

Estimates of the strength of seawater circulation around Baffin Bay come from data acquired as early as 1928 (Kiilerich 1939). Barnes (1941) used data from 1928 and 1940 to create a first sea-level topography map, and observations from the 1950s and 1960s have been discussed by Palfrey and Day (1968) and Muench (1971). Data reveal a net southward flow out of Baffin Bay at a rate of 1–3 million cubic metres per second, with high year-to-year variation. Data collected during 2004–10 across Davis Strait might suggest a substantial decrease from earlier estimates (Curry et al. 2014, Munchow et al. 2015), although the difference may be readily attributable to inter-annual variation and limitations of the observational data sets (Barber et al. 2019).

Circulation within Baffin Bay is baroclinic, which means that the location and strength of currents are shaped by the differences in temperature and salinity across the bay at each depth (Figure 11, Muench 1971, Tang et al. 2004). The general movement of seawater around Baffin Bay is counter-clockwise (Muench 1971, Fissel et al. 1982, Ross et al. 1991, Melling et al. 2001). The West Greenland Current (WGC) flows up the west coast of Greenland to Melville Bay where most of its water turns west along the 600-m depth contour towards Devon Island (Figure 11). The lesser fraction continues north along the Greenland side and enters Nares Strait (see below for a detailed description of this water mass). The greater fraction crossing Baffin Bay merges with water flowing south from Nares Strait. This combined flow turns south on reaching Ellesmere Island, but splits again into greater and lesser fractions when passing the entrance to Jones Sound. The lesser fraction heads west along the north side of the sound while the greater continues south, to be joined by a second Arctic outflow emerging along the south side of Jones Sound. The same split-and-merge pattern occurs when the south-flowing current reaches Lancaster Sound. Beyond Lancaster Sound, the continuing southward flow is known as the Baffin Island Current (BIC) (Fissel et al. 1982, Wang et al. 2012). It has been observed moving water down the western side of Baffin Bay at a rate of 5.1 ± 0.3 Sv during the summer (Munchow et al. 2015).

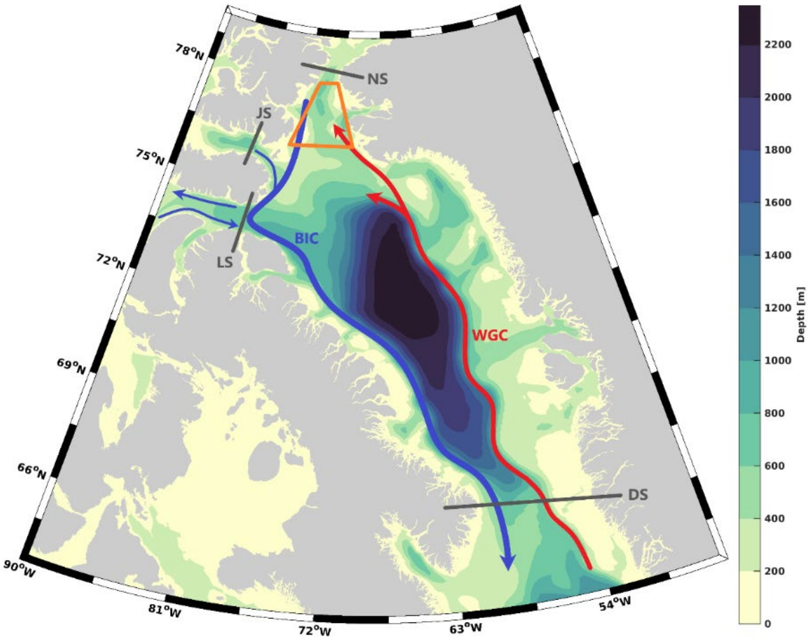

*Figure 11. A simple depiction of bathymetry (depth in meters) and ocean circulation in Baffin Bay/Davis Strait (DS). Atlantic inflow water moves north via the West Greenland Current (WGC-red) into the North Water region (orange polygon), while Jones Sound (JS), Lancaster Sound (LS), and Nares Strait (NS) all transport water from the Arctic Ocean into Baffin Bay via the Baffin Island Current (BIC-blue) (Source: Buchart et al. submitted[1])*

### 3.1.4.3. Structure of water column

There are four distinct layers of seawater within Baffin Bay: (1) Arctic outflow water of relatively low salinity (Arctic Surface Water: ASW), close to freezing temperature for much of the year but as much as 7°C warmer for 2–3 months in summer; (2) Arctic outflow water (Pacific Water: PW) of higher salinity (up to about 34.1), above its freezing temperature but cooler than 0°C, rich in dissolved nutrients; (3) Atlantic inflow via the West Greenland Current, warmer (up to 2°C) and yet more saline, referred to as the Atlantic Intermediate Water (AIW); (4) Baffin Bay Deep Water (BBDW) below about 1,200 m depth, with salinity comparable to the AIW, but temperature below 0°C. The interfaces between these layers have transitional properties that result from mixing across the boundaries (Bourke et al. 1989, Bâcle 2000, Tang et al. 2004, Curry et al. 2014).

The ASW extends to about 100 m in northeast Baffin Bay and to more than 200 m in the northwest. During the summer months, this water is freshened by ice melt-water near the surface and may be warmed by insolation to as deep as 75 m (Bâcle 2000). PW extends to about 300 m in the northwest and AIW to 1,200 m (Bâcle 2000). The BBDW is likely decades old (or older) because water of such high density is not currently observed to pass over the sills to the north and to the south. There is no consensus on the origin of this water mass. Table 1 provides a summary of the characteristics of the water masses found within the North Water.

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[1] Buchart L., Castro de la Guardia, L., Xu, Y., Ridenour, N., Marson, J,M., Deschepper, I., Hamilton, A.K., Grivault, N., and Myers, P.G. Submitted. Future Climate Scenarios for northern Baffin Bay and the Pikialasorsuaq (North Water Polynya) region. Atmos-Ocean. Submission # AO-2021-0014.R1.

Jones Sound, Lancaster Sound, and Nares Strait all transport water from the Arctic Ocean into Baffin Bay (Muench 1970, Tang et al. 2004, Munchow et al. 2015). Before arriving at Baffin Bay, this Arctic water passes over sills that restrict flows: a 180 m sill at the west end of Jones Sound (at Cardigan Strait); a 125 m sill in Lancaster Sound (at Barrow Strait); and a 220 m sill in Nares Strait (at Kane Basin). The amount of water that enters Baffin Bay through Nares Strait and Lancaster Sound is roughly the same (1.0 ± 0.2 Sv), but the proportion of freshwater flowing out of Lancaster Strait is more than double that exiting Nares Strait (Munchow et al. 2007, Peterson et al. 2012, Munchow et al. 2015). Curry et al. (2011) estimate smaller, but still nearly equal outflows from Lancaster Sound and Nares Strait, of 0.70 and 0.72 Sv, respectively. A smaller volume of water, only 0.3 ± 0.1 Sv, flows into Baffin Bay via Jones Sound and the freshwater component is unknown (Melling 2000, Munchow et al. 2015). These inflows all contribute to the presence of ASW within Baffin Bay (Bâcle 2000, Tang et al. 2004).

The WGC carries Arctic and Atlantic Ocean water northward from Davis Strait into Baffin Bay over a 640 m sill (Munchow et al. 2015). From a summer survey, 3.8 ± 0.3 Sv of water was estimated to flow northward into Baffin Bay along the east side of Davis Strait. Within Davis Strait and southern Baffin Bay, the WGC has two components: cool and less saline water freshened by ice-sheet meltwater that flows north along Greenland’s coastline and (2) warmer, saltier waters of Atlantic origin that flows along the shelf and slope further offshore (Curry et al. 2011, Hamilton and Wu 2012). Run-off from the ice sheet is estimated to contribute 15 mSv (15,000 cubic metres per second) of freshwater to the coastal current (Azetsu-Scott et al. 2012, Curry et al. 2011), although the contribution is likely larger in more recent years (Bamber et al. 2018). By the time the WGC reaches 76°N (the north shore of Melville Bay), the coastal current, which is approximately 100 m deep at the coast, sits on top of the warmer, saltier Atlantic water (AIW), which extends to the bottom (Bâcle 2000, Bâcle et al. 2002). Maximum depth in the North Water is only 700 m, so water from the BBDW is not present there.

*Table 1. Summary of water masses present within the North Water (adapted from Bâcle 2000).*

| Water Mass | Variant | Temperature | Salinity | Comments |
|---|---|---|---|---|
| Arctic Surface Water | Cold months | Below -1.5°C | Below 33 | Arrives via Nares Strait |
| | Warm months | -1 to 5°C | Below 32 | Arrives via Nares Strait. (warmed locally) and via West Greenland Current |
| Pacific Water | Pacific Summer Water | -1.5 to 0°C | 31 to 32 | Warmed during summer transit of the Chukchi Sea. Arrives via Nares Strait |
| | Pacific Winter Water | Below -1.5°C | 32–34 | Chilled during winter transit of the Chukchi Sea. Arrives via Nares Strait |
| Atlantic Intermediate Water | n/a | 0–3°C | 34 to 34.5 | Arrives via West Greenland Current |

#### 3.1.4.4. Temperature and Salinity

Differences in the properties of waters that enter Baffin Bay via Nares Strait, via Jones Sound and via Lancaster Sound are related to: 1) the particular reservoirs within the Arctic basin from which source waters are drawn; and 2) the maximum depth of shallow sills crossing each pathway that block deeper more saline water from passing. That depth is 220 m for Nares Strait, 180 m for Jones sound and 125 m for Lancaster Sound (Melling 2001). Water reaches Nares Strait from the shelf edge in the Lincoln Sea whereas water reaching Jones and Lancaster Sounds originates from the shelf edge along the north-eastern Canada Basin. Knowledge of seawater in these remote areas is not yet sufficient to characterize the differences between these two reservoirs. So in general terms, Nares Strait enables passage of Arctic Surface Water, warmer Pacific Summer Water, colder Pacific Winter Water and warmer-again Lower Halocline Water, which is a modified version of the Atlantic Intermediate Water that originates in the Barents Sea; maximum through-flow salinity is a little above 34.1 (Melling et al. 2008). Jones Sound, with a shallower sill, enables much the same because of very fast flows through the constriction in Cardigan Strait. The highest salinity arriving via Lancaster Sound is lower, about 33, a value characteristic of the upper part of the Pacific Winter Water.

Water carried into northern Baffin Bay by the WGC has two components: water that is cold (< -1°C) and fresh (< 33.5) in the 100 m closest to the surface, and warmer (ranging from 0–2°C), saltier (salinity greater than 33.5) water that extends down from 100 m depth (Bâcle et al. 2002) (Figure 12, Figure 13). The former is a variant of the latter, diluted by ice-sheet meltwater. Most of the WGC heads west across Baffin Bay from Cape York but a small part continues onward to the North Water (Melling et al. 2001). The water mass that travels west is warmer and more saline than the Arctic Ocean water flowing south out of Smith Sound, so that it is overrun by the Arctic outflow as it approaches the Canadian side of Baffin Bay. The temperature and salinity profile along the east coast of Baffin Island immediately south of Lancaster Sound reveals a cold (-1.5°C ), fresh (< 33.8 ) surface layer to approximately 300 m, on top of a warmer (0°C), more saline (≥ 33.8 ) layer (Figure 12) (Munchow et al. 2015). Water from the

WGC that flows north past Cape York quickly cools as it moves through Smith Sound and is less than -1.0°C when it reaches the northern end (Melling et al. 2001).

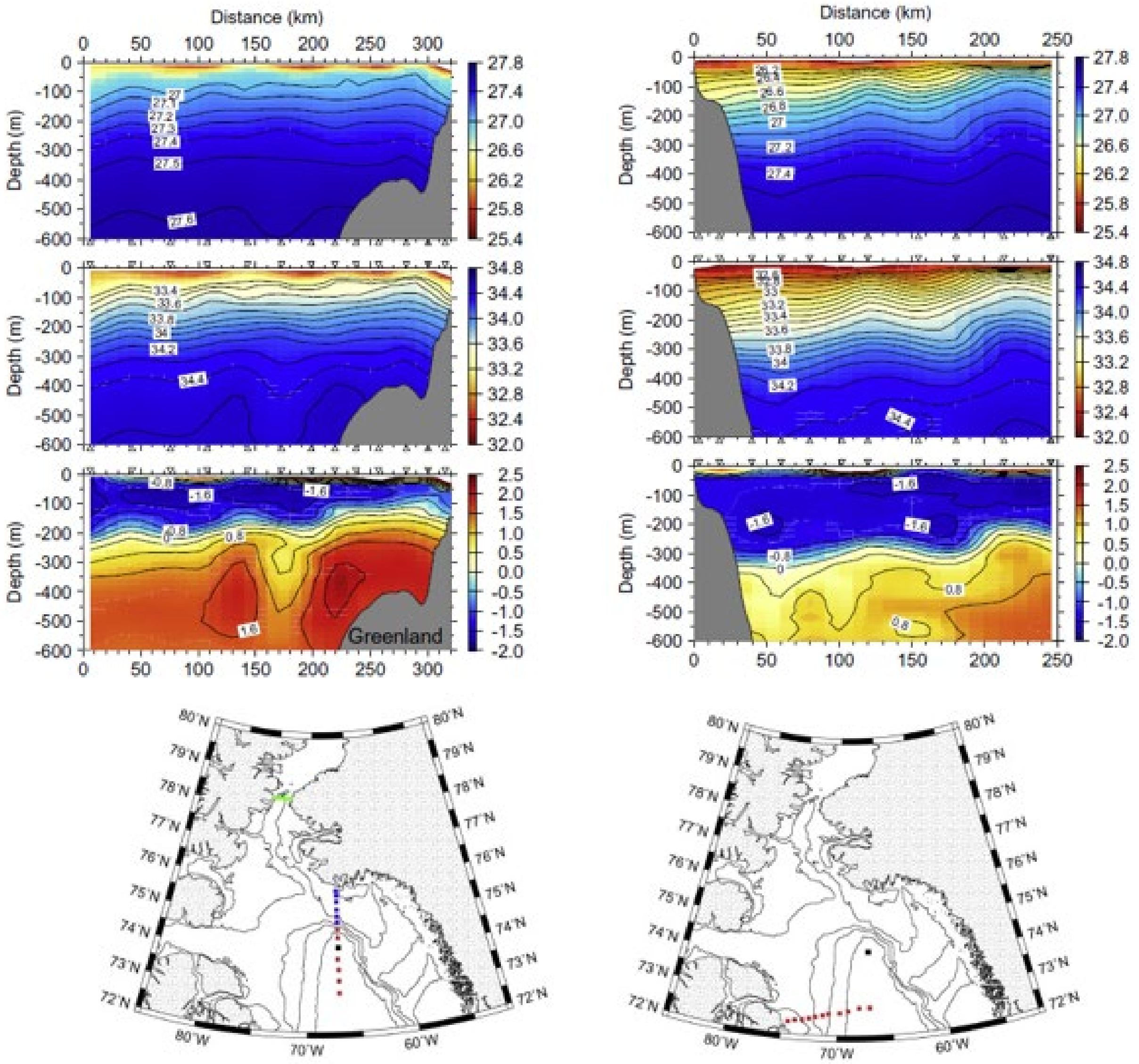

*Figure 12. Density (top), salinity (mid) and temperature (bottom) profiles extending south from Cape York across the West Greenland Current, July 30/31, 2003 (left panel), and profiles extending east from Baffin Island across the Baffin Island Current near Pond Inlet, July 26/27, 2003 (right panel). Station locations are indicated by triangles (Source: Münchow et al. 2015).*

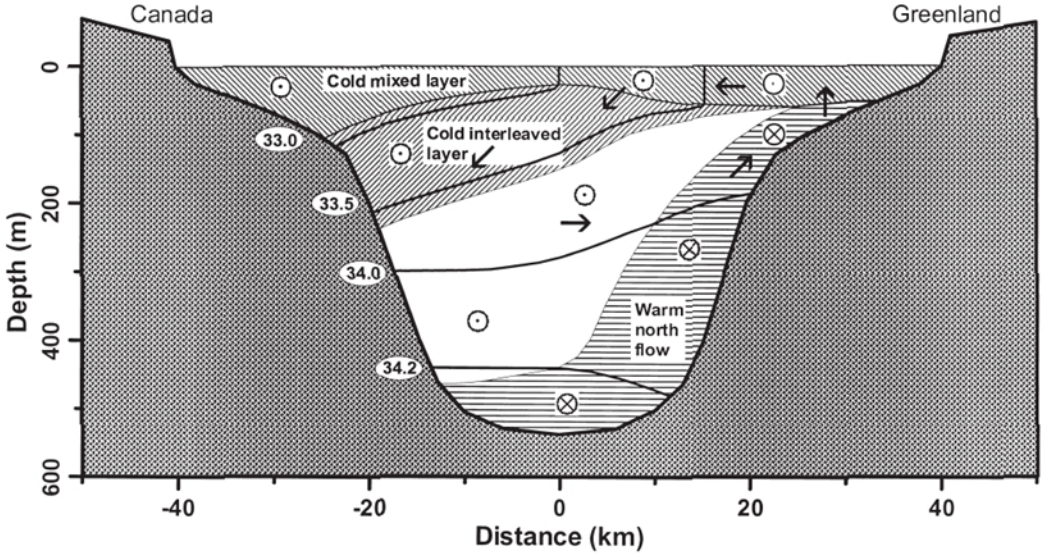

*Figure 13. A schematic cross-section of water structure and ocean current within the North Water. Circled crosses and dots indicate currents directed into and out of the plane of the Figure, respectively. Small arrows represent the circulation in the vertical plane (Source: Melling et al. 2001).*

The portion of the WGC that continues along the Greenland coast reaches Smith Sound at 78.5°N (Bourke et al. 1989, Melling et al. 2001) and has been tracked up the Greenland side of Nares Strait almost to the Lincoln Sea (Munchow et al. 2007). The north and south-flowing currents loop, interact and mix in this region. The arrows shown in Figure 14 are intended to illustrate the general circulation, rather than how the water moves all the time at a given location (Melling et al. 2001). Although the pattern shown is consistent with the observations made during the International North Water Polynya (NOW) Study (Fortier et al. 2001), those observations were far too sparse and short-lived to define a detailed and fully authentic picture. Unfortunately, there have been no projects of comparable ambition in the 20 years since that project. Reference to numerical simulations is problematic because there are so few data available to assess the reliability of such models in this area; however, basic model dynamics suggesting penetration of Atlantic Water into this region and towards the Ellesmere coast are reasonable (P. Myers, University of Alberta, pers comm).

Available measurements of current suggest an average counter-clockwise ocean circulation within the North Water, with average flow faster (10 to 15 cm/s over the top 100 m) on the Canadian side than on the Greenland side (3 to 5 cm/s) (Melling et al. 2001). The difference reflects the downward slope of the sea surface from the Arctic Ocean, and the dominant and strong north wind that emerges into the western side of the North Water from Nares Strait. Further south, the westward flow across Baffin Bay at 200 m depth at 75.5°N is slow (2 to 4 cm/s). The southward flow of the Baffin Island Current is intermediate in speed (7 cm/s at 70°N).

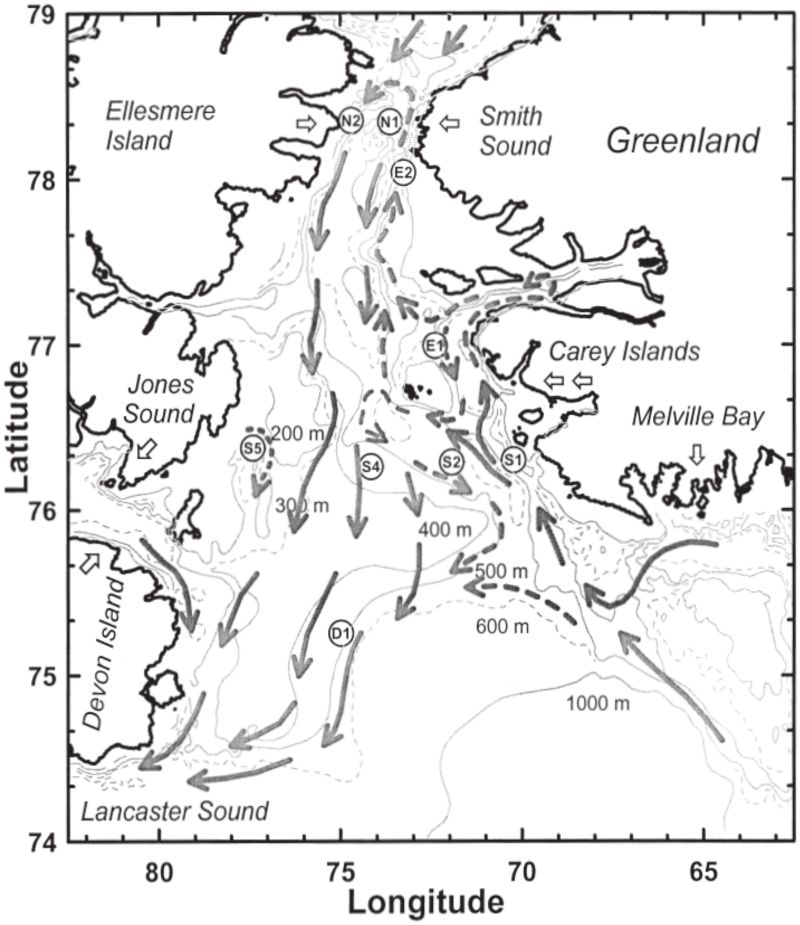

*Figure 14. General circulation in northern Baffin Bay, including the North Water EBSA region. Solid arrows depict the flow direction of Arctic outflow at the surface and dashed arrows that of submerged water from the West Greenland Current (WGC). Labelled circles mark the location of year-round oceanographic moorings during the International North Water Polynya Study (NOW), 1997–99 (Source: Melling et al. 2001).*

Not surprisingly, observations and computer models indicate that flows entering the North Water via Smith Sound vary with storms, by season and from year to year. Variability in the outflow volume transport from Lancaster Sound shows a clear correlation with surface winds (Peterson et al. 2012), and those from Nares Strait and Jones Sound (based on less data) appear to follow suit (Aksenov et al. 2010). The WGC appears to flow fastest in November and December (Tang et al. 2004). Current observations during the Bedford Institute of Oceanography’s program from 1983–1990 indicated that velocity generally increased with depth in Baffin Bay, while decreasing with depth in Lancaster Sound (Tang et al. 2004).

#### 3.1.4.5. Upwelling and Downwelling

The latent-heat mechanism is primarily responsible for the North Water’s existence (Figure 15). The strong north winds that open the polynya also drive upwelling on the Greenland side. Although intermittent cells of warm water (maximum of -0.1°C) at the surface were thought to have been detected along the west coast of Greenland in winter (Steffen 1985, Steffen and Omhura 1985), these observations appear to have been spurious (Melling et al. 2001). Therefore, upwelling appears to have little impact on polynya formation, though it does play an important role in nutrient transfer.

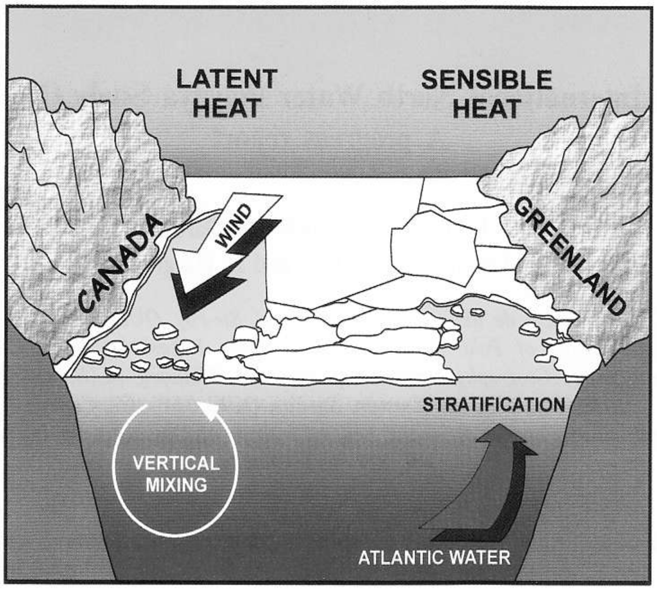

*Figure 15. Schematic representation of opening mechanisms of the North Water. (Source: Fortier et al. 2001).*

Moored instruments during the NOW study in 1997 and 1998 detected warm Atlantic water along the coast of Greenland at approximately 200 m below the surface, but there was no evidence of upwelling to the surface during that time (Melling et al. 2001, Bâcle et al. 2002). Instead, the authors argued that brine rejection from growing ice provides the link between warm, nutrient-rich water at depth and the photic zone near the surface. Brine is formed as a result of salt exclusion from rapidly growing new ice and drives convection to a depth sufficient to entrain the underlying warmer nutrient-rich water and mix it towards the surface. This mechanism only operates in the winter because, as air temperatures increase and ice formation stops, brine production also ceases. It is suggested that thinner ice on the east side of the polynya throughout the winter is a consequence of this entrainment and a contributing factor to an earlier loss of ice cover to melting in summer (Steffen 1985, Melling et al. 2001, Yackel et al. 2001, Bâcle et al. 2002).

The North Water is a more-or-less fixed geographic feature through which water and ice move rapidly. The impact of the North Water's existence on ice, seawater properties and ocean structure is not instantaneous, but cumulative. The impacts are revealed in spatial gradients in ocean and ice properties – mainly from north to south – rather than in changes over time at a point, because the seawater and ice continue to move with the flow. It is therefore easier to describe the North Water in terms of processes than in terms of characteristics at each point. We have already seen this in the ice cover: it may always be thin where seawater is first exposed at the surface near the floe edge, but will be thicker, progressively at points further south in the direction which it is drifting. While not explored by observation, some effects may reasonably be hypothesized, such as: north-to-south increases in mixed-layer depth and upward fluxes of nutrients and oceanic heat; north-to-south decreases in upper ocean stratification and light availability; east-to-west gradients as depicted in Figure 13

No oceanographic instruments have been moored in Smith Sound and Kennedy Channel since 1999 and 2012 respectively, and only two moorings have been maintained near 76.5N (by ArcticNet); the latter have been primarily supporting sediment traps and have not been collecting a wide range of physical oceanography data.

### 3.1.4.6. Tides

The tides in Baffin Bay are semi-diurnal, and the $M_2$ tidal constituent here is the largest in the eastern Arctic (Figure 16) (Griesman et al. 1986, Tait et al. 1986). In central Baffin Bay, approximately 100 km offshore of Home Bay, there is an $M_2$ tidal amphidrome (Griesman et al. 1986, Ingram et al. 2002, Kleptsova and Pietrzak 2018). In northern Davis Strait, just south of Cape Dyer along the Baffin Island coastline, there is a second amphidrome, this one for the $K_1$ tidal constituent. Diurnal and semi-diurnal tidal amplitudes in Baffin Bay increase with distance from these points, resulting in higher amplitudes in the north of Baffin Bay than the south. Both the $M_2$ and $K_1$ tidal constituents propagate west into Lancaster Sound and Jones Sound and northward into Nares Strait (Kleptsova and Pietrzak 2018). Maximum amplitudes for the $K_1$ constituent occur in Smith Sound (0.35 m), while the $M_2$ constituent achieves a maximum amplitude of 1.3 m in Kane Basin. The $N_2$ and $S_2$ tidal constituents in Kane Basin are also strong (0.30 m and 0.55 m, respectively).

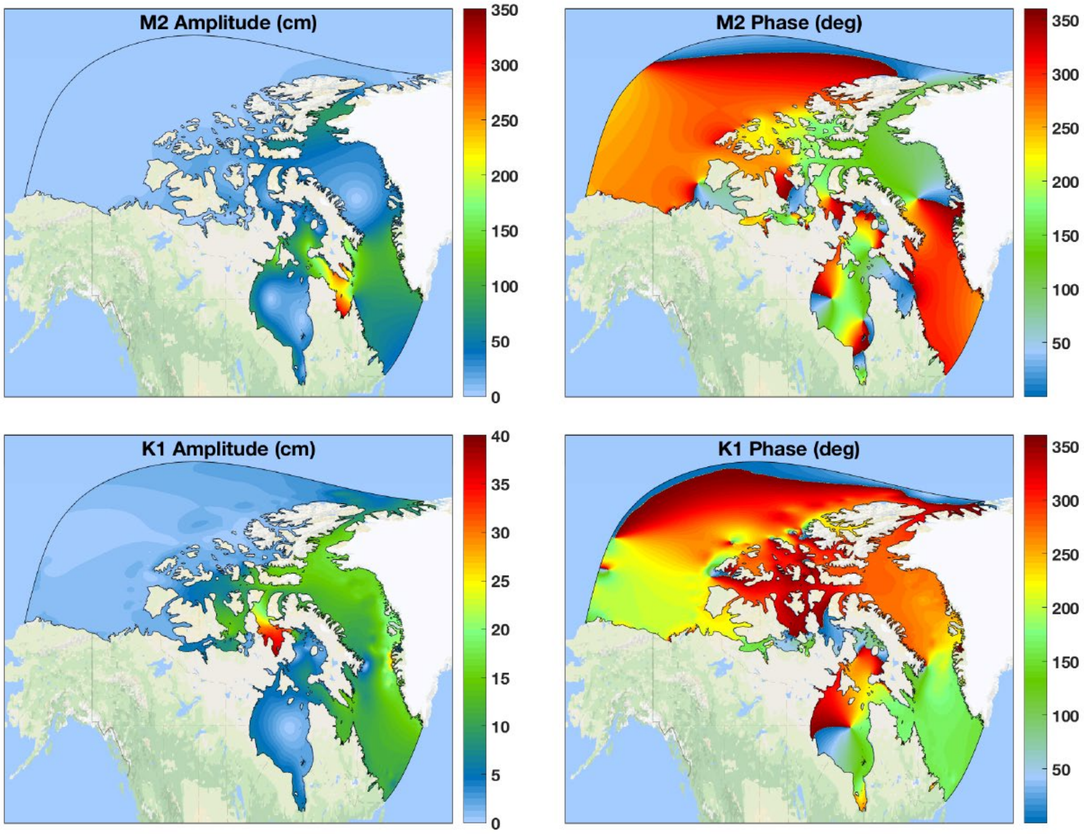

*Figure 16. Annual mean amplitude and phase of the M2 and K1 tidal constituents in the Canadian Arctic Archipelago, including Baffin Bay, Hudson Strait and Hudson Bay. A small portion of the tidal signal entering through the Labrador Sea flows into Baffin Bay forming an amphidromic system there. The semi-diurnal tidal wave propagates north along the west coast of Greenland, reaches the maximum amplitude of over 1m in Kane Basin and enters the Archipelago through Barrow Strait (Source: Kleptsova and Pietrzak 2018).*

Similar to tidal amplitudes, tidal currents increase south to north in Baffin Bay and within the North Water itself (Ingram et al. 2002). The prevailing current flows south through Nares Strait, but switches with the tide from 0.3 m/s north to 0.7 m/s south (Vincent 2006). In northwestern Baffin Bay, observed $M_2$ tidal currents have varied from 0.07 m/s along the coast of Devon

Island to 0.02 m/s at the entrance to Lancaster Sound (Fissel et al. 1982). $K_1$ tidal currents in these same areas are much weaker (< 0.01 m/s), but the combined $M_2$+$K_1$ velocities reach 0.1 m/s. The largest spring-tide velocities occur at the north end of the polynya (away from the amphidrome), where surface values of 0.4 m/s have been measured (Melling 1999). These values decrease with depth, from 0.35–0.40 m/s (at the surface), to 0.20–0.25 m/s (within the top 300 m of the water column), to 0.10–0.15 m/s (below 300 m) (Melling 1999).

Modeled tide elevations within the North Water (Collins et al. 2011, Kagan and Sofina 2012, Kleptsova and Pietrzak 2018) compare favourably with field observations (Griesman et al. 1986). The model results presented in Figure 17 illustrate that the $M_2$ tidal constituent in northern Baffin Bay is the largest in the eastern Arctic (in fact, it is the largest in the whole Canadian Arctic Archipelago). Such large tides can generate variations in ice concentration and ice pressure over a tidal cycle. These variations depend on the proximity and orientation of “immovable” boundaries (coastlines, floe edges) and are relative to the size and orientation of the ellipse representing the tidal current.

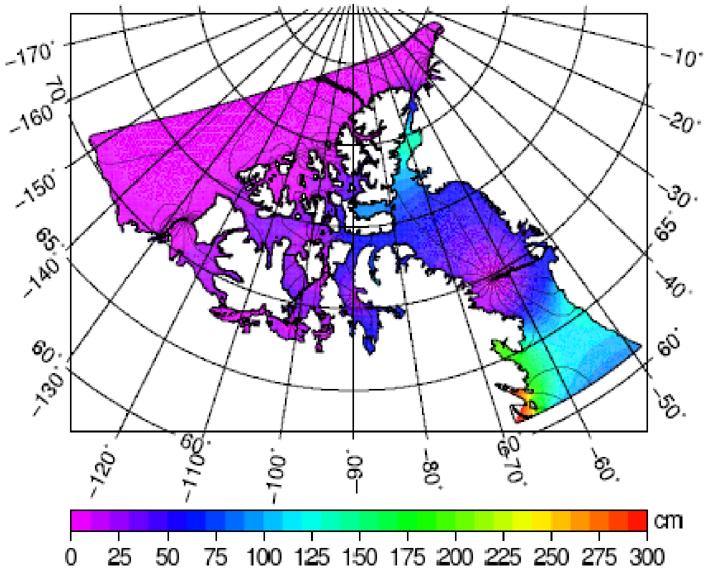

*Figure 17. Modeled output for M2 tidal elevations in the Canadian Arctic Archipelago (Source: Collins et al. 2011).*

### 3.1.5. Nutrients

Flows entering Smith Sound and northern Baffin Bay carry dissolved nutrients (phosphate, silicate, and nitrate) that support the growth and proliferation of primary producers within the polynya in spring and summer. Flows entering northern Baffin Bay from Jones Sound and Nares Strait include a high proportion of winter Bering Sea water, which contains nutrients regenerated within the Bering Sea inflow at the seabed of the Chukchi Sea in winter. Bering Sea water contains 24 $\mu$M silicate (and similar concentrations of phosphate) and 10 $\mu$M nitrate (termed Silicate Rich Arctic Water; SRAW) (Tremblay et al. 2002a). Within the North Water, SRAW from the north and west mixes with the water that flows northward into Baffin Bay on the WGC (referred to as Baffin Bay Water; BBW), which contains roughly equal concentrations of silicate and nitrate (11.6 $\mu$M and 11 $\mu$M, respectively). Primary productivity within the North Water has a 1:1 ratio of nitrate: silicate consumption and, because silicate is present in higher concentrations than nitrate in both the SRAW and BBW, nitrate is likely the limiting nutrient for primary productivity (Tremblay et al. 2002a).

In May 1991, surface concentrations of these three nutrients increased from east to west within the North Water as a result of primary productivity (phosphate from 0.5 to 1.4 mmol/m$^2$, nitrate from 3.7 to 10.98 mmol/m$^2$ and silicate from 6.8 to 34.2 mmol/m$^2$) (Lewis et al. 1996). Warmer water had lower levels of nutrients and higher levels of phytoplankton. Surface temperatures on the west side of the basin were closer to freezing (only 0.06–0.12°C above freezing) compared to the east side (0.14–0.28°C). Phosphate and silicate both decreased rapidly on the east side of the basin and more gradually on the west side; while nitrate decreased from the Greenland shoreline to the middle of Northumberland Island and then increased gradually through to the west side of the basin. By June, severe silicate and phosphate depletion was evident in the south portion of the North Water, but the depletion of nitrate at the surface was more widespread. In May, nitrate in the upper 25 m was almost exhausted in the southeast and had also decreased in the northeast. Only mild depletion had occurred in the northwest. By July, nitrate depletion was also detected in the northwest. A unique feature of Baffin Bay is that it acts as a sink for biogenic silicate. At depths of > 500 m, silicate concentrations are up to eight times higher than in adjacent basins (up to 95 $\mu$M), which may indicate degradation of surface-derived organic matter (Michel et al. 2002a, Tremblay et al. 2002a). While there is evidence of degradation of nitrate and carbon in the upper 100 m of the water column, only about 10% of silicate is lost through dissolution (Michel et al. 2002a).

With its proximity to the Greenland Ice Sheet and many marine-terminating glaciers, glacial runoff and glacier-ocean interactions likely play an important role in nutrient cycling in the North Water and adjacent coastal areas. These processes have only recently been identified as significant contributors to the carbon cycle globally (Wadham et al. 2019) and remain poorly studied in the North Water region, though they are important to consider in a warming climate as meltwater runoff increases and glaciers retreat. Runoff from glaciers and ice sheets can be a direct source of nutrients including inorganic and organic forms of nitrogen and phosphorous, as well as silicon and iron (Wadham et al. 2019). However, in Greenland, the most important influence is likely the upwelling of phosphorus- and nitrogen- rich deep water caused by buoyant plumes of subglacial meltwater at the termini of tidewater glaciers (Kanna et al. 2018, Cape et al. 2019, Wadham et al. 2019). This supply of nutrients has been linked to spring and summertime phytoplankton blooms in fiord systems elsewhere in Greenland (Meire et al. 2017). The availability of these high nutrient waters to primary producers is dependent on the formation of a plume in deep, nutrient-rich waters, and on the plume arriving to the photic zone before it reaches neutral buoyancy (Hopwood et al. 2018). Optimum conditions for maximum upwelling into the photic zone likely vary for each glacier. For most of Greenland's tidewater glaciers, nutrient fluxes will diminish as they retreat out of deep, nutrient-rich water, though some deeper glaciers may temporarily increase as the plume moves temporarily into the photic zone (Hopwood et al. 2018).

## 3.1.6. Atmosphere/Ocean Interface

### 3.1.6.1. Climatically Active Gas Fluxes

To determine if a region is an overall source or sink of greenhouse, and other climatically-active gases, the concentrations of each gas in seawater is compared with the concentrations in the overlying atmosphere. If the concentration in the seawater is less than in the atmosphere, the ocean can absorb more (sink). If the concentration in the seawater is higher than in the atmosphere, the ocean can release gases to the atmosphere (source). Whether an Arctic region is an overall source or sink depends on water mass properties near to the sea surface, including water biogeochemistry, temperature, the distribution of freshwater from rivers, sea ice and glacier melt, sea ice distribution and the timing of its formation and melt, and the balance between the biological processes of primary production and ecosystem respiration (Klein et al.

2002). Collectively these water properties and processes can impact the local biogeochemical system that moderates the gas exchange at the water's surface. It is not known to any degree of confidence whether the North Water is an important site for air-sea exchange of the climatically-active gases. Only a few studies have been conducted in this region and our knowledge is largely based on observations from discrete research cruises over the open water season and assumptions of wintertime processes.

The few measurements that do exist for the North Water region reveal a strong degree of regional, seasonal and interannual variation in the partial pressure of $CO_2$ ($pCO_2$) in surface seawater (the main driver of air-sea $CO_2$ exchange). Seawater $pCO_2$ in the region can toggle between a slight oversaturation (i.e., greater than atmospheric levels) in the early spring (Miller et al. 2002), but was found to be undersaturated during the summer and fall (Burgers et al. 2017, Geilfus et al. 2018, Miller et al. 2002). While there is not an annual $CO_2$ budget, any early springtime oversaturation would likely be capped by ice cover and thus limiting $CO_2$ outgassing to the atmosphere, suggesting that the region may be a net annual sink for atmospheric $CO_2$ based on the strength of uptake during the remaining ice-free seasons (Miller et al. 2002). The supply of freshwater from fiord systems in Greenland is increasing, and case studies suggest glacial meltwater promotes undersaturation (relative to atmospheric levels) of $pCO_2$ and $CO_2$ uptake within fiords and adjacent coastal waters (Azetsu-Scott et al. 2010, Cape et al. 2019, Meire et al. 2015, 2016). It is expected that continued meltwater freshening (e.g., Castro de la Guardia et al. 2015, Bamber et al. 2018) will impact the $CO_2$ sources/sink status of the region, although wide occurrence of this phenomena has yet to be confirmed. Increases in dissolved $CO_2$ cause decreases in pH, known as ocean acidification (OA). Indices of OA have been measured in the region, but the effects on the ecosystem remain unknown.

Few studies have examined dissolved $CH_4$ in the eastern Canadian Arctic and none in the North Water region. The majority of measurements within the upper water column of the Canadian Arctic Archipelago and Baffin Bay show near equilibrium concentrations to modest oversaturation (relative to the atmosphere) of dissolved $CH_4$ (Kitidis et al., 2010, Punshion et al. 2014, Fenwick et al. 2017). Based on these observations, we expect the North Water to be a source of $CH_4$ to the atmosphere, but perhaps not a strong source. The North Water could however be a source of other biogenic gases (those produced by living organisms, such as phytoplankton), like dimethyl sulphide (DMS). Direct DMS measurements in the North Water were made once – during spring 1998 – and showed DMS concentrations to be lower than expected due to the dominance of diatoms in the phytoplankton community (Bouillon et al. 2002), however, this does not represent a strong observational base. Results from recent studies conducted in the Canadian Arctic Archipelago during summer reveal high concentrations of DMS in open waters and in the overlying atmosphere, with the highest values found in association with localized peaks of chlorophyll a, a proxy of phytoplankton biomass (Mungall et al. 2016, Jarníkova et al. 2018, Abbatt et al. 2019, Ghahremaninezhad et al. 2019, Lizotte et al. 2020). Sea ice age and the timing of melt may affect the source-strength of DMS-producing algal communities that have been found to thrive at the bottom of the ice, in the underlying waters, as well as in melt ponds at the ice-air interface (Galindo et al. 2014, Gourdal et al. 2018, Lizotte et al. 2020). Model simulations of spikes in sea-air fluxes of DMS at the vicinity of ice margins have been shown to be comparable in magnitude to some of the local maximum summertime fluxes estimated for ice-free waters in the Arctic (Hayashida et al. 2017).

## 3.1.7. Projections

### 3.1.7.1. Climate Projections

Climate change, along with inter-annual variability, has been well documented by the scientific community in Canada's north since the 1960/70s. There are a variety of climate models available to aid in future climate predictions (e.g., Prowse et al. 2009, Steiner et al. 2013, 2015 IPCC 2014, AMAP 2018), however, currently the scale of climate models is not fine enough to make accurate predictions about regions as small as the North Water. Global climate models typically run on a grid, where the separation of computation points is comparable to the width of the North Water. Misrepresentation in climate models can often arise where terrestrial station data are the only data available to represent marine areas (Steiner et al. 2015). As such, most Arctic-wide models are not sensitive to the important aspects of the North Water, such as microclimate, steep-sided mountains, terrain-channeled wind, and the polynya itself (H. Melling, DFO Pacific, pers. comm.). Still, some models are relevant to the wider region (i.e., BB/DS), and may offer some insight into the future of the North Water; these are discussed below.

Steiner et al. (2013) analysed available data from 1986–2005, and modelled projections from 2046–2065. Results showed that northern Baffin Bay is expected to warm by 5–10°C in February, with little change in May and August, and a significant warming of 1–15°C in November (Steiner et al. 2013). Modelled data for a fifty-year period between 2012 and 2061 shows an increase in mean precipitation of 0.03–0.04 mm/day/decade for the Baffin Bay region (Steiner et al. 2013). Limited observations of ocean properties also show summer warming in Baffin Bay (Steiner et al. 2015).

In a more recent analysis, climate projections for the BB/DS region show that air temperatures are expected to increase in winter by about 1–4°C by 2030 and 1.5–10°C by 2080, and in summer by 0.5–2°C by 2030 and 1–5°C by 2080 over the reference climate period of 1986–2005 (AMAP 2018). An overall increase in precipitation from the 1986–2005 period is forecasted for the BB/DS region, with projected changes in winter of about -10% to +25% by 2030 and -10% to +70 % by 2080, and in summer -5% to +15% by 2030 and 0% to +35% by 2080 (AMAP 2018). The overall predicted change for the region is an increase in precipitation, particularly in winter and in the northwestern parts of the region (AMAP 2018). Mean near surface wind speeds are predicted to change within ±5% by 2030 and ±10% by 2080 for the BB/DS region over all seasons (AMAP 2018). Extreme weather projections for the BB/DS region include increases in annual minimum and maximum temperatures and an increase in heavy precipitation events (AMAP 2018).

#### 3.1.7.2. Ocean and Sea Ice Projections

The numerical modelling framework of the Nucleus for the European Modelling of the Ocean (NEMO) is now widely used throughout Canada. Recently, Myers et al. (2019) and Buchart et al. (submitted[1]) used the Arctic and Northern Hemisphere Atlantic (ANHA) regional configuration developed at the University of Alberta to present an overview of modelling capabilities and results for the North Water region and northern Baffin Bay. To determine how global warming will influence this key region, they drove the ocean and sea-ice model with a 5 member ensemble of bias-corrected historical, RCP4.5 and RCP8.5 CMIP5 model simulations. The climate runs also included projected changes in Greenland melt from a mass balance model (Laenearts et al. 2015) and runoff from a hydrological model forced by the same CMIP5 simulations (MacDonald et al. 2018). Experiments were carried out at ¼ resolution from 1981 to 2070. All ensemble members show a strong reduction in sea-ice concentration (Figure 18A) and thickness (Figure 18B) in the North Water. Significant upper-ocean warming also occurs (Figure 18C). Salinity changes depend on the size of the estimated future runoff from Greenland (Figure 18D), leading to scenarios with more, or less, stratification in the region. Changes in stratification potentially will have large impacts on the productivity in the region. In addition, a recent study (Olsen 2017) suggests that conditions in the polynya are a primary driver of variability in upper-layer stratification in nearby fiord systems, thereby influencing both the growth rate of fast ice and melting of submerged glacial ice.

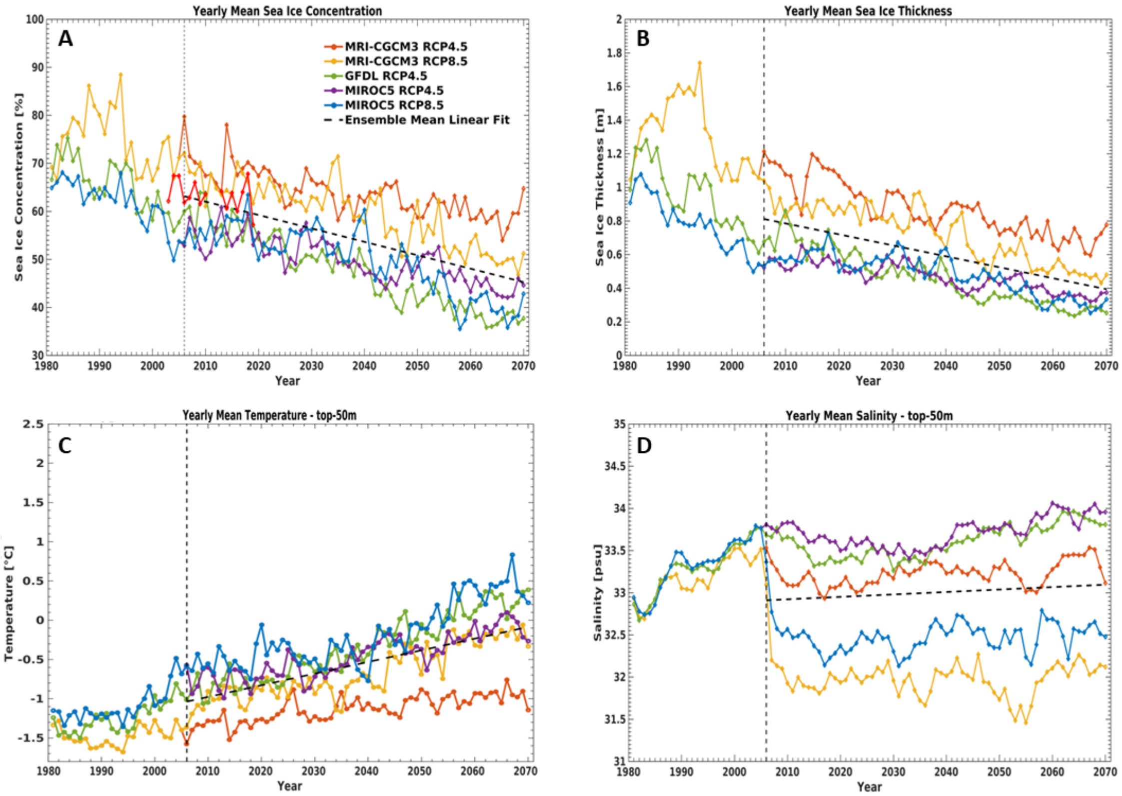

*Figure 18. NEMO model output, forced by a 5 member ensemble of bias-corrected historical, RCP4.5 and RCP8.5 CMIP5 model simulations. A) Sea-ice concentration, averaged over the North Water region of Baffin Bay, for spring (March-May). Trend line is based on all 5 ensemble members. B) As for A, but for sea-ice thickness. C) As for A, but top 50 m averaged temperature, and D) for top 50 m averaged salinity. (Source: Buchart et al. submitted[1]).*

### 3.1.8. Summary of Physical System: Knowledge Gaps and Climate Impacts

Climate change is likely the biggest stressor on the North Water region. However, there is uncertainty about how regional dynamics of the North Water are linked to global climate change and variability, and how this affects future conditions of the polynya and surrounding area. From a pan-Arctic perspective, sea ice has thinned and the minimum summer extent has been below the climatological norm almost every year since 2001 (AMAP 2011). The pace of retreat and the number of days with low sea-ice concentration have also increased (Deser and Teng 2008). However, the North Water is small, occupying at most 0.5% of the northern sea-ice covered area in winter, and is a local anomaly, attributable to local geography, weather and ocean conditions specific to northern Baffin Bay. As such, there is limited usefulness in the application of a pan-Arctic perspectives to the North Water in particular, and should be studied locally to obtain a meaningful viewpoint.

Local changes to the physical system have already been observed by surrounding communities, such as extreme weather events, increased precipitation and changes to the type of precipitation (i.e., rain), a transition towards a thinner and mechanically weaker ice cover, melting glaciers, and increased ice movement through Nares Strait. Since this area is prone to extremely strong winds, created by pressure patterns and local geography, it is highly sensitive to climate-driven changes in pressure patterns. Communities in the region have emphasized that winds throughout Baffin Bay are now stronger, more erratic, and less predictable than they have been in the past (L. Audlaluk, Hamlet of Grise Fiord, pers. comm.). There is an overall lack of precipitation data for the whole Arctic, and arguably less for the North Water. Specifically, more information is needed on precipitation type (e.g., rain, accumulated snowfall on ice caps, ice regime through evaporation, runoff), and amount of accumulated precipitation over the North Water marine environment and glaciers. In addition, the relationship between hemispheric changes in atmospheric circulation and water movement to the variability of the North Water (i.e., global change and influence of local weather on the polynya) is also poorly understood.

The recurrent nature of the polynya appears to be changing, with a transition towards a thinner and mechanically weaker ice cover, which has reduced the duration of the ice bridge and increased ice flux through Nares Strait (Vincent 2019). The ice bridge is also becoming increasingly unstable and variable, as are the fast ice edges around the periphery of the North Water, which has increased the quantity of drifting ice in the polynya (Mosbech and Kyhn 2019). The Smith Sound ice bridge did not form in the winters of 2006/07 and 2008/09, and only formed for a two-month period in 2007/08 and 2009/10 (Kwok et al. 2010, Stark 2016, Dansereau et al. 2017, Vincent 2019). In 2009, the absence of the ice bridge resulted in low ice coverage in the North Water and unseasonably high surface temperatures in July (Vincent 2013, 2019). The lack of an ice bridge may also result in increases in southward-flowing ice and ocean velocities in the Nares Strait, and a decrease in surface water salinity (Kwok et al. 2010, Münchow 2016). Although there is a conceptual understanding of the formation and break-up of the ice bridge, there is no effective way to predict aspects of formation and break-up in the future. Inter-annual variation in the timing and extent of landfast ice surrounding the North Water (Galley et al. 2012) is large and time series are short, such that observed trends are not statistically significant to a useful level of confidence.

Changes across the north Baffin region have been also been noted by local Inuit, who describe the floe edge as being closer to land, and say that the sea ice is freezing later, breaking up earlier, and is generally thinner and less stable (Nunavut Tunngavik Inc. 2001, Nunavut Tunngavik Inc. 2005, Government of Nunavut 2012, QIA 2018). Local hunters also describe the ice edge of the North Water adjacent to Greenland as moving and widening at unexpected times (Hastrup et al. 2018). Long-time hunters from Qaanaaq and Savissivik, with memories of previous conditions on the sea ice platform, have documented a wide range of seasonal shifts in sea ice formation, strength/safety and breakup dates. Detailed documentation of changes to sea ice extent and characteristics (flaws, leads, recurring polynyas, extent, thickness, and safety) are presented in maps in Gearheard et al. (2013). Marine mammals and birds are most often hunted near communities, in the coastal ice-free environment or along the floe edge surrounding the polynya, thus any changes to this environment may result in reduced access to subsistence harvesting and safety of local transportation routes. In general, floe edge and coastal processes (marine and terrestrial) are relatively unknown and understudied by science in the North Water. Specifically, there is limited knowledge of glacial fiord dynamics, including spatial and temporal variability in meltwater discharge from adjacent glaciers at the surface and depth, influence on the near-ice circulation and mixing of water masses in fiords, as well as processes that play a key role in primary production and biogeochemistry coupling.

The impact of melting glaciers (e.g., increased calving events and freshwater flux) from both atmospheric and oceanic warming on the North Water in the future could be substantial. The increased glacial meltwater from the Greenland and Ellesmere Island ice sheets are expected to have a strong freshening effect on the surrounding waters and salinity changes in the North Water will depend on the size of future runoff. Impacts on stratification and nutrient and biogeochemical cycling (suppressed ocean mixing and nutrient transfer) will have resulting effects on local productivity in the region, however, this remains a knowledge gap. As such, there is a need to better understand the inter-annual variation in the North Water system and to increase our ability to accurately model local to regional scale processes, and their interactions between the ocean, sea ice and atmosphere in order to provide future predictability.

## 3.2. LOWER TROPHIC LEVELS

The North Water can be characterized by high phytoplankton productivity and biomass (Klein et al. 2002, Vidussi et al. 2004) driven by advective inputs of inorganic nitrogen and other nutrients (Mostajir et al. 2001, Tremblay et al. 2002b, Garneau et al. 2007). Phytoplankton, which support the entire food web, are abundant with high biomass from April through October in the North Water, which is comparable to other productive Arctic areas (Table 2 and Table 3). The early phytoplankton blooms are supported by the reduced sea ice cover compared to surrounding areas, and the tight coupling between primary productivity and zooplankton provide early food for filter feeders and is fundamental in supporting fishes and birds (Booth et al. 2002, Klein et al. 2002, Tremblay et al. 2002b, Vidussi et al. 2004, Marchese et al. 2017). This is particularly important as the North Water is at a higher latitude than other Arctic areas with comparable phytoplankton biomass (Klein et al. 2002). The magnitude, distribution, and development of phytoplankton within the North Water is influenced by the timing of the polynya formation, existing pool of available nutrients, water mass characteristics (e.g., temperature and salinity), and circulation patterns, that allow for the introduction of nutrients from the north and from beneath the upper mixed layer. High primary productivity provides the basis for a very diverse community of zooplankton.

The benthic community on the west side of the North Water is considered a hotspot of biodiversity. Importantly, functional diversity, a component of biodiversity that addresses the range of niches within an ecosystem, is higher than the rest of the Canadian Arctic. The productivity of the North Water is further enhanced by the efficient energy transfers to the pelagic and benthic ecosystem. Studies of pelagic-benthic coupling (the cycling of carbon and transfer to pelagic and benthic grazers) have shown that the longer productive season in the North Water provides a longer period over which the benthos receives inputs of organic carbon from the pelagic zone.

### 3.2.1. Phytoplankton and Other Protists

Early information on the phytoplankton community in this region of the Arctic is available from the Gothaab Expedition that was conducted in 1928 (Grøntved and Seidenfaden 1938). Borstad and Gower (1984) presented information on chlorophyll *a* and phytoplankton community composition from an August 1979 survey that was conducted in the eastern Canadian Arctic, including a small portion of the southwestern area of the North Water near Devon and Coburg Islands. Lewis et al. (1996) then published information on phytoplankton biomass in the North Water in May 1991, though this data was generated from a short two-day survey. This was followed by the International North Water Polynya Study conducted from 1997–1999, which provided much of the information on phytoplankton that is currently available (Bélanger 2001, Mostajir et al. 2001, Booth et al. 2002, Klein et al. 2002, Lovejoy et al. 2002, Odate et al. 2002, Sampei et al. 2002, Tremblay et al. 2002b, Bussey 2003, Saunders et al. 2003, Caron et al. 2004, Vidussi et al. 2004, Garneau et al. 2007). More recent studies have been carried out in late summer and fall since 2005, with data published from 2005–2007 by Ardyna et al. (2011) and in August 2013 by Joli et al. (2018). Satellite imagery has also been used to study the phytoplankton dynamics of the North Water (Bélanger 2001, Marchese et al. 2017, Joli et al. 2018). Primary production that supports food webs ultimately depends on initial nutrient concentration and ongoing supply rates (Tremblay and Gagnon 2009). However, except for the 1998 study, information on starting conditions is lacking. In addition, some production does occur after ice formation in October, for example, Fortier et al. (2019) identified late fall-winter

(September/October to February) microalgal production in the North Water in 2012–2013 and 2014–2015 and winter production starting in February 2016, suggesting greater activity during this season than previously thought. They recognized that some of this production was associated with ice-algae, but information on the balance between pelagic and ice-associated algae is limited.

#### 3.2.1.1. Community Structure

Information on the size structure of the phytoplankton community is available for the North Water. Appendix 1 lists phytoplankton and other algal taxa reported from the polynya. Large phytoplankton (i.e., cells > 5 *µ*m) and small phytoplankton (i.e., cells < 5 *µ*m) tended to follow similar seasonal trends in biomass (Klein et al. 2002, Mei et al. 2002, Lovejoy et al. 2002). Microscopy and size fractionated chlorophyll indicated that, at least during the 1998 study, large phytoplankton generally accounted for a greater proportion of the community's biomass than did small phytoplankton; however, there are exceptions. For example, the biomass of small phytoplankton was occasionally higher than large phytoplankton in the southern area of the polynya (Klein et al. 2002), and, in April, the phytoplankton community in the north was primarily composed of picophytoplankton (i.e., cells 1 to 3 *µ*m; Lovejoy et al. 2002). Throughout the growing season, production/biomass ratios were generally similar for large and small phytoplankton. The exception was later in the season (July in this case) when the ratios for small phytoplankton were more than four times that of large phytoplankton. This indicates that, although growth rates were higher for small forms than for large forms, they remained a smaller component of the overall phytoplankton community in May and June (Klein et al. 2002). This difference is likely due to intense preferential grazing of small phytoplankton by gelatinous and micro-zooplankton (Bussey 2003). Grazing by Calanus zooplankton was relatively low during the phytoplankton bloom (Mei et al. 2002) and was shown not to be a significant factor controlling phytoplankton biomass earlier in the season (Saunders et al. 2003).

Phytoplankton size distribution in the North Water appears to be related to water temperature and nitrate concentrations such that picophytoplankton are more abundant in warmer waters of the polynya and nanophytoplankton (i.e., cells 2 to 20 *µ*m) are more abundant in waters with higher concentrations of dissolved nitrogen (Mostajir et al. 2001). In fall 1999, picophytoplankton were more abundant on the east side of the polynya than on the west side, and nanophytoplankton were most abundant in the north and least abundant in the south (Mostajir et al. 2001). Additionally, picophytoplankton tended to be concentrated near the surface of the water column; whereas nanophytoplankton were more evenly distributed throughout the euphotic zone (Mostajir et al. 2001, Hamilton et al. 2008). In 2013, picoplankton accounted for two thirds of cells in most of the August samples reported in Joli et al. (2018).

The taxonomy of the phytoplankton community in the North Water has been described in detail from samples collected during the International North Water Polynya Study in 1997–1999. The most comprehensive taxonomic survey from the period identified a total of 333 known or probable distinct species based on samples collected during April–July 1998 (Lovejoy et al. 2002). The authors describe the identified taxa as being typical of Arctic marine habitat. Polynya-wide, diatoms accounted for 70% of the total phytoplankton biomass observed (0.36 *µ*gC/L to 1980 *µ*gC/L from April to July 1998), of which nearly half were large-celled, chain-forming, centric diatoms (e.g., *Thalassiosira* spp. and *Porosira glacialis*). The rest of the community was composed primarily of dinoflagellates and ciliates (26%), and a smaller fraction (6%) was made up of smaller flagellates. However, the distribution of phytoplankton taxa was observed to vary temporally and spatially within the polynya and community structure was largely driven by water mass characteristics (Lovejoy et al. 2002, Vidussi et al. 2004).

The International North Water Polynya Study expeditions in August 1997, April-July 1998, and August-September 1999, demonstrated the high degree of spatial and seasonal variation in the North Water. In April, the composition in the north region was mostly flagellates and dinoflagellates, similar to the Arctic Basin community, while centric diatoms (*Actinocyclus* spp., *Coscinodiscus* spp., and *Thalassiosira* spp.), ciliates and dinoflagellates dominated throughout the rest of the North Water (Booth et al. 2002, Lovejoy et al. 2002). In May and June, the phytoplanktonic bloom began on the along the Greenlandic coast and southeastern portion of the North Water, triggering a transition to a community dominated by large centric diatoms, particularly *Thalassiosira* spp. (Vidussi et al. 2004). The colder Canadian coast remained dominated by flagellates (Vidussi et al. 2004) and its diatom community contained a higher proportion of ribbon-forming pennate diatoms (e.g., *Fragilariopsis oceanica)*, and fewer centric diatoms (e.g., *Thalassiosira* spp.) (Lovejoy et al. 2002). By June, the whole of the polynya was dominated by diatoms, except the southern region, which consisted of proportionally fewer diatoms and increased quantities of smaller flagellates and gymnodinoid dinoflagellates compared to the rest of the polynya (Lovejoy et al. 2002). June also marked the beginning of a *Chaetoceros gelidus* (historically reported as *Chaetoceros socialis*; Chamnansinp et al. 2013) bloom in the southern part of the polynya (Booth et al. 2002). By July and early August, *C. gelidus*, along with *Thalassiosira* spp. dominated biomass throughout the polynya except in the southeastern area of the North Water where the phytoplankton assemblage was a mixture of diatoms. By mid August and into September, *C. gelidus* dominated the phytoplankton biomass throughout the polynya (Booth et al. 2002). Recently, analysis of DNA using a taxonomic marker along the 76 °N transect from 2005 up until 2019, shows that there is a major difference in phytoplankton species communities between summer (July and August) and October (Freyria et al. 2021). Seasonality in phytoplankton community composition was also reflected in the sinking export of dominant species (Caron et al. 2004).

The diatoms *C. gelidus* and *Thalassiosira* spp. appear to be responsible for the most primary production in the North Water (Booth et al. 2002). Thalassiosira spp. forms very intense, yet transient blooms, while *C. gelidus* blooms form later, are longer-lasting, and may be critical to overall biological richness in the North Water (Booth et al. 2002). The longevity of *C. gelidus* is likely due to its unique characteristics including its ability to survive at lower nutrient concentrations than *Thalassiosira*, its propensity to sink slowly (because of spines and its smaller size), and the production of resting spores, which survive zooplankton digestive processes and enables the species to reinvade the euphotic zone (Booth et al. 2002).

In August 2013, Joli et al. (2018) sampled the east and west sides of the North Water over two 24-hour periods in order to capture short term variation in the phytoplankton community. DNA analysis, verified by microscopy, showed differences in the microbial eukaryote communities on either side of the North Water. Joli et al. (2018) found that the Greenland side of the polynya was characterized by *Pseudo-nitzchia* spp. dominated communities, while the Canadian side displayed a more mixed community. *Pseudo-nitzchia* spp. is a taxa capable of producing the neurotoxin domoic acid, which is harmful to marine mammals. According to Joli et al. (2018), high concentrations of *Pseudo-nitzchia* spp. had not been previously observed in the North Water. The authors suggested that increases in meltwater from the Greenland ice sheet due to climate change may favour *Pseudo-nitzchia* blooms and, thereby, increase the potential for the production of harmful neurotoxins in this highly productive Arctic ecosystem. On the west side of the North Water, large differences in the phytoplankton community were observed, which was attributed to the mingling of multiple water masses that occurs in that area of the polynya, and therefore thought to be responsible for the mixed community that was observed in the Canadian side of the North Water (Joli et al. 2018).

### 3.2.1.2. Productivity and Biomass

The earliest available production data for the North Water are based on data collected from 1997–1999 and provided by Klein et al. (2002). It has been recognized that 1998 was a highly productive year in the North Water, and these productivity levels have not been seen since, although maximum production was in May and June and the area has not been revisited during that bloom period. Klein et al. (2002) estimated the total annual production in the region ranged from 76–254 $gC/m^2/yr$. Similar rates of production have been estimated using less direct methods in other studies, indicating that total annual production in the North Water is high (Tremblay et al. 2002b, Ardyna et al. 2011). Klein et al. (2002) estimated that there is the potential for 42–155 $gC/m^2$ of particulate organic carbon to be exported from the euphotic zone per year. Based on these data, Garneau et al. (2007) estimated the annual new production (i.e., production driven by nutrients from outside the euphotic zone) in the North Water to be 143–152 $gC/m^3$, indicating that new production accounted for approximately 60% of the total annual production in the North Water as reported by Klein et al. (2002). Similar findings have been reported elsewhere (Tremblay et al. 2006a).

A large proportion of the carbon produced in the euphotic zone is initially retained within the planktonic food web before being distributed to more mobile species, or settling into the benthic zone (Klein et al. 2002, Sampei et al. 2002, Tremblay et al. 2006a). It is estimated that approximately two thirds of the carbon produced by phytoplankton remains within the euphotic zone and, therefore, the pelagic food web (Mei et al. 2003, Caron et al. 2004). A seasonal progression in carbon cycling of initial export in the spring followed by retention later in the season occurred in the North Water (Amiel et al. 2002, Caron et al. 2004). Regional variations in carbon export have also been detected, which are related to regional patterns in diatom (specifically, *C.gelidus*) development; such that the west side exhibits higher rates of carbon flux than other areas of the North Water (Amiel et al. 2002). Since the 2000s, more primary production (phytoplankton) is reaching the seafloor (based on fatty acid content of benthos), possibly indicating a mismatch between phytoplankton production and zooplankton grazing (Gaillard 2016, Bell and Brown 2018, Olivier et al. 2020).

*Table 2. Maximum chlorophyll a concentrations observed in the euphotic zone in the North Water and other Arctic environments. Reproduced from Klein et al. (2002).*

| **Region** | **Chlorophyll *a*** | | **References** |
|---|---|---|---|
| | **$mg/m^3$** | **$mg/m^2$** | |
| North Water Polynya | 19.8 | 300[a] | Klein et al. (2002), Mei et al. (2002) |
| | 19.5 | 506[a] | Lewis et al. (1996) |
| Northeast Water Polynya | 9.9 | 27.5 | Smith et al. (1997) |
| St. Lawrence Island Polynya | - | > 300[b] | Grebmeier and Cooper (1995) |
| Bering Strait | - | > 200[b] | Sambrotto et al. (1984) |
| Bering Sea | > 30 | - | Sakshaug and Skjoldal (1989) |
| Ice edges | 8–20 | - | Sakshaug and Skjoldal (1989) |

a. Integration depth of 16–25 (Klein et al. 2002, Mei et al. 2002) or 30 m (Lewis et al. 1996).

b. Whole water column (< 50 m).

*Table 3. Phytoplankton biomass (mean ±SE) in three oceanographic regions of the Canadian High Arctic during late summer 2005, early fall 2006, and fall 2007. Adapted from Ardyna et al. (2011).*

| **Region** | **Chlorophyll *a* (mg/m$^2$)** | | |
|---|---|---|---|
| | **Late Summer 2005** | **Early Fall 2006** | **Fall 2007** |
| Beaufort Sea | 23.2 ± 11.2 | 25.5 ± 15.7 | 17.7 ± 3.0 |
| Canadian Arctic Archipelago | 38.3 ± 15.7 | 22.6 ± 7.7 | 12.4 ± 1.0 |
| Baffin Bay[a] | 56.8 ± 17.8 | 71.4 ± 10.7 | 62.4 ± 20.1 |

a. All sites located in northern Baffin Bay were within the North Water.

The biomass and production in the North Water vary spatially. A survey of the phytoplankton communities across the Canadian High Arctic found that northern Baffin Bay was the most productive area in the region (Ardyna et al. 2011). Phytoplankton data gathered from surveys conducted in the North Water from 1997–1999 showed the highest biomass and production on the east side of the polynya, followed by the north, and then the west, with a clear seasonal trend in chlorophyll a, and phytoplankton biomass and production (Klein et al. 2002, Odate et al. 2002, Vidussi et al. 2004). Chlorophyll a was lowest in April (pre-bloom), increased to a maximum in May and June (bloom), and then was followed by a decrease that remained fairly constant through the rest of the growing season (post-bloom) (Figure 19). Similarly, Lewis et al. (1996) found that phytoplankton biomass was higher in the east than on the west side of the polynya in May 1991. Berreville et al. (2008) analysed the 1998 seasonal patterns in phytoplankton biomass, and showed that diminishing ice cover corresponded with increased temperatures, stratification, nutrients, and biomass of both small and large phytoplankton. The modeling exercise indicated that following the peak bloom, phytoplankton biomass decreased as a result of increased grazing pressure by zooplankton (Berreville et al. 2008).

More recent satellite data and water samples showed similar surface chlorophyll a concentrations on the west and east sides of the polynya in mid-August despite differences in salinity; however, chlorophyll a concentrations at depth (starting near the bottom of the polar mixed layer) varied spatially (Joli et al. 2018). There was little variation in chlorophyll a throughout the water column on the west side of the polynya, whereas, on the east side, there was a large peak in chlorophyll a that was associated with a highly stratified water column. Phytoplankton data for the south are limited for this year due to a longer period of ice cover that lasted through April and May; however, the available data show that biomass and production were low.

Nitrate and light are considered to be the most important limiting factors to the timing and location of productivity in the North Water (Klein et al. 2002, Tremblay et al. 2002a, Vidussi et al. 2004). Garneau et al. (2007) supported this and showed that based on nutrient ratios, phytoplankton growth was limited by both nitrate and light in late summer and early autumn. High initial phytoplankton concentration could trigger self shading and could limit light availability during peak nutrient concentration and therefore slow the timing of the peak bloom (Mei et al. 2002). Further, the development of a subsurface chlorophyll maximum, and the depth at which it occurs in the North Water, is a result of increased stratification and irradiance (UV light) (Vasseur et al. 2003).

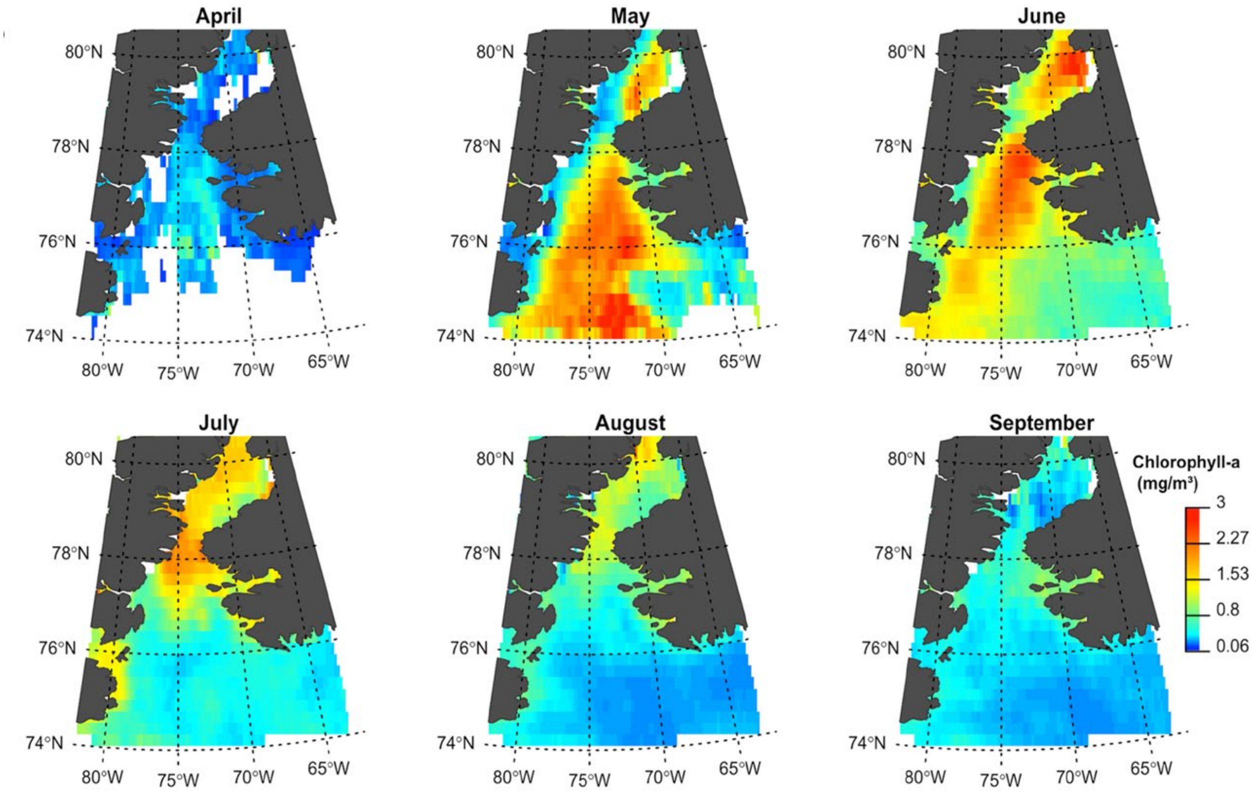

*Figure 19. Seasonal progression of the phytoplankton bloom in the North Water region, based on remote-sensing estimates of chlorophyll a concentration. The colors indicate different chlorophyll a concentrations (red = highest concentration which indicated peak bloom in May in the central part of the study area). These maps likely underestimate the total magnitude of primary production, since it only shows chlorophyll a in the surface layer and does not reflect subsurface chlorophyll a maxima or ice associated production. Our knowledge of chlorophyll a in the water column is yet very limited (Source: Marchese et al. 2017).*

#### 3.2.1.3. Distribution, magnitude and duration of the bloom

Spatially, the annual North Water phytoplankton bloom starts in the southeast region of the polynya, peaking in May and June, gradually moving north and then west, peaking approximately one month later (Booth et al. 2002, Odate et al. 2002, Saunders et al. 2003, Vidussi et al. 2004, Marchese et al. 2017). As mentioned, the distribution and development of phytoplankton within the North Water is influenced by water mass characteristics (e.g., temperature and salinity) and circulation patterns (Lewis et al. 1996, Lovejoy et al. 2002, Odate et al. 2002, Tremblay et al. 2002b, Vidussi et al. 2004, Joli et al. 2018) with phytoplankton blooms occurring earlier and at higher concentrations where surface waters are dominated by warmer Baffin Bay water compared to colder Arctic water (Tremblay et al. 2002b, Saunders et al. 2003).

Satellite imagery has also been used to track the extent and timing of the phytoplankton bloom (Bélanger 2001, Brunelle et al. 2012, Marchese et al. 2017, Joli et al. 2018). Satellite imagery collected from 1998–2014 showed that the phytoplankton bloom is an annual event with surface chlorophyll *a* peaking in late May or early June (Marchese et al. 2017). In any particular year, the start of the bloom may vary by as much as two months between the east and west sides of the polynya (Marchese et al. 2017). Light penetration and mixed layer depth determine the timing such that the phytoplankton bloom develops first in the high salinity warmer waters on the eastern side of the polynya (Figure 19) (Tremblay et al. 2002b). There, the earlier stabilization of the shallow, mixed layer allows algal cells to build up in the presence of grazers (Mei et al. 2002). As the season progresses, the ice melts and stratification develops in the north and the bloom advances northward and then down the west side of the polynya following the nutrient-rich arctic waters (Tremblay et al. 2002b). Figure 20 shows this, when extremely low surface concentrations of nitrate and chlorophyll fluorescence (an index of phytoplankton biomass) in the cold and relatively fresh Arctic Outflow, where stratification (i.e., vertical salinity gradient) is strongest (AMAP 2018).

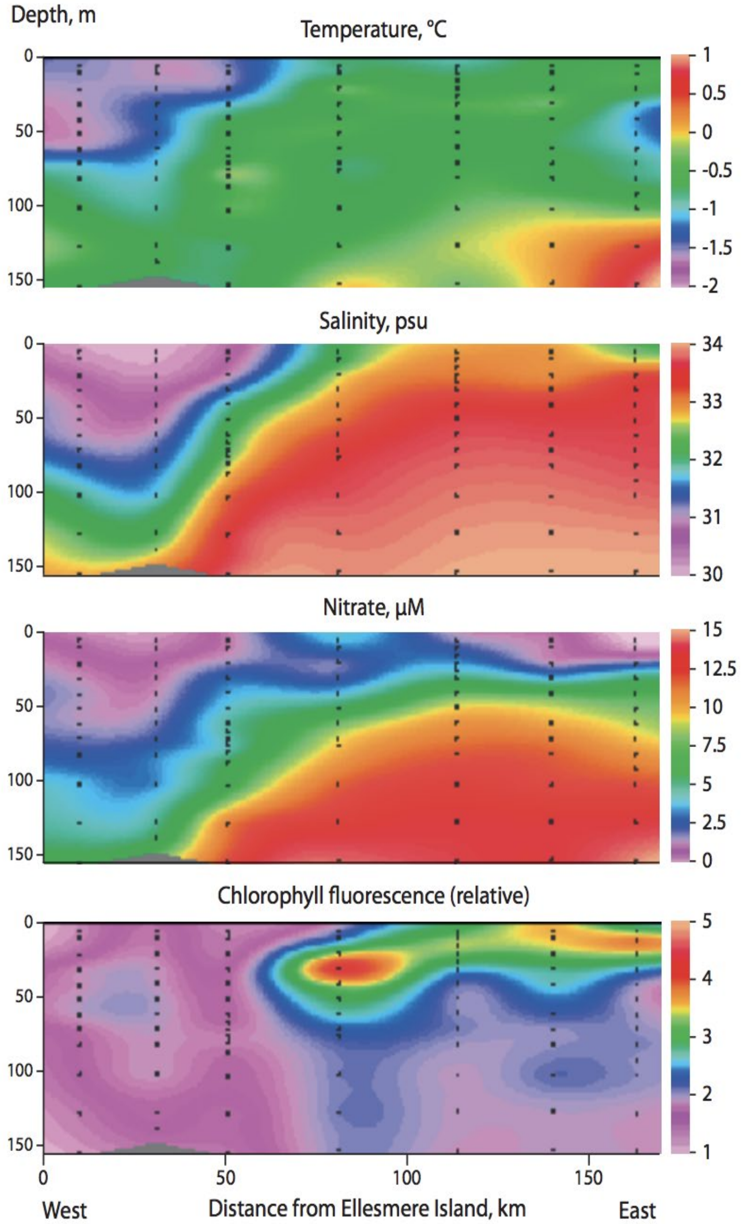

*Figure 20. East–west cross-sections of selected ocean properties in Smith Sound (North Water) between Ellesmere Island and Greenland, 0–150 m: temperature, salinity, nitrate concentration, and relative chlorophyll fluorescence (an index of phytoplankton biomass) (data from the 2005 ArcticNet expedition; Source: AMAP 2018).*

The magnitude of the bloom depends on the existing pool of available nutrients and the conditions that occur to allow for the introduction of nutrients from beneath the upper mixed layer (Tremblay et al. 2002b). The size structure of the phytoplankton community (large phytoplankton allow for deeper light penetration) influences the depth of the euphotic zone, which can also affect the magnitude of the bloom (Mei et al. 2002). The peak euphotic zone chlorophyll *a* concentration reported from the 1998 spring bloom ranged from 17.45 mg/m$^3$ (Vidussi et al. 2004) to 19.8 mg/m$^3$ (Klein et al. 2002), depending on the methods used (high-performance liquid chromatography versus fluorometry). The maximum area chlorophyll *a* integrated across the euphotic zone in the North Water ranged from 300 mg/m$^2$ (Klein et al. 2002) to 724 mg/m$^2$ (Bussey 2003). Similarly, high levels of chlorophyll *a* during the North Water bloom have been reported in other years (Lewis et al.1996, Bélanger 2001, Ardynya et al. 2011).

There is also evidence that, in some years, a second phytoplankton bloom may occur in the fall (Odate et al. 2002, Ardyna et al. 2011, Marchese et al. 2017). There is annual variation in the timing, duration, and magnitude of the bloom, which may start from mid-May to June, and ends from June to mid-July (Bélanger 2001, Klein et al. 2002, Marchese et al. 2017). This variation is determined by annual differences in atmospheric (e.g., air temperature, winds, and cloud cover) and oceanic conditions (e.g., sea-ice concentrations and meltwater inputs) that control stratification and therefore the transport of heat and nutrients to the surface layer (Bélanger 2001, Tremblay et al. 2002b, Vidussi et al. 2004, Marchese et al. 2017). The bloom tends to start earlier and last longer (up to three months) in years with less ice and cloud cover and a longer open-water period as these two factors have the potential to affect the depth of the mixed layer (Marchese et al. 2017).

### 3.2.2. Microbial Community

Similar to warmer water marine environments, bacteria are important in the recycling of carbon and other nutrients within the pelagic zone of the North Water (Huston and Deming 2002, Middelboe et al. 2002, Bussey 2003). In 1998, bacterial biomass in the North Water increased in May, peaked in June, and then began to decline as a result of grazing pressure (Bussey 2003). Spatial differences in the distribution of bacterial cell size within the North Water have been observed with smaller cells dominant in the east, perhaps due to lower nutrient levels, and larger cells dominant in the north and west (Bussey 2003). Additional research suggests that near the end of the production season, nutrients become more limited, and heterotrophic bacteria may contribute substantially to production in the North Water (Garneau et al. 2007). As the phytoplankton bloom decays, there is a corresponding increase in growth and activity of bacteria (Huston and Deming 2002, Middleboe et al. 2002) suggesting that a significant part of the organic carbon that is produced by the phytoplankton bloom is taken up by planktonic bacteria (Middleboe et al. 2002). Therefore, a large part of the carbon produced by phytoplankton within the eutrophic zone is retained and recycled within the planktonic food web and less settles into the benthic zone (Klein et al. 2002). Bacteria associated with the sediments are also involved in nutrient and carbon cycling, but these taxa are not well characterized (Nelson 2013). The number of microbial taxa in the Arctic has been estimated at 9,500, although projections are as high as 54,500 (Archambault et al. 2010).

### 3.2.3. Ice Algae

As part of the North Water project, spatially-distributed sampling of ice algal communities and ice micro- and meio-fauna was conducted from April to June (Nozais et al. 2001, Michel et al., 2002b). The ice algal chlorophyll *a* (chl *a*) biomass varied between 1 and 56 mg m$^{-2}$ (Nozais et al. 2001), comparable to other studies in Arctic coastal environments. These studies also show that only a small fraction of the ice algal biomass is utilized by micro and meio-fauna within the ice, with the bulk of the biomass being exported to the water column where it becomes available to pelagic grazers (Michel et al. 2002b). The composition of the ice algal community in the North Water was comparable to that in the adjacent landfast ice of Barrow Strait, with a dominance of pennate diatoms, of which *Nitzschia frigida* was the dominant species (Michel et al. 1996, 2002b). Seasonal changes in ice algal species were observed, but the pennate diatom dominance remained, similar to adjacent landfast ice of Barrow Strait (Michel et al., 1996, Lee et al. 2001, Michel et al. 2002b). Lee et al. (2001) provided the first measurements of the sulfur compound dimethylsulfoxide in ice algae in their study of sea ice algae in the North Water. These authors found low concentrations of sulfur compounds in ice algae, slightly lower than in phytoplankton, challenging the hypothesis that these compounds would act as cryoprotectants in ice algae. The role of ice algae or sea ice constituents in seeding the phytoplankton bloom remains unclear. For example, Apollonio et al. (2002) observed enhanced growth of phytoplankton with the addition of sea ice derived organic material in Jones Sound. Sinking ice algae have also been suggested to seed the water column in other areas of the Arctic (Michel et al. 1993, Yamamoto et al. 2014) and organic carbon produced by ice algae can fuel under-ice bacterial production and modify the composition of microbial communities (Underwood et al. 2019). In the North Water and adjacent areas, the biomass of ice algae accumulated during the growth season is predominantly transferred to the water column or the benthos where it is channelled through the pelagic or benthic food webs (Michel et al. 1996, 2002b, Kohlbach et al. 2019).

### 3.2.4. Marine Macrophytes/Benthic Macroalgae

Macroalgae, or seaweed, consists of large, frequently multicellular algae often living attached to the seafloor in dense beds. In the Canadian Arctic, there are an estimated 210 taxa of seaweed belonging primarily to the phyla Rohodophyta (red algae), Chlorophyta (green algae), and Phaeophyceae (brown algae) (Archambault et al. 2010). Macroalgae serve as food for benthic organisms and create habitat (e.g., shelter from predators, waves, currents (Merkel et al. 2012). Appendix 1 lists some of the marine macrophyte and algal taxa present in the North Water.

Existing information on the abundance or species diversity of macroalgae specific to the North Water or nearby water bodies is minimal. There are widely distributed kelp beds on the western Greenland coast that may include portions of the North Water (AMAP 2018). Marine macroalgae is also found on coastal Greenland shorelines with hard, stable substratum (e.g., stone, boulders, rocks) (Merkel et al. 2012). Conditions required by marine macroalgae include low temperatures, seasonal changes in the light regime, and ice cover for a large part of the year (Merkel et al. 2012). These conditions may not be present in portions of the North Water area.

Evidence to date suggests rapid change in kelp forests in the Arctic as the oceans warm and sea ice retreats (Krause-Jensen and Duarte 2014). Long-term research from Greenland and Norway indicates that a warmer Arctic with less sea ice will support higher kelp productivity and the expansion of the northern range and lower depth limit of these habitat-forming species (Krause-Jensen et al. 2012, Barscht et al. 2016). Yet, along the coasts of Murmansk, Russia and in the Beaufort Sea and Gulf of Alaska, USA intense coastal erosion from melting sea ice, fragmenting permafrost, and unusually high glacial inputs are increasing sediment loads and freshwater inputs in the coastal zone (Fritz et al. 2017), resulting in direct kelp die-offs (Konar et al. 2017, Filbee-Dexter and Wernberg 2018) and buffering any positive impacts of increased light and warmer temperatures (Bonsell et al. 2018). Therefore, any positive effects of environmental changes on kelps will likely vary regionally, and depend on coastline stability (Filbee-Dexter et al. 2019). While there is significant uncertainty in current predictions, the possible expansion of kelp forests into areas like the North Water should provide new habitats for fish and other organisms, increase carbon storage, and increase other ecosystem services along Arctic coasts.

### 3.2.5. Zooplankton and Ice-associated Invertebrates

Surveys in the North Water have shown that a wide variety of species comprise the zooplankton community, with copepods accounting for the greatest diversity (see Appendix 2). Copepods are the most important group of zooplankton in the Arctic, consistently dominating the biomass (Ringuette et al. 2002). For example, in a 1984 survey by Longhurst et al. (1984) in the eastern Arctic, copepods comprised > 92% of the zooplankton samples. However, it should be noted that gelatinous zooplankton are also present in the North Water and at times later in summer have higher grazing rates than copepods (Deibel et al. 2017).

Herbivorous, omnivorous, and carnivorous copepods are all present in the North Water. The three main herbivorous copepods in the area are *Calanus finmarchicus, C. glacialis,* and *C. hyperboreus*. These three copepods are the most abundant herbivores in Arctic waters, and are an important link in food webs, converting carbohydrates and proteins in ice algae and phytoplankton to high energy lipids (Falk-Petersen et al. 2009). A study of the zooplankton community in the North Water during April–July 1998 found that *C. hyperboreus* was the dominant species, a pattern also observed in the Greenland Sea and central Arctic Ocean (Grainger 1961, Prokopowicz and Fortier 2002). The greatest abundance of all three species was found in the centre of the North Water (Prokopowicz and Fortier 2002). Grainger (1961) stated that *C. glacialis* was found in polar water, *C. finmarchicus* was found in Atlantic water, and the two were only found together in the region of mixed polar and Atlantic water, such as occurs in the North Water. More recent literature also demonstrates that both species can co-occur, especially in coastal areas (e.g., Choquet et al. 2017). Evidence indicates that *C. finmarchicus* is also likely reproducing in the North Water, something that was previously thought to be impossible at such a high latitude (Grainger 1961, Prokopowicz and Fortier 2002, Møller and Neilsen 2019). The two Arctic specialist species, *C. glacialis* and *C. hyperboreus* have been estimated to live in the North Water for two and four years, respectively (Prokopowicz and Fortier 2002). The population of *C. hyperboreus* in the North Water were observed reproducing a month before *C. glacialis* (Prokopowicz and Fortier 2002) such that by early June, the biomass of copepods was dominated by *C. hyperboreus* and, to a lesser extent, *C. glacialis*. Stable isotope analysis indicated that the diet of these herbivorous copepods was composed mainly of phytoplankton, and that ice algae was not a major food item (Tremblay et al. 2006a). These results confirmed that the major pathway of carbon flux in the North Water is the herbivorous food web (Tremblay et al. 2006a). Copepod grazing was found to be only a minor mechanism in the release of di-methylated sulfur compounds in the North Water (Lee et al. 2003).

An analysis of carbon flux in the eastern North Water during the phytoplankton bloom found that approximately 79% of primary production was consumed by pelagic consumers between April and July of that year (Tremblay et al. 2006a). The abundance of smaller omnivorous copepods (mainly *Oithona similis*) was two orders of magnitude smaller than that of the herbivores (Tremblay et al. 2006a). Stevens et al. (2004) used lipid composition to determine the level of omnivory from copepods in the deep water of the North Water. The authors found that *Metridia longa*, a species that is less dependent on phytoplankton as a food source, had a different lipid composition than the herbivores. A stable isotope study of the North Water food web also indicated that *M. longa* has an omnivorous diet that is more dependent on carnivory than herbivory (Hobson et al. 2002a). *Paraeuchaeta glacialis* is the largest carnivorous copepod in Arctic waters; its trophic level was found to be higher than both Arctic Cod (*Boreogadus saida*) larvae and Dovekie (Hobson et al. 2002a). The diets of carnivorous zooplankton are size-dependent, with adults eating more and larger animal prey than juveniles (Hobson et al. 2002a).

When recruitment and population development in calanoid copepods were compared between the North Water and the Barrow Strait, a polynya-free area, it was found that the phytoplankton bloom and recruitment of large herbivorous copepods started 6–12 weeks earlier in the polynya, and consequently, those taxa were at more advanced population stages later in the summer compared to the polynya-free area (Ringuette et al. 2002). In contrast, there was no difference in recruitment and growth for smaller herbivorous copepods. Recruitment success depended on chlorophyll *a* concentration for *C. glacialis*, temperature for *Pseudocalanus* spp., and both for *C. hyperboreus* (Ringuette et al. 2002). Takahashi et al. (2002) found that respiration rates of copepods in the North Water increased with chlorophyll *a* concentration, and hypothesized that this indicated activated feeding behaviour, an adaptation to allow the copepods to take full advantage of the entire phytoplankton bloom in the North Water. The accelerated growth of copepods in the North Water likely shortens the annual life cycles, leading to earlier reproduction and a decreased chance of mortality before reproduction (Ringuette et al. 2002). Tidmarsh (1973) observed that the polynya did not affect the distribution of copepods in the area, but did have a profound effect on the life cycles and adult sizes of herbivorous species. This was related to the early bloom of phytoplankton, which allows large herbivorous copepods to spawn earlier and grow and mature quickly. The greatest effects were noted for *C. hyerboreus* and *C. glacialis* in surface layers of the North Water during the spring; mesopelagic and deep-living species were less affected (Tidmarsh 1973).

The role of copepods in the North Water food web is seasonally variable. Comparison of zooplankton fecal pellet carbon fluxes in the North Water in June and July found that much more fecal pellet carbon was found at depths of 200 m in July compared to June (Sampei et al. 2004). This was attributed to a greater amount of coprophagy by *C. hyperboreus* in June, when primary production had not yet peaked. In July, there was more primary production and *C. hyperboreus* had higher rates of herbivory than coprophagy, therefore more fecal pellets sunk to the bottom (Sampei et al. 2004). Saunders et al. (2003) found that copepod biomass increased in response to the spring phytoplankton bloom, with overwintering adults migrating to the surface in response to the bloom. However, copepod grazing rates had little impact on daily phytoplankton production. In the North Water, the biomass of copepods in the spring is low relative to the very high amount of primary production (Saunders et al. 2003). Primary production was shown to be higher than most other areas in the Arctic, but copepod biomass was similar to other systems (Saunders et al. 2003). Later in the summer, after the large spring phytoplankton bloom began to subside, copepod grazers had more of an impact on primary production. It was hypothesized that population size of *Calanus* spp. in the North Water was controlled by predation, especially by seabirds such as Dovekies, thus explaining why their biomass was not as high as expected for such a productive region (Saunders et al. 2003). A multivariate analysis (PCA) of physical, chemical and biological data collected from April to July 1998 was undertaken by Berreville et al. (2008). The analysis revealed clear seasonal patterns in food web structure. Corresponding with the phytoplankton bloom that developed, there was an increase in heterotroph biomass; copepods (nauplii and adults) however, showed a different and delayed response. Post-bloom, smaller heterotrophs decreased while copepod (and appendicularian) biomass increased (Berreville et al. 2008).

There are spatial differences in the distribution of copepods within the North Water. Saunders et al. (2003) found that copepod herbivory rate and biomass were larger and peaked earlier in the southern and eastern North Water, which is dominated by Baffin Bay water, compared to the northern and western North Water, which is dominated by Arctic water rich in silica. The vertical distribution of copepods was found to be related to the life stage (Ringuette et al. 2002). Early stages of herbivorous calanoid copepods were found in the base of the Arctic surface water layer, which was cold and chlorophyll-rich while older stages were found in warmer water layers near the surface during the spring-summer period (Ringuette et al. 2002). Longhurst et al. (1984) found that zooplankton in the eastern Arctic, including in the North Water, did not exhibit diel migration in the late summer, and that vertical distribution was primarily determined by season and life stage. In addition, other studies in the high Arctic confirmed the absence of synchronized diel vertical migration during the midnight sun (Blachowiak-Samolyk et al. 2006), but asynchronous vertical migrations might prevail (see Wallace et al. 2010). Microzooplankton (e.g., flagellates and ciliates), though comprising a much smaller proportion of the biomass, also play a role in the North Water food web. Bussey (2003) found that microzooplankton preferentially grazed on small phytoplankton (those less than 5 $\mu$m) but switched to bacteria later in the season as phytoplankton became less available.

Nozais et al. (2001) looked at meiofauna associated with sea ice in the North Water, which included nematodes, copepods, crustacean nauplii, polychaete larvae, and turbellarians. They found that, in spring, the grazing of sea-ice meiofauna had a negligible impact on ice algal biomass accumulation and that the sea ice meiofauna was a minor contributor to the North Water carbon flow during spring. The highest densities of sea ice meiofauna in the North Water were found in the lowest 2 cm of ice (Nozais et al. 2001). Appendicular tunicates also are an important component of the North Water zooplankton community. Acuña et al. (2002) estimated that tunicates consumed up to 10% of the daily primary production (primarily diatoms) during the month of July. Similar results were obtained from stable isotope analysis (Tremblay et al. 2006a). During July, appendicularians removed more carbon from the surface water layer than copepods, ranging from 38 to 11,248 m$^{-2}$ (Acuña et al. 2002).

Zooplankton in the North Water are a significant food source for seabirds. Karnovsky et al. (2008) found that copepods were found in the stomachs of 53% of Dovekies in the summer and 68% in the winter, comprising almost 100% of the prey items consumed. Kittiwakes and Murres also ate copepods and other zooplankton, such as the pteropod *Limacina* sp. (Karnovsky et al. 2008). Stable isotope analysis of the North Water trophic food web confirmed the importance of *C. hyperboreus* (and to a lesser extent, *C. glacialis*) to the diets of Dovekie, Arctic Cod larvae, larger carnivorous copepods (e.g., *P. glacialis*), and the amphipod *Themisto libellula*. (Hobson et al. 2002a). In turn, *T. libellula* is an important food source for Beluga and Narwhal, Ringed Seals, Dovekie and other seabirds, adult Arctic Cod, and Bowhead Whales (Hobson et al. 2002a, Tremblay et al. 2006a). Stable isotope analysis indicates that *T. libellula* comprises a large part of the diet of Bowhead Whales in the North Water, along with *C. hyperboreus* (Hobson et al. 2002a).

The large Arctic *Calanus* copepods that form an important link in the transfer of nutrients from algae to higher trophic levels are expected to experience changes concurrent with changes in algal production in the North Water (Mosbech and Kyhn 2019). Recent examinations of the North Water mesozooplankton during winter showed that reproduction of *Calanus hyperboreus* can be disrupted by the increasing variability in the timing and availability of their microalgal food source. Arctic copepods may also experience greater competition and/or predation pressure as new species invade from the south (Mosbech and Kyhn 2019). Of particular concern is a potential shift towards smaller species that are less rich in lipids than the high Arctic species (Mosbech and Kyhn 2019, Møller and Neilsen 2019), a shift that is already occurring further south in the Labrador Sea (Maillet et al. 2019, Bélanger et al. 2019). This could result in negative effects on the energetics of zooplanktivorous fauna (fish, some seabirds, baleen whales).

### 3.2.6. Benthic Community

Benthic communities are important components of the marine ecosystem in the Arctic. Benthic organisms play an important role in carbon cycling by decomposing organic matter on the seafloor, return nutrients to the water column through remineralisation, serve as a food source for fish, marine mammals and seabirds, provide structure and habitat for other organisms (e.g., corals and sponges), and may be harvested commercially (e.g., scallops, crabs, shrimp, mussels, sea urchins, and sea cucumbers) (Chalut et al. 2014, Kenchington et al. 2011, Roy et al. 2014). The species richness of the zoobenthos of the Arctic has been estimated at more than 4,000 species/taxa (Bluhm et al. 2011, Piepenburg et al. 2011, CAFF 2017). The primary factors that control the structure and function of benthic communities in the Arctic include water masses, sediment characteristics, ice gouging (Carey 1991) and food supply (Roy et al. 2015a, Olivier et al. 2020). The eastern region of the Canadian Arctic has a greater species richness of benthic macrofauna than the western and central regions (Cusson et al. 2007) and the Canadian Arctic has a greater biodiversity than the Canadian Atlantic region (Wei et al. 2019). Polychaete worms, crustaceans (Malacostraca), and molluscs dominate the benthic fauna of the Arctic (Carey 1991, Archambault et al. 2010). The biomass of the macrobenthos at locations in the North American Arctic in the vicinity of the North Water averaged 200–438 g/m$^2$ (wet weight) for the northern Baffin Island region and 48–320 g/m$^2$ for the western Greenland area (Ellis 1960 in Carey 1991).

Historically, there have been few studies of the benthic communities specific to the North Water, but more recently there has been an increase in survey efforts (CAFF 2017). The North Water is known to have a high benthic diversity and biomass (DFO 2011a, Mäkelä et al. 2017). Specifically, the west side of the North Water is considered a hotspot of benthic biodiversity. The functional diversity – a component of biodiversity that addresses the range of niches within an ecosystem – of the North Water is among the highest known in the Canadian Arctic. Studies of pelagic-benthic coupling (the cycling of carbon and transfer to pelagic and benthic grazers) have shown that the longer open water production season in the North Water (which is also linked to its higher production compared to adjacent regions) provides a longer period over which the benthos receives inputs of organic carbon from the pelagic zone (Lewis et al. 1996, Grant et al. 2002). The highest benthic oxygen consumption and carbon deposition occurs at the western side of the North Water. The consumption of organic matter by the benthos accounts for about 5% of the ice-free primary production in the North Water (Grant et al. 2002). Sediment pigment and organic carbon content (indicators of food supply) are relatively high throughout the North Water, which suggests the area supports highly productive and diverse benthic communities (Kenchington et al. 2011). Benthic fluxes (a measurement of the oxygen use by the benthos for respiration) reported for the North Water are among the highest measured in the Canadian Arctic (Kenchington et al. 2011, Link et al. 2013). There are limited studies on the Greenlandic side of the North Water, but investigations further south in Baffin Bay (Sejr et al. 2011) suggest that this area is species-rich, with high densities of organisms. The high occurrences of Walruses and eiders in the region, species whose primary food is shellfish, also indicates a rich benthic fauna, at least at the depths they normally forage (eiders to about 25 m, Walrus to 100 m) (Christensen et al. 2017).

The benthic communities in the North Water consist primarily of clams, scallops, sponges, sea worms, anemone, crabs, and sea stars (Wilkinson et al. 2009, Hargrave et al. 2002). Benthic taxa that have been identified in or near the North Water in the published literature are presented in Appendix 3. The list includes some benthic invertebrates that have been observed in the stomachs of seabirds and Walruses captured in or near the North Water, although it is not possible to confirm the prey items originated in the region. The benthic community shifts from one dominated by meio-microbenthos in spring to macrofauna in the summer (Grant et al.

2002). Meiofauna (e.g., nematodes, copepods, ostracods) account for about 85% of benthic organisms and polychaetes are the dominant group of megafauna in box core samples (259–609 m depth) from the North Water (Lalande 2003). Megafaunal taxonomic composition in trawl samples from the North Water (2007–2011) was 25% Arthropoda, 19% Annelida, 17% Echinodermata, 11% Bivalvia, 9% Bryozoa, 8% Gastropoda, and 6% each Cnidaria and Other (Roy et al. 2015b). The biomass composition was 48% Echinodermata, 33% Porifera, 9% Cnidaria, with the other taxa accounting for < 3% (Roy et al. 2015b). Macrobenthic abundance and diversity is very high in the center of the North Water and lowest on the east side, where concentrations of organic carbon and nitrogen are highest (Lalande 2003). Similarly, bottom trawl samples have shown that the number of megafauna species/taxa is generally low in the eastern section of the North Water (< 25 species) compared to the western section (< 80 species) (CAFF 2017). Rare species that have been documented in the area include Torquaratorid acorn worms (*Allapasus fuscus* sp.) (Jabr et al. 2018) and the polychaete species, *Macrochaeta polyonyx* (López et al. 2016).

Somewhat contrastingly, Roy et al. (2014) measured several benthic community characteristics at stations located in the North Water and found that biomass was generally higher at sites located in the east side (21–39 g/m$^2$) compared to the west-central section (3.5–10 g/m$^2$); density was uniformly low (0.08–7.64 ind./m$^2$); and two biodiversity metrics showed high variability among sites (taxonomic richness density, 15.8–257.0 taxa/1000 m$^2$, and Shannon-Wiener's diversity index, 0.5–3.2). Cluster analysis based on biomass, depth, and substrate variables resulted in the sites in the west-central polynya as "local hotspots", while those in the east were categorized as "hard substrate" and "deep soft substrate" (Roy et al. 2014). Both the "deep soft substrate" and "local hotspots" clusters were dominated by echinoderms; the "deep soft substrate" cluster had a higher proportion of Cnidaria and Bivalvia and the "local hotspots" had a higher proportion of the Arthropoda. The "hard substrate" cluster was dominated by Porifera, with a smaller proportion of Echinodermata. The "local hotspots" was characterized by a much greater cumulative total biomass than the other two clusters.

Sampling of food web components for a stable isotope food web model identified 24 species of invertebrates that are associated with benthic habitats in the North Water during April-June 1998 (Hobson et al. 2002a). Benthic organisms such as molluscs and echinoderms were enriched in $^{13}$C compared to pelagic organisms, as is commonly observed in other systems. Isotope tracing studies ($^{13}$C– $^{15}$N) indicated that benthic macrofauna from the North Water are N-limited and, based on the decoupling of C and N uptake, may adjust diet to preferentially uptake N (Mäkelä et al. 2017). Benthic macrofauna consume more ice algae compared to phytoplankton, but are able to use both ice algae and phytoplankton as a food source (Mäkelä et al. 2017).

### 3.2.7. Summary of Lower Trophic Levels: Knowledge Gaps and Climate Impacts

The North Water is a vastly productive area, characterized by high overall phytoplankton biomass and production. The magnitude, distribution, and development of phytoplankton within the North Water are influenced by light availability (e.g., long open water season, timing of polynya formation), coupled with water mass distribution and dynamics, the pool of available nutrients, and circulation patterns. An important distinction of the North Water compared to other Arctic regions is not only the high phytoplankton biomass and production, but the early timing (e.g., April-May), and duration of the bloom. The majority of our knowledge of the lower trophic system, and species within the North Water, is based on the International North Water Polynya Study (NOW) from the late-1990s, and many knowledge gaps exist within this theme. For example, the coastal distribution and species diversity of primary producers in the North Water are relatively unexplored, data on phytoplankton production during ice-covered periods is generally lacking – including a limited knowledge of ice-associated algae and the magnitude of this production – and the exact timing and degree of biophysical coupling in the system is not well understood. The fiord and coastal systems are very important to lower trophic species, such as macroalgae (i.e., kelp), which serve as food for higher trophic levels and create habitat sheltered from predators, waves, and currents. However, information on their spatial distribution is limited, particularly on the Greenland side of the North Water. In addition, there is a lack of knowledge on the spatial (and vertical) distribution of phytoplankton and zooplankton, between the two sides of the North Water, specifically in the fiords and coastal areas.

Recent work in the region suggest that phytoplankton production in the North Water has changed from what was observed in 1998 during the NOW study, and the potential impacts of climate change to overall nutrient and phytoplankton production, and duration of blooms in the North Water remains unknown. In northern Baffin Bay, Bergeron and Tremblay (2014) observed a 66% decline in diatom-mediated net primary production from 1997–1998 (63.6 $gC/m^2$) to 2009–2011 (21.6 $gC/m^2$) suggesting that the North Water is becoming oligotrophic. Others noted a decline in centric diatom abundance as well as phytoplankton biomass and production in the fall over the same time period (Blais et al. 2017). These declines are thought to be a product of changing climatic conditions, including changes to the seasonal progression, that have resulted in physical changes to the environment (e.g., changes to sea ice dynamics, increased stratification, reduced mixing and/or upwelling, and warming of inflowing water masses altering spatial development of bloom). Mei et al. (2002) predicted that “changes in physical factors due to climate change [would] modify the timing, duration and spatial pattern of the phytoplankton bloom” in the North Water. A recent time-series analysis of remote sensing estimates of phytoplankton biomass in the North Water over the past two decades (1998–2014) shows a significant decline in the amplitude of the bloom, despite inter-annual variability in the observational series (Marchese et al. 2017). Remote sensing analysis also shows that the spring bloom tends to start earlier and last longer during years with less sea ice cover (i.e., longer open-water period), and that cloud cover may also play an important role for bloom conditions through light availability. However, cloud cover has also been recognized as an important light limiting factor for production across the Arctic, and there is limited information available to make accurate predictions on its overall impact on productivity into the future.

In some Arctic regions there has been an increase in primary productivity associated with a changing climate (Arrigo and van Dijken 2011, Frey et al. 2015, 2017, Ardyna and Arrigo 2020), and an expectation that this trend will continue as upwelling events become more frequent and the ice thins to allow greater light penetration (Tremblay et al. 2012). An increase in primary production is, however, not anticipated for all regions of the Canadian Arctic, as different ecosystems respond differently to climate change and the changing sea ice cover (Ardyna et al. 2011). There is evidence that the North Water is experiencing the opposite trend and recent changes in the bloom dynamics point to important impacts of the changing sea ice regime (Michel et al. 2015) to the productivity across the region (Bell and Brown 2018). A decreasing trend in productivity has been particularly evident on the western side of the North Water, which receives Arctic water input from the north through Kane Basin (Bell and Brown 2018). Increases in drifting ice through the North Water, which can occur when the Nares Strait ice bridge does not form or persists for only a short period of time, may reduce primary production in the North Water due to decreases in overall light penetration (Mosbech and Kyhn 2019). Changing sea ice conditions may also be increasing primary production in Kane Basin, thereby impacting nutrient inventories reaching the polynya (Bell and Brown 2018). The North Water polynya is also influenced by far-field processes in the Lincoln Sea, from which it receives sea ice and ocean water via Nares Strait. An increase in primary production, and the associated drawdown in nutrients, in the Lincoln Sea and the coastal region north of Ellesmere Island due to declines in sea ice could subsequently impact production in the North Water through biogeochemical processes and interactions. An improved spatial and temporal coverage of observations is needed in order to establish long-term trends, and define spatial variability across the North Water.

The productivity of the North Water is further enhanced by the efficient transfer of energy to the pelagic and benthic ecosystems. Studies of pelagic-benthic coupling (the cycling of carbon and transfer to pelagic and benthic grazers) have shown that the long production season in the North Water provides a long period over which the benthos receives inputs of organic carbon from the pelagic zone. The tight coupling between primary productivity and zooplankton in the region is also fundamental to supporting higher trophic levels like fishes and birds (match-mismatch hypothesis, Michaud et al. 1996). Data from sediment traps characterizing the amount, composition, and seasonality of sinking material as it is exported to depth also point to this tight coupling between zooplankton and primary producers (Caron et al. 2004). Recent analyses have shown a large increase in carbon input to benthos since the 2000s, possibly due to a mismatch between the timing of peak production and zooplankton grazing due to earlier blooms (Gaillard 2016, Bell and Brown 2018) or due to increased production and sinking of organic matter upstream of Smith Sound (Bell and Brown 2018). Recently, Olivier et al. (2020) revealed a shift in growth variations and Ba/Ca ratios in the bivalve *A. moerchi* since the late 1970s, which were likely related to a change (increase) in food availability. The authors suggest changes are likely due to local changes in sea ice dynamics, which typically regulate phytoplankton production, or to a mismatch between phytoplankton bloom and zooplankton grazing due to change in their phenology. Both possibilities could result in more regular and increased transfer of food to the seabed. It is hypothesized that this will continue in the future also.

Two major threats to Arctic benthic communities are climate change and bottom trawling from commercial fishing (Jørgensen et al. 2016). The use of trawling equipment can severely damage the sea floor structure and benthic communities (Jørgensen et al. 2016). Climate change can affect the benthos through shrinking of the pack ice, change the amount, quality, timing, or source of carbon to the benthos, ocean acidification, freshwater river/glacier discharge, and colonization by invasive aquatic species (Archambault et al. 2010, CAFF 2017, AMAP 2018). Similar to other Arctic regions, the consequences of species shifts – to smaller species that are less rich in lipids, or via the northward movement of southern species – are poorly understood. Thyrring and Sejr (2019) suggest that Blue Mussel (*Mytilus edulis*), a largely temperate species currently found at the southern boundary of the North Water, could expand throughout the polynya in response to a warmer climate. Because these mussels create hard substrates that increase abundance of other biota, they could have a noticeable impact on the community structure within the North Water (Thyrring and Sejr 2019).

The North Water is an important site for gas exchange and the region could be a strong source of other biogenic gases (those produced by living organisms, such as phytoplankton), like dimethyl sulphide (DMS). We currently lack a strong observational base specific to the North Water region, however, evidence comes from recent studies conducted in the Canadian Arctic Archipelago during summer, which revealed high concentrations of DMS in open waters and in the overlying atmosphere, with the highest values found in association with localized peaks of chlorophyll *a*, a proxy of phytoplankton biomass. Overall, there is a need for a better understanding of spatial and temporal changes of the drivers in ocean acidification and its impacts on the Arctic ecosystem.

## 3.3. FISHES

There is limited information available on the fish community of the North Water and surrounding water bodies. The North Water is located at the northern extent of the Northwest Atlantic Fisheries Organization (NAFO) zones 0A (Canada) and 1A (Greenland) (DFO NAFO Zones map, accessed Mar 18, 2019). However, there is no commercial fishing within the North Water polynya itself. Coad and Reist (2018) identified 21 fish species likely found within the North Water, though the actual fish community is expected to be more diverse (Appendix 4). In addition, the Conservation of Arctic Flora and Fauna (CAFF) assessment on marine fishes reported at least 50 species of Arctic fishes in and near the North Water (Mecklenburg et al. 2018). Sculpins, gadids, and eelpouts are among the more common taxa likely to be found in the North Water (Coad and Reist 2018, Mecklenburg et al. 2018). Given the proximity to the North Water and the mobility of many fish species, it is likely that the Jones Sound fish community bears some resemblance. Sculpins, flounders, eelpouts, Arctic Cod, Greenland Halibut (*Reinhardtius hippoglossoides*), Arctic Skate (*Amblyraja hyperborea*), and Greenland Shark (*Somniosus microcephalus*) have all been reported from coastal areas in Jones Sound near Grise Fiord by residents (Government of Nunavut 2012). A recent study used a novel application of satellite tags to track the movements of Greenland Sharks and revealed a previously unknown directed migration from the Canadian High Arctic (Jones Sound) to Northwest Greenland (Hussey et al. 2018).

Local observations from Qaanaaq indicated that Greenland Halibut (or turbot), Catfish, and Grenadier are all found in and around Inglefield Bredning (Pikialasorsuaq Commission 2017). The community of Savissivik also describes seeing Greenland Halibut, as well as Greenland Shark, char, Polar Cod (*Arctogadus glacialis*) and wolfish in the waters near their community (Pikialasorsuaq Commission 2017). On the Canadian side, Polar Cod are also found off the coast of Devon Island, as well as in northwest Greenland, however their relative abundance in the North Water is unknown. They are also part of the local subsistence fishery and are often used in Greenland for fish-meal and oil (Coad and Reist 2018). Capelin (*Mallotus villosus*), an abundant species in other areas such as Atlantic Canada and the southern Arctic, is present in the North Water, but its importance to the local food web is unknown (Coad and Reist 2018). It is found near Grise Fiord, Coburg Island, Pond Inlet, and the western coast of Greenland (CAFF 2017, Coad and Reist 2018).

Arctic Cod and Arctic Char (*Salvenlinus alpinus*) are both valuable food sources for the Thule people on the west coast of Greenland (Hastrup 2018). The community of Grise Fiord reports abundant Arctic Cod in the coastal waters of Jones Sound (Government of Nunavut 2012). We discuss Arctic Char, Arctic Cod, and Greenland Halibut in more detail below, as they are important ecological and economic species for subsistence; there is growing interest for expanding the Greenland Halibut fishery further north into the North Water region. Following this, a summary of this theme is provided, specifically mentioning current and future climate impacts and knowledge gaps relevant to marine fishes in the North Water and surrounding area.

### 3.3.1. Arctic Char (*Salvelinus alpinus*)

Arctic Char are primarily lake-adapted and exist in both anadromous and freshwater resident forms (Sawatzky and Reist 2008). As they are associated with rivers and nearby, shallow coastlines, they are only found at the edge of the North Water and do not comprise a large proportion of its fish community (Pikialasorsuaq Commission 2017). Arctic Char are found in coastal rivers on Devon Island, Ellesmere Island, and western Greenland (Pikialasorsuaq Commission 2017, Coad and Reist 2018). On the Greenland coast of the North Water, Arctic Char are a valuable subsistence species for local Thule people (Hastrup 2018). They are similarly common in coastal marine habitat near the community of Grise Fiord (Government of Nunavut 2012 The relative abundance of Arctic Char in the North Water is unknown.

### 3.3.2. Arctic Cod (*Boreogadus saida*)

Arctic Cod is an abundant circumpolar marine fish species (Figure 21) (Sameoto 1984, Mecklenburg et al. 2018). Arctic Cod are widespread in the eastern Canadian Arctic, including northwestern Baffin Bay (Bradstreet et al. 1986). However, movements of these cod in the northern Baffin Bay/North Water region are somewhat limited. They can migrate a few hundred kilometers (Kessel et al. 2017), but they do not disperse into the western Canadian Arctic, likely because sea ice in the Parry Channel (northern Canadian Arctic Archipelago) and shallow areas in the Kitikmeot region of the southern Canadian Arctic Archipelago are physical barriers to fish movement (Bouchard et al. 2018). However, declining sea-ice levels in the Parry Channel may lead to increased mixing of populations between the eastern and western Canadian Arctic (Bouchard et al. 2018). Arctic Cod are vertically distributed from the surface to as deep as 900 m (Coad and Reist 2004, Marz 2010). During their first summer, after hatching near the surface, larvae and young-of-year colonize the top 100 m and most of them descend below 100 m in the fall (2016). Some juvenile Arctic Cod, possibly late hatchers, remain near the surface where they feed on ice-associated crustaceans and shelter in wedges and channels in the ice (Sameoto 1984, Marz 2010) until they reach maturity at each 2 or 3 (David et al. 2016). In the Canadian Arctic, most adult Arctic Cod remain in the Atlantic water mass, below 200 m, throughout the year and prefer demersal and pelagic habitats to surface waters (Geoffroy et al. 2011, 2016). During the summer, occasional schools of older cod (2+ years) can also be found in nearshore shallow habitat (Sameoto 1984, Welch et al. 1993). When present, these schools attract a variety of predators such as birds, marine mammals, and other fish (Coad and Reist 2004, QIA 2018). Arctic Cod larvae were found to dominate the ichthyoplankton in Lancaster Sound and western Baffin Bay, near the North Water (Sameoto 1984, Bouchard et al. 2018). Additionally, LeBlanc et al. (2019b, 2020) identified the North Water as one of the biological hotspots for Arctic Cod recruitment due largely to the high density of mesozooplankton present in surface waters within the polynya.

Arctic Cod are considered to be a key species as the main link between plankton and higher-level consumers in the Arctic (Welch et al. 1992, Coad and Reist 2018). Arctic Cod have been found, often as the dominant prey type, in the stomachs of seabirds, seals, Arctic Char, and Narwhal (Sameoto 1984, Holst et al. 2001, LeBlanc et al. 2019a). This importance as a link between trophic levels makes them a target species for biodiversity monitoring in the North Water (Nelson 2013). Stable isotope modelling of the North Water trophic food web placed larval Arctic Cod at a low trophic level of 2.7, which likely indicated a diet consisting largely of copepod nauplii and copepodites (Hobson et al. 2002a). In comparison, adult cod had slightly enriched isotopic values indicating a probable diet consisting largely of adult *Calanus* copepods and amphipods. Adult Arctic cod are also known to feed on amphipods, mysids and other Arctic cod in the western Canadian Arctic (Benoit et al. 2010, Walkusz et al. 2013) In turn, the isotopic values of several seabird and marine mammal species in the North Water indicate probable predation on Arctic Cod (Hobson et al. 2002a). Dietary analysis of three species of seabird on the east side of the North Water (Dovekie, Black-legged Kittiwake [*Rissa tridactyla*], and Thick-billed Murre) showed that all three species consumed cod as part of their diets (Karnovsky et al. 2008). In particular, Arctic Cod comprised up to 40% of the spring diet of the Black-legged Kittiwake. Arctic Cod are also frequently consumed by the endangered Ivory Gull in the North Water (Karnovsky et al. 2009).

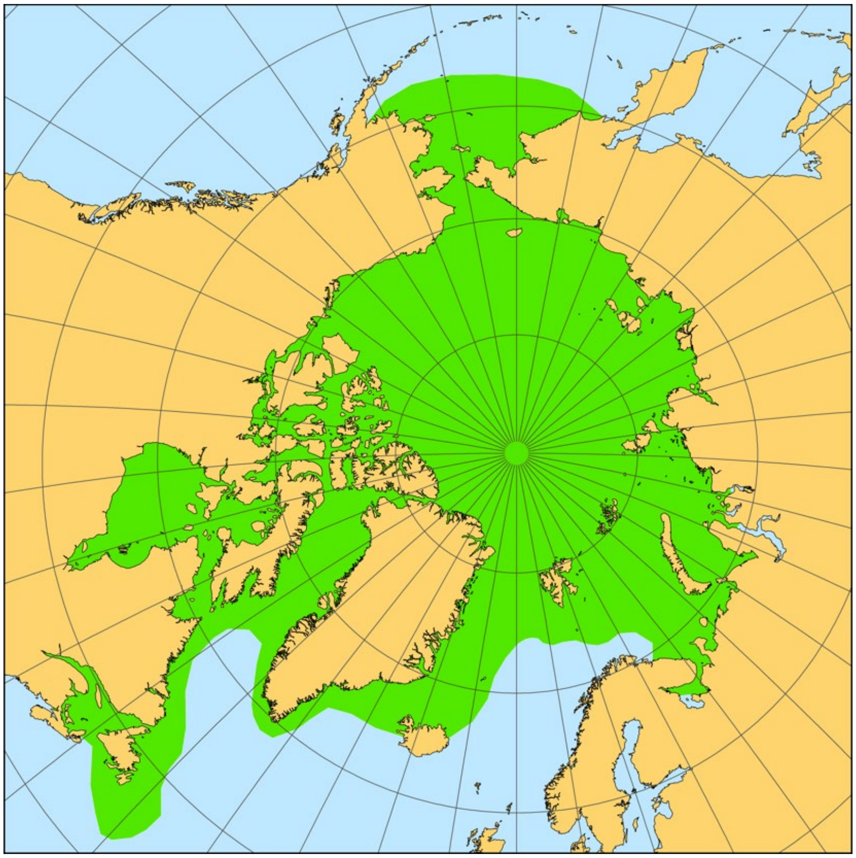

*Figure 21.Circumpolar distribution of Arctic Cod (Boreogadus saida), which are widespread throughout Arctic seas and the Central Arctic Basin (Source: Mecklenburg et al. 2018).*

### 3.3.3. Greenland Halibut (*Reinhardtius hippoglossoides*)

Greenland Halibut have been documented throughout the northwest Atlantic Ocean, occurring at least as far north as Smith Sound (78°N) and including the North Water (Figure 22) (Coad and Reist 2018, Mecklenburg et al. 2018), but are more abundant to the south in the deeper (800–2,000 m) waters of Baffin Bay and Davis Strait (Stephenson and Hartwig 2010). The Greenland Halibut stock in Baffin Bay and Davis Strait (Northwest Atlantic Fisheries Organization Subarea 0; NAFO SA 0) is assessed annually using data from bottom trawl surveys conducted by DFO. The Baffin Bay-Davis Strait Greenland Halibut stock is likely all recruited from deep water spawning grounds in Davis Strait near the submarine ridge between Baffin Island and Greenland (Templeman 1973, Boje 2002, DFO 2014a). Similar to the standing stock in Cumberland Sound, Greenland Halibut found in the fiords of northwestern Greenland appear to be residents and do not intermingle with fish in the offshore or southern fiords (Boje 2002, Hussey et al. 2017). Roy et al. (2014) concluded that there was a common gene pool in the Northwest Atlantic based on microsatellite DNA markers, and to date, the Greenland Halibut population between Greenland and Canada is considered a single stock unit (Bonje 2002, Westgaard et al. 2016, DFO 2020). Surveys in northern Baffin Bay, including the eastern North Water, estimated a local abundance of 53,900 t of Greenland Halibut in 2004 (Jørgensen 2005). Estimated biomass on the Canadian side of northern Baffin Bay is similar and is thought to have increased in recent decades (Treble 2005, 2013).

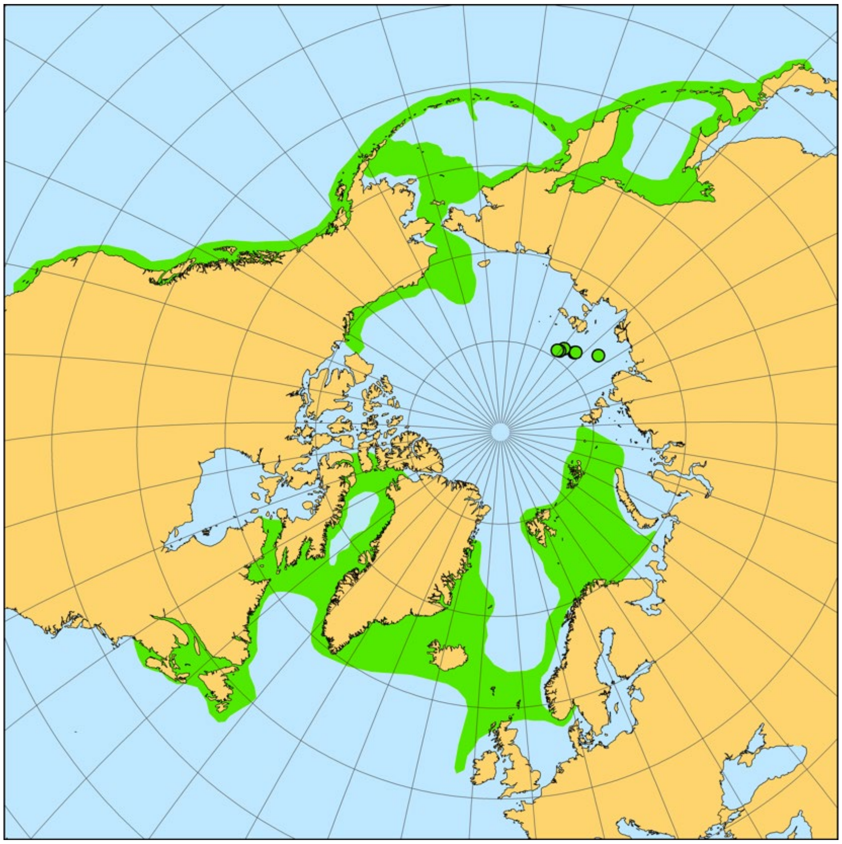

*Figure 22. Nearly circumpolar distribution of Greenland Halibut (Reinhardtius hippoglossoides); the most northern record from the North Water region was 77-78˚N in Smith Sound off western Greenland (Scott and Scott 1988) (Source: Mecklenburg et al. 2018).*

Given the value of the commercial Greenland Halibut fishery to Nunavut, movement patterns are of particular interest. Offshore Greenland Halibut exhibits high mobility within Baffin Bay and Davis Strait, migrating extensively between feeding and spawning areas (Boje 2002). Along the coasts of Baffin Island and Greenland, juvenile halibut are thought to inhabit relatively shallow (< 400 m) waters (DFO 2014a). Greenland Halibut are marine predators and different life stages will feed on a variety of species, as feeding ecology is strongly linked to individual size, followed by depth and latitude (Orr and Bowering 1997, Simonsen et al. 2006). Copepods are the main prey for larval Greenland Halibut (Simonsen et al. 2006) and small juvenile halibut typically feed on small pelagic crustaceans. Eventually once they reach about 20–60 cm, halibut will prey on a variety of small fish, squid and northern shrimp. Large adult Greenland Halibut (> 60 cm) prefer larger species such as redfish (*Sebastes* spp.) and grenadiers (Macrouridae) (Orr and Bowering 1997, Dwyer et al. 2010). In Baffin Bay, Greenland Halibut are an important prey species for Greenland Sharks and overwintering Narwhals, comprising approx. 50–75% of their winter diet (Laidre et al. 2004a). Greenland Halibut have also been found in the stomachs of seals (Richard et al. 1998a, QIA 2018) and there is some evidence that Greenland Halibut will periodically disappear, followed by reduced catches, when Beluga Whales are present in Greenlandic waters (DFO 2020).

There is a large Canadian commercial fishery for Greenland Halibut in Baffin Bay (2019 Total Allowable Catch 9,592.5 tonnes), but it currently does not extend into the North Water (Coad and Reist 2018). In Baffin Bay, most ship-based commercial fishing for Greenland Halibut occurs along the Baffin Island and Greenland shelf slopes in waters 800–1,500 m deep, as far north as 73°N (DFO 2014a, 2019c), just south of the North Water. Greenland Halibut are captured using either fixed (longline or gillnet) or mobile (dual or single beam otter trawls) gear (DFO 2014a). The Total Allowable Catch (TAC) and harvest for Division 0A has increased over time, with an initial increase in TAC from 3,500 t in 2001 to 8,575 t for 2017 and 2018 (DFO 2020).Harvests have approached quotas in recent years (Treble and Noguiera 2018). Bycatch from the inshore and offshore Greenland Halibut commercial fishery (bottom trawl and benthic longline) is particularly high for the Greenland shark, a recent examination of Greenland shark bycatch in Canada found that 36% of sharks caught in bottom trawls (both Greenland Halibut and northern shrimp fisheries) and 16% of sharks caught on benthic longlines were already dead when released (NAFO 2018, Bryk et al. 2018) and the percentage of dead sharks increased with trawl duration (Bryk et al. 2018).

Halibut has become an increasingly important food source for the Thule communities on the western shore of Greenland, as rising sea temperatures have attracted them into the Smith Sound region (Hastrup 2018). Landings of Greenland Halibut in Qaanaaq were 252 tonnes in 2018 (Nygaard 2019) and this may increase as there is a plan to start direct export of high quality products to restaurants in Denmark. The development of nearshore fisheries for Greenland Halibut (similar to Cumberland Sound), could provide employment and economic opportunities for northern communities in Canada and Greenland, yet there is concern it would put too much pressure on the NAFO SA 0 stock. Exploratory fishing for Greenland Halibut has occurred at Qikiqtarjuaq, Clyde River and Pond Inlet, all on eastern Baffin Island. Further north, the community of Grise Fiord applied for an exploratory fishery license to fish for Greenland Halibut using longlines with a TAC of 2,000 kg (DFO 2008a). The application was made for a late winter fishery (April to July of 2008) in the waters of Jones Sound. DFO approved the exploratory fishery and recommended that Greenland Halibut length and CPUE data be recorded, along with all bycatch (DFO 2008a). However, information regarding the establishment or success of this fishery could not be located. Arctic Fisheries Alliance/Memorial University conducted three years of exploratory fisheries surveys in the Jones Sound area (summer/fall 2013, 2014, and 2016). Catches of Greenland Halibut were low, and the authors suggested that the results may reflect unsuitable temperatures and depths for the species, or may be indicative of seasonal differences in the distribution of Greenland Halibut in the Jones Sound area (AFA 2014, Wheeland et al. 2015, Wheeland and Devine 2017).

### 3.3.4. Summary of Fishes: Knowledge Gaps and Climate Impacts

There is a general lack of knowledge of fish species in the North Water. There is insufficient data on the relative abundance and spatial distribution of most marine fish species, as well as a lack of data on life histories, spatial connectivity, and seasonal migrations (vertical and horizontal) within the North Water. The Baffin Bay and Davis Strait area are both known for very high fish diversity (170 species) (Niemi et al. 2019), however knowledge of the exact diversity in the North Water and distribution of high Arctic fishes is limited due to a lack of sampling. Key economic and harvested species, such as Arctic Cod, Greenland Halibut, and Arctic Char, are known to play a vital role in the North Water ecosystem (i.e., transfer of energy) and are important prey species for seabirds and marine mammals. Inshore and offshore fisheries of Greenland Halibut are of key importance for Canadian and Greenlandic communities surrounding the North Water, both as a source of food and as a commercially exported product (Boertmann and Mosbech 2011, Merkel et al. 2012). However, there is currently insufficient data on stock assessment of Greenland Halibut, including connectivity between stocks and migrations (relationship between offshore-inshore), which is vital to future fisheries management and the prospect of expanding fishery opportunities for Inuit. Improved knowledge of marine fish movement and genetic separation is required to inform management strategies for harvested species.

Across the Arctic, most marine fishes respond to changes in water temperature. With warming waters, it is expected that some southern species will experience a northward expansion into the North Water. As climatic conditions in the North Water change, Capelin may become an increasingly important predator of large, grazing copepods in the near future, possibly competing with Arctic Cod and zooplanktivorous seabirds (Mosbech and Kyhn 2019). Further, changes in nutrients, blooms, and shifts in productivity associated with climate change could have negative implications for larval fish, but also create new opportunities (i.e. increased population sizes, growth potential) for fishes (e.g., Bouchard et al. 2017); this remains a knowledge gap. There is some recent evidence of increased local catches of Greenland Halibut on the eastern side of the North Water, which may suggest greater abundance possibly due to climate change effects (Heide-Jørgensen 2019).

Climate change may also result in significant and rapid habitat alterations (indirect effects) as well as direct effects (e.g., thermal stresses) which challenge fish (CAFF 2013). For example, some Arctic fishes, specifically juvenile Arctic Cod, are strongly associated with bottom ice during the ice-covered period (Kohlbach et al. 2017), while others show seasonal movement in relation to sea ice (e.g., Greenland Halibut), such that loss of this habitat could negatively impact the North Water food web. Localized stressors (e.g., fisheries, industrial activities, noise pollution) will affect fish populations in the North Water either directly or indirectly, and lack of monitoring in this region is problematic when determining responses to specific divers or stressors.

## 3.4. MARINE MAMMALS

The high biological productivity of the North Water attracts seasonal aggregations of several Arctic marine mammal species (Innes and Stewart 2002, DFO 2011a, 2015a, Heide-Jørgensen et al. 2013, 2016, Higdon 2017, QIA 2018). The North Water has been identified as important spring and summer feeding habitat and/or overwintering habitat for the three main Arctic cetacean species (Beluga, Narwhal, and Bowhead Whales), as well as Polar Bears and several species of seals (DFO 2011a, 2015a, Heide-Jørgensen et al. 2013, 2016, Chambault et al. 2018, QIA 2018). Killer Whales (*Orcinus orca*) have been described as occasional visitors to the western part of the region (Higdon et al. 2011, 2013, Reeves and Mitchell 1998, Stephenson and Hartwig 2010, Lefort et al. 2020); however, they are more commonly observed southeast of the North Water in and around Eclipse Sound, near the communities of Pond Inlet and Arctic Bay (Government of Nunavut 2018, QIA 2018). In recent decades, more temperate whale species such as Minke (*Balaenoptera acutorostrata*) and Humpback (*Megaptera novaeangliae*) Whales have also been observed in the North Water during summer, likely as a consequence of warming seas (Heide-Jørgensen 2019).

Below the most common species are discussed in more detail, these species either reside year-round, or use the North Water seasonally or as a migratory pathway. Following this theme, a summary on marine mammals is provided, specifically drawing attention to current and future climate impacts and stressors that may alter species distributions, demography, feed ecology, and overall health. There are also many knowledge gaps associated with marine mammal seasonal use in the North Water (see Seasonally Important Areas), and in many cases data is lacking, incomplete, or outdated. It is important to highlight these inconsistencies, as the majority of these marine mammals are hunted by communities in the North Water region (both Canada and Greenland), and remain integral to food security.

### 3.4.1. Beluga Whale (*Delphinapterus leucas*)

There are seven managed stocks of Beluga Whales in the Canadian Arctic (Figure 23) (COSEWIC 2016, NAMMCO 2018). All Belugas that reside and migrate through the North

Water belong to the Eastern High Arctic-Baffin Bay (EHA-BB) stock (COSEWIC 2004a, 2016), which has been defined by summering aggregations found in the Canadian High Arctic Archipelago, principally around Somerset Island, but also in Lancaster Sound and some adjacent waterbodies (Koski 1980, Richard et al. 2001, Stewart 2001, Stephenson and Hartwig 2010, COSEWIC 2016, NAMMCO 2018). Genetic analysis, movement and habitat use patterns suggest a single, shared Canada-Greenland stock in northern Baffin Bay (Richard et al. 2001, Heide-Jørgensen et al. 2003a, NAMMCO 2018). Early genetic studies (Brown Gladden et al. 1997, 1999) identified significant differences between EHA-BB whales and other stocks (though there may be some overlap in southeast Baffin Island), but were unsuccessful at differentiating between different sampling locations within the EHA-BB range. The biology of Beluga (high mobility, long, overlapping generations) can increase the likelihood of genetic differentiation going unnoticed (Petersen et al. 2010). Subsequent studies using larger sample sizes and more detailed genetic analyses were able to demonstrate possible substructure within the EHA-BB stock (de March et al. 2002, Palsbøll et al. 2002). For example, Palsbøll et al. (2002) identified a large amount of spatial genetic heterogeneity and proposed that maternal pod structure, in addition to non-random breeding and site-fidelity, may contribute more to the observed differences than population structure. Using a longer mitochondrial DNA region than Palsbøll et al. (2002), de March et al. (2002) were able to differentiate Beluga sampled at Grise Fiord from all other Baffin Bay Beluga, except those in Lancaster Sound and west Greenland. This uncertainty across studies, combined with relatively few sampling locations, and small sample sizes over the northern and central portions of the stock's range, has resulted in DFO (2016) designating the EHA-BB as a single stock for management purposes. However, as a precautionary approach, the NAMMCO-JCNB (North Atlantic Marine Mammal Commission - Joint Commission on Narwhal and Beluga) Scientific Working Group treats the Belugas inhabiting the North Water region in summer as a putative stock separate from the EHA-BB (NAMMCO-JCBN 2020).

The only population estimate for the EHA-BB stock presently is 21,213 (95% CI 10,985 to 32,619), which was estimated from aerial surveys in 1996 (DFO 2002, Innes et al. 2002). Using a modeling exercise, Innes and Stewart (2002) also estimated that 17,328 (5,750–27,996) Belugas spend the summer in the High Arctic and remain in the Baffin Bay/ North Water region in the winter. Satellite telemetry studies have shown that the EHA-BB stock has two core wintering areas, one portion of the stock resides in the North Water region and another uses the coastal ice-free areas along the Baffin Bay sea ice edge in West Greenland (Figure 24, Figure 40) (Doidge and Finley 1993, Heide-Jørgensen and Laidre 2004). Using historical (1998–99) estimates of Beluga wintering in West Greenland (7,941, 95% CI 3,650–17,278), Heide-Jørgensen et al. (2003a) suggested that approx. 13,000 Belugas are likely wintering in the North Water and adjacent areas. More recent (2013) survey efforts focused on West Greenland during winter and early spring estimated 9,072 individuals (95% CI 4,895 to 16,815), and propose the number of Belugas wintering in the North Water exceeds 10,000, however these estimates are likely to be negatively biased due to limited coverage of their potential habitat (Heide-Jørgensen et al. 2016). Although the North Water region has been identified as an important Beluga Whale wintering area (Remnant and Thomas 1992, Richard et al. 1998b, Heide-Jørgensen et al. 2013, 2016, Higdon 2017), there are uncertainties whether this region is used extensively for feeding or calving/nursing habitat during other seasons (Higdon 2017).

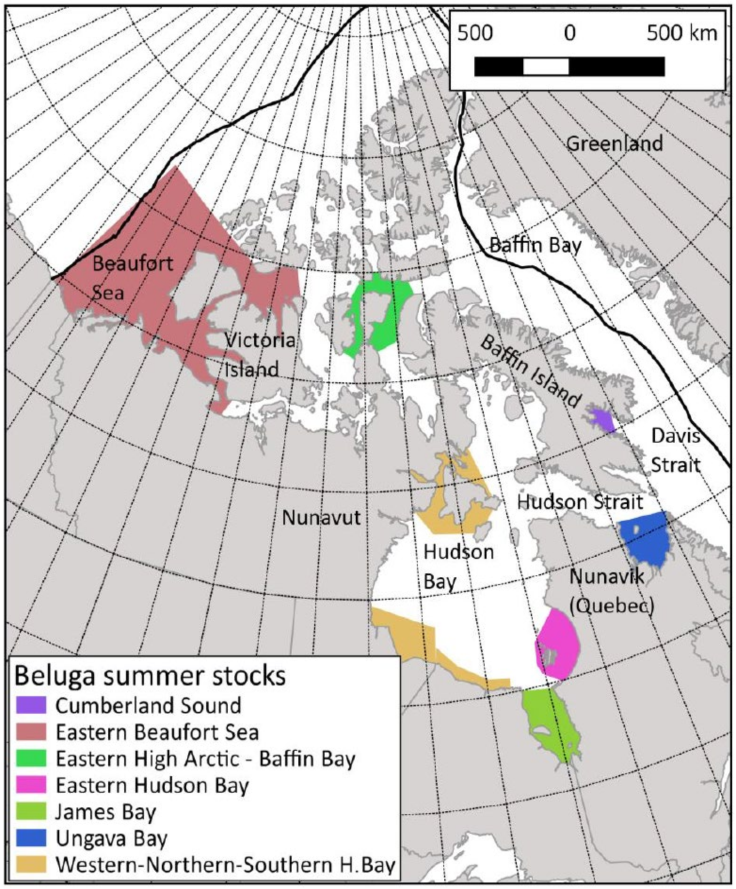

*Figure 23. Beluga Whale stocks in the Canadian Arctic. Neon green shows the core summer aggregation of Eastern High Arctic-Baffin Bay population that reside and migrate through the North Water region (Source: NAMMCO 2018).*

Satellite tracking of EHA-BB Belugas tagged in core summer areas in Canada showed rapid early fall movements east towards Devon Island and into the southern limits of the North Water (Barber et al. 2001b, Richard et al. 2001). There they joined fall-tagged whales, moving east and north along the east coast of Devon Island towards Jones Sound and north Baffin Bay. During this time, Belugas occupied the many bays along the Devon Island coast and often dove to greater than 200 m depths. Similarly, residents of Grise Fiord have described areas where Belugas concentrate along the shore and in fiords near the community, in particular, at the entrance to Jones Sound during the fall (see Figure 43) (Remnant and Thomas 1992, Government of Nunavut 2012). The entrance to Jones Sound has been identified as a calving and feeding habitat (Remnant and Thomas 1992), and east-west spring and fall migration routes along both shores of the sound and the south shore of Devon Island (Government of Nunavut 2012). Bethune Inlet on the east coast of Devon Island is also described as a major September feeding area for Beluga (Government of Nunavut 2012).

By the late fall and early winter, a portion of the EHA-BB Beluga stock moves into the North Water, where most remain until they begin westward spring migrations (Figure 24) (Stewart et al. 1995, Richard et al. 1998a, 2001, QIA 2018). In addition, approximately 15% of the Somerset Island Belugas migrate through the North Water to wintering areas along the west Greenland coast (Figure 24) (Richard et al. 2001, Heide-Jørgensen et al. 2003a). Richard et al. (1998a) noted two main areas of movement around Devon Island during fall; southeast and east Devon

Island in nearshore habitat where the whales were likely foraging for Arctic Cod, and over deep water in eastern Jones Sound (Lady Ann Strait) and southeast of Coburg Island, where they likely hunt deep-water prey (squid and Greenland Halibut). It is the larger males that moved farther north off southeastern Ellesmere Island and into the North Water region by late October and early November (Richard et al. 1998a). In a concurrent study of dive patterns of Belugas off eastern Devon Island in or near the North Water, Heide-Jørgensen et al. (1998) noted a reduction in swimming speeds, along with a decline in surface times and dive rates in late October, which are considered behaviours of the whales moving into their overwintering habitat (Heide-Jørgensen et al. 1998). Winter aerial surveys of the North Water have identified shore leads off southeastern Devon Island, in the polynya near the entrance to Jones Sound, and offshore pack ice of Smith Sound, as important habitat for Belugas (Richard et al. 1998b). There are some records of Belugas becoming trapped in ice near the entrance to Jones Sound (Heide-Jørgensen et al. 2002a, QIA 2018). During early spring, when the Greenland side of the polynya tends to have more open water, Belugas have been observed in greater numbers off the northwest coast of Greenland and into the central North Water (Heide-Jørgensen et al. 2013). Belugas have typically been rare or absent in the northern limits of the North Water during winter and early spring (Richard et al. 1998b, Heide-Jørgensen et al. 2013). In addition, most whales observed overwintering in the North Water are solitary adults (Richard et al. 1998b, Heide-Jørgensen et al. 2013).

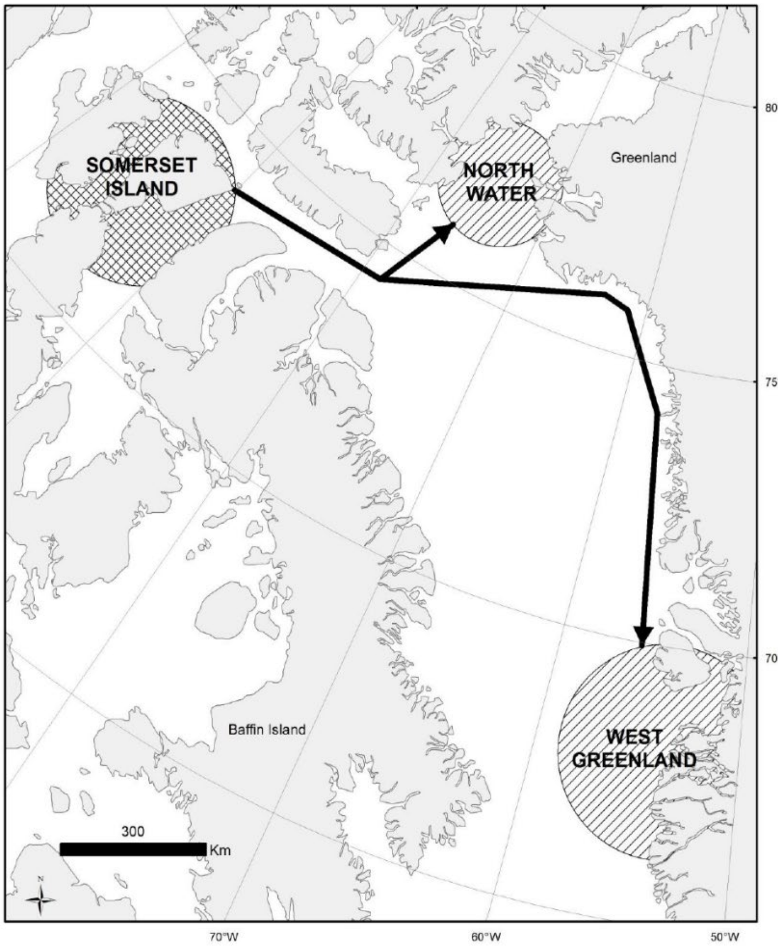

*Figure 24. Movement of EHA-BB Belugas from summering grounds (double hatched areas) around Somerset Island in Northeast Canada to wintering grounds (hatched area), either in the North Water or along West Greenland, south of Disko Bay (Source: NAMMCO 2018).*

Generally, Belugas feed on a variety of pelagic and benthic fish, and macroinvertebrates with some variation observed among stocks and age groups, and between sexes (Kilabuk 1998, Loseto et al. 2009, Marcoux et al. 2012, Yurkowski et al. 2016a). Hobson et al. (2002a) modeled the North Water trophic food web using stable isotopes and Belugas occupied an intermediate trophic level, though slightly lower on the western side of the polynya than the east. The isotopic model suggested that Beluga diet was dominated by lower trophic level prey, such as squid or pelagic crustaceans, rather than Arctic Cod. In contrast, fatty acid biomarker studies that include Belugas sampled in Grise Fiord/Jones Sound showed a preference for Arctic Cod prey (Thiemann et al. 2008a, Kelley et al. 2010). This may be due to lower ecological opportunity at higher latitudes (Yurkowski et al. 2016a) or fundamental differences between the two methods.

Globally, Belugas are considered “Least Concern” by the International Union for Conservation of Nature (IUCN; Lowry et al. 2017b) The listing for the EHA-BB stock is currently being updated, however, it was assessed as “Special Concern” by the Committee on the Status of Endangered Wildlife in Canada (COSEWIC 2004a, 2016) in 2016. Due to historic overharvesting in west Greenland, the 2018 Red List has classified Beluga as *Vulnerable,* but there are signs the population is slowly recovering. However, as changes in ice conditions (i.e., less ice and more access to open water) allow for increased hunting opportunities in west Greenland, more protection measures and quotas may be put into place (Heide-Jørgensen et al. 2010b). Small numbers of Belugas wintering in the North Water are harvested (NAMMCO 2016), but most of the hunting pressure occurs along migratory routes and in summering areas.

### 3.4.2. Narwhal (*Monodon monoceros*)

Narwhals in the Canadian High Arctic, including the North Water, are part of the Baffin Bay population (Figure 25; Petersen et al. 2011, DFO 2015b). Stock status of this population has been determined by genetic (Palsbøll et al. 1997, de March et al. 2003, Petersen et al. 2011), contaminant (de March and Stern 2003), stable isotope (Watt et al. 2012), trace elements (Watt et. al 2019), and movement studies (Dietz et al. 2008, Heide-Jørgensen et al. 2012). These studies have confirmed separation of a Baffin Bay population from others to the south and east and, in some cases, provided evidence of multiple, distinct stocks within the Baffin Bay population, however due to the lack of genetic diversity, and the precise number of stocks is somewhat unclear (Richard 2010, NAMMCO 2018). In a study of mitochondrial DNA, Palsbøll et al. (1997) identified only a small amount of variation among Narwhal samples, suggesting a recent expansion within the high Arctic following establishment of a small founding population. Despite the observed low variability, however, there were strong indications of isolation of pods, even over a short geographic distance, and high fidelity to specific feeding grounds.

Narwhals are highly migratory and are therefore managed by their summering aggregations in Canada and Greenland (Doniol-Valcroze et al. 2015b, NAMMCO 2018). Currently, the Baffin Bay population is managed in six stocks in Canada (Somerset Island, Eclipse Sound, Admiralty Inlet, Eastern Baffin Island, Jones Sound, and Smith Sound) and two stocks in Greenland (Inglefield Bredning, and Melville Bay). Several of these stocks mix in wintering grounds in central and southern Baffin Bay, but maintain separation through specific summering site and migration route fidelity, and apparent lack of interbreeding (Heide-Jørgensen et al. 2012, Richard et al. 2014). Since Narwhals are susceptible to hunting as they migrate between Canada and Greenland, a bilateral management body was established, the Canada/Greenland Joint Commission on the Conservation and Management of Narwhal and Beluga (JCNB), and is responsible for managing the exploitation, issuing annual hunting quotas, and conservation of these Narwhals.

The most recent population estimate for the Canadian Baffin Bay Narwhal population, based on a robust aerial survey data set (High Arctic Cetacean Survey) and analyses, is 141,909 individuals (95% CI 102,464–196,536) (DFO 2015b, Doniol-Valcroze et al. 2015a). This was more than double the previous estimate (66,000), which covered only a relatively small proportion of the Narwhal's extensive area of occupation (Richard et al. 2010). In 2007, the Melville Bay and Inglefield Bredning were estimated to number 6,024 (95% CI 1,403–25,860) and 8,368 (95% CI 5,209–13,442), respectively in 2007 (Heide-Jørgensen et al. 2010b). A more recent (2014) abundance estimation using aerial photos and observations shows a decline in abundance, estimating the Melville Bay population at 2,536 (coefficient of variation (CV) = 0.51, 95% CI: 1,003–6,406) with image analysis, and 2,596 individuals (CV = 0.51; 95% CI: 961–7,008) with aerial observers (Bröker et al. 2019); the Inglefield Bredning population is still being analysed. For the Canadian stocks using the North Water region, abundance was estimated at 12,694 for Jones Sound Narwhal and 16,360 for Smith Sound whales (DFO 2015b, Doniol-Valcroze et al. 2015a). Estimates of whales in the fiords and narrow inlets of Jones and Smith sounds during the same High Arctic Cetacean Survey were 45 and 1,916 individuals, respectively (Doniol-Valcroze et al. 2015b), In addition, Narwhals have been aerial photographed in Inglefield Bredning and adjacent fiords in Northwest Greenland in August 2001 and 2002 (Heide-Jørgensen 2004), however, in most coastal fiords and inlets surrounding the North Water there remains limited knowledge of Narwhal behaviour and distribution. Laidre et al. (2016) analyzed the movements of 15 Narwhals relative to 41 ocean-terminating glaciers in Melville Bay and suggested that it was "unknown at what distances glacier fiords attract Narwhals." The study did find at least three Narwhal locations almost 1 km from the glaciers and concluded that regions within ~ 7 km of calving fronts were attractive to Narwhals.

Narwhal (Admiralty Inlet and Eclipse Sound) spring and fall migrations pass through Tallurutiup Imanga (Lancaster Sound), following the receding ice edge, with small numbers of Narwhals observed year-to-year in the southern limits of the North Water and at the entrance to Jones Sound (Figure 41 and Figure 43) (Koski 1980, Richard et al. 1994, Heide-Jørgensen et al. 2003b, Laidre et al. 2004b, Government of Nunavut 2012). Due to their geographical proximity, Narwhals from the Jones Sound, Smith Sound, and Inglefield Bredning are most likely to occupy the North Water in the summer (Figure 42). Residents from Savissivik, Greenland, describe summers where Narwhals (from the Melville Bay stock) have spent time foraging in the waters around their community, but specify that in general Narwhals stay in different places from year to year (Pikialasorsuaq Commission 2017). Residents of Grise Fiord have confirmed a high probability of occurrence of Narwhals at the entrance to Jones Sound during spring, at the floe edge and in coastal areas and fiords near the community during summer (herds of 20–50 animals) (Government of Nunavut 2012). Narwhals are believed to also mate at the entrance to Jones Sound, and feed along its coast and in its fiords during late spring and summer (Remnant and Thomas 1992, Stewart et al. 1995, Stewart 2001). Preferred summer habitat includes deep, steep-sided inlets with partial ice cover, possibly to provide protection from Killer Whales (Kingsley et al. 1994, Petersen et al. 2011, Breed et al. 2017). Killer Whales tend to be uncommon on the Greenlandic side of the North Water in summer, however, in one case, local observations from the Savissivik region in Greenland described Narwhals behaving differently near Qaanaaq during a summer where Killer Whales appeared, making the whales easier to catch (Pikialasorsuaq Commission 2017).

Winter and spring habitat for Narwhal includes broken pack ice or along the fast ice edge of continental shelves (Koski and Davis 1994, Dietz et al. 2001, Heide-Jørgensen et al. 2002b, COSEWIC 2004b, Stephenson and Hartwig 2010, Laidre and Heide-Jørgensen 2011). Although core wintering areas for Narwhals are located in central Baffin Bay and southern Baffin Bay/northern Davis Strait (Dietz et al. 2001, Stephenson and Hartwig 2010) where high densities of their preferred Greenland Halibut prey are found (Laidre et al. 2004a, Kenyon et al. 2018), they also occur in the North Water (Figure 40) (Remnant and Thomas 1992, Richard et al. 1998b, Heide-Jørgensen et al. 2013, 2016, QIA 2018). Narwhals appear to use the

Greenland side of the North Water in the spring (more than the Canadian side), especially at the entrance to Inglefield Bredning (Heide-Jørgensen et al. 2016, Christensen et al. 2017). Marine mammal aerial surveys conducted in the spring of 2009 and 2010 in the North Water estimated the abundance of Narwhals in the polynya (7,726, 95 % CI 4,311–13,848), and confirmed that Narwhals were widely distributed on the Greenland side and further north off Ellesmere Island, but were particularly concentrated at the entrance to Inglefield Bredning (Heide-Jørgensen et al. 2013); which has also been identified as a breeding area by local observations from residents of Qaanaaq (Pikialasorsuaq Commission 2017). Most whales were detected over deep water and were solitary, though some larger groups were noted on the Greenland side (Heide-Jørgensen et al. 2013). Another spring aerial survey (April 2014), focused on the eastern side of the polynya, produced a lower estimate of 3,059 (95 % CI 1,760–5,316) individuals, but was not significantly different from the average spring abundance in 2009/2010, and provided further evidence that larger numbers of Narwhal do overwinter in the polynya (Heide-Jørgensen et al. 2016).

Narwhal have highly specialized predation behaviour in their wintering grounds, and during this time it is assumed they obtain the majority of their energy input and commonly make dives > 1800m to forage (Laidre et al. 2004 a,b, Watt et al. 2013, 2017). Narwhal diets are variable and flexible across their range, but typically include Arctic Cod, Polar Cod, decapods, squid, shrimp, and Greenland Halibut (Hay 1984, Watt et al. 2013, 2017, QIA 2018). Greenland Halibut, likely juveniles, appear to be particularly important prey during winter (Laidre et al. 2004a,b, Richard et al. 2014), however, the degree to which Narwhals forage on Greenland Halibut in the North Water is unknown. In a study of seasonal habitat associations in the high Arctic, Laidre et al. (2004b) found that bottom temperature range was the greatest predictor of habitat selection, particularly during the winter, as it is directly linked to availability of Halibut prey and open water conditions. Contrary to this, a stable isotope analysis of the North Water food web placed Narwhals at an intermediate trophic level of 4.1, which is more consistent with a diet dominated by lower trophic level prey, such as squid or pelagic crustaceans (possibly shrimp) (Hobson et al. 2002a). A closer examination of Narwhal diet and diving behaviour showed greater dietary plasticity in the species than previously assumed (Watt et al. 2013, 2015). For example, Baffin Bay Narwhals hunted from the floe edge in the spring appear to have more Arctic Cod in their diet, as determined by stable isotope analysis of tissues (Watt et al. 2017). These data suggest that Narwhals could be more adaptable to changes in sea ice than previously thought, though indirect impacts from sea ice and climatic shifts, such as changes to prey population structure and distribution, may ultimately influence future trends in winter habitat selection for the species.

The IUCN listed the global Narwhal population as “Least Concern” since the species is widely distributed in several subpopulations, many of which are considered stable (Lowry et al. 2017a). In Canada, the Baffin Bay population was designated as “Special Concern” by COSEWIC (2004b). Local traditional knowledge has suggested that the population is stable (Remnant and Thomas 1992 Stewart et al. 1995) or increasing (Government of Nunavut 2012). The recommended annual total allowable landed catch by Fisheries and Oceans for Baffin Bay Narwhals in Canada is 1,540 animals (Doniol-Valcroze et al. 2015b), however this number does not correspond to actual harvest (see NAMMCO 2017). There has been a decline in Narwhal catches in West Greenland, especially in Uummannaq and Disko Bay (NAMMCO 2017). There was an increased harvest of whales reported from the Greenland side of Smith Sound in the 2000s, attributed to earlier access to Smith Sound due to changing sea-ice conditions that allowed for greater harvest opportunities (Nielsen 2009).

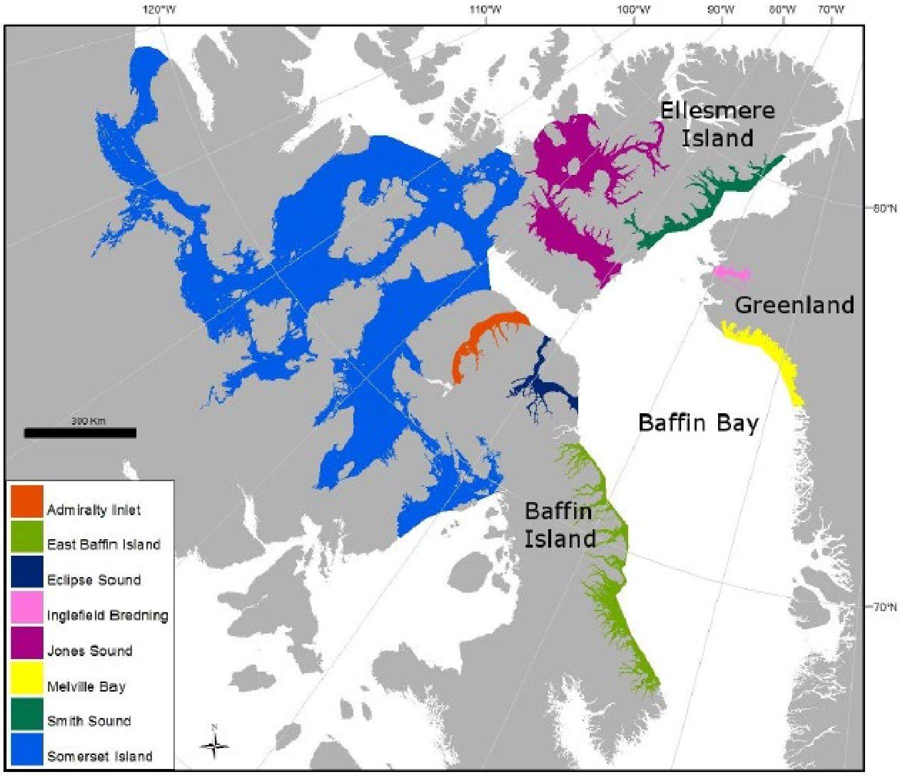

*Figure 25. Map of Baffin Bay Narwhal stocks determined by their summer aggregations in Canada and northwest Greenland (Source: NAMMCO 2016).*

### 3.4.3. Bowhead Whale (*Balaena mysticetus*)

Bowhead Whales in the eastern Canadian Arctic belong to the Eastern Canada – West Greenland (EC-WG) population (Frasier et al. 2015) (Figure 26). The population ranges throughout Baffin Bay, east to West Greenland, as far west as Parry Channel, and south to Hudson Bay (Heide-Jørgensen et al. 2003c, 2006, Dueck et al. 2006, Postma et al. 2006, COSEWIC 2009, Alter et al. 2012), but is partially segregated by age and sex, and reproductive class during spring and fall migrations and in summer feeding areas (Heide-Jørgensen et al. 2010a, Fortune et al. 2020a). Euphausiids, mysids, amphipods, and copepods are particularly important prey species for the EC-WG Bowhead Whale population (Pomerleau et al. 2011, 2012, Fortune et al. 2020b).

The most recent size estimates for this population from aerial and genetic mark-recapture surveys are 6,446 (DFO 2015c, Doniol-Valcroze et al. 2015a) and 7,660 whales (Frasier et al. 2015), respectively. Although their range includes Smith Sound (Stephenson and Hartwig 2010, Alter et al. 2012, Christensen et al. 2017), typically only small numbers of Bowhead Whales have been observed during aerial surveys of the North Water, mostly in its southern limits and near the entrance to Jones Sound and around Coburg Island (Koski 1980, Richard et al. 1998b) and on the Greenland side (Heide-Jørgensen et al. 2013, 2016). Four Bowheads were observed during spring aerial surveys of the east side of the North Water (Heide-Jørgensen et al. 2013) and one during a winter 2014 survey (Heide-Jørgensen et al. 2016). Residents of Grise Fiord have observed Bowheads at the entrance to Jones Sound and offshore near the community, but sightings in the area are rare (Government of Nunavut 2012). Large groups (~ 20) of Bowhead Whales have also been observed in the north part of Melville Bay, close to the community of Savissivik, Greenland (Pikialasorsuaq Commission 2017).

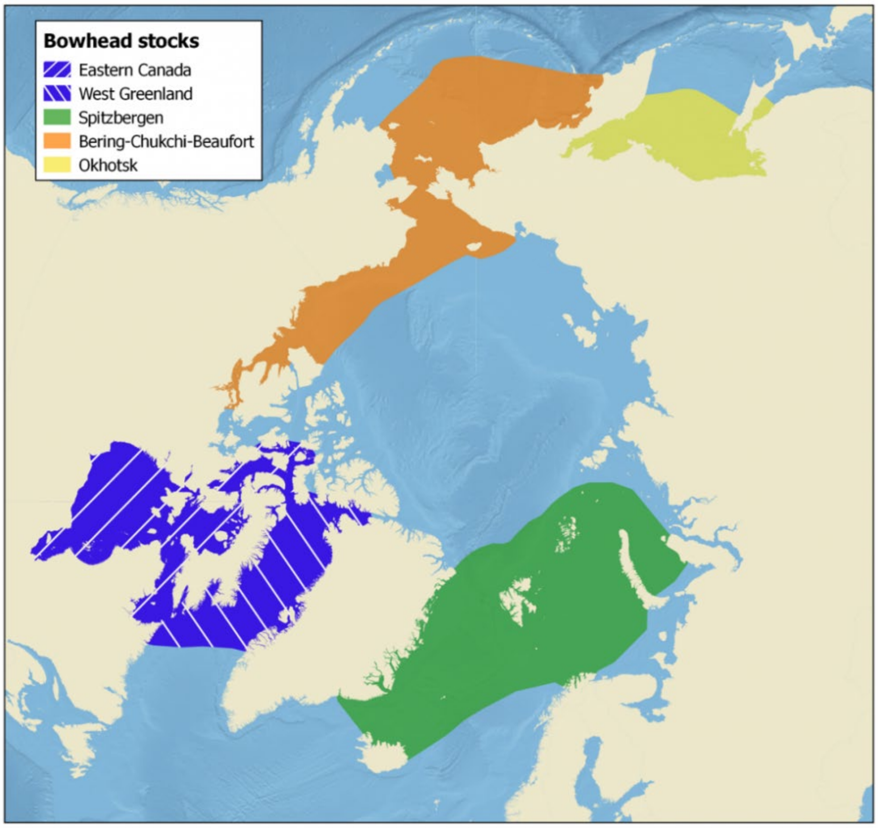

*Figure 26. Four geographic stocks of Bowhead Whales are currently recognised globally (for management purposes) and are geographically separated by landmasses or extensive sea ice. The whales that utilizes the North Water region belong to the Eastern Canada-West Greenland (EC–WG) stock, shown in blue (Source: NAMMCO 2016).*

In Baffin Bay, the whales range from the ice edge in Davis Strait to the North Water, and along Baffin Island and west Greenland coast (COSEWIC 2009, Christensen et al. 2017) (Figure 27). Preferred winter habitat types include low ice coverage, thin ice, and small floe areas to avoid entrapment (Ferguson et al. 2010, Chambault et al. 2018). The Baffin Island coast, Hudson Strait, and Disko Bay in Greenland are important wintering locations for the species (Nielsen et al. 2015). The North Water does not appear to be as important for overwintering Bowheads as it is for other Arctic cetaceans (Heide-Jørgensen et al. 2016, Fortune et al. 2020a), though residents of Grise Fiord have stated that some Bowheads do overwinter there (QIA 2018). Furthermore, there are currently no critical calving or nursing areas, important foraging habitat, or migration routes for Bowhead Whales in the North Water (Higdon 2017).

Satellite-tracked whales tagged in their Disko Bay wintering habitat showed spring movements largely towards northeast Baffin Island/Lancaster Sound/Smith Sound (Heide-Jørgensen et al. 2003c, 2006, Dueck and Ferguson 2008, Chambault et al. 2018). Measurements of dive behaviour and movement speed indicated that these Bowheads were feeding in Disko Bay during early spring, traveling rapidly across Baffin Bay and feeding again in or near the North Water during late spring/early summer, which suggests the North Water provides consistently important foraging habitat, particularly from April to June (Heide-Jørgensen et al. 2003c, 2006, Chambault et al. 2018). Nielsen et al. (2015) also observed some whale movement and diving behaviour in southern North Water, but the area was not identified by the authors as important foraging habitat for the species. By early-spring, the North Water is a predictable and presumably important region for early foraging, as algal blooms begin earlier in these locations providing an opportunity to replenish energy stores (Dueck and Ferguson 2008). Whales initiate migration to northwestern Baffin Bay and the North Water prior to peak bloom in Greenland (Dueck and Ferguson 2008). Chambault et al. (2018) found that Bowhead movements away from Disko Bay largely followed sea surface temperature patterns, specifically targeting a narrow range of -0.5 to 2°C. With such a small range of preferred temperatures, the authors suggested that Bowheads could be particularly vulnerable to a warming Arctic. Bowheads also prefer heavy ice conditions (> 90%), which may also provide cover from Killer Whales (Matthews et al. 2020). Shallow continental shelves, areas with troughs, upwelling and eddies are also important habitat as they concentrate zooplankton prey (Dueck and Ferguson 2008, Laidre et al. 2008, Ferguson et al. 2010).

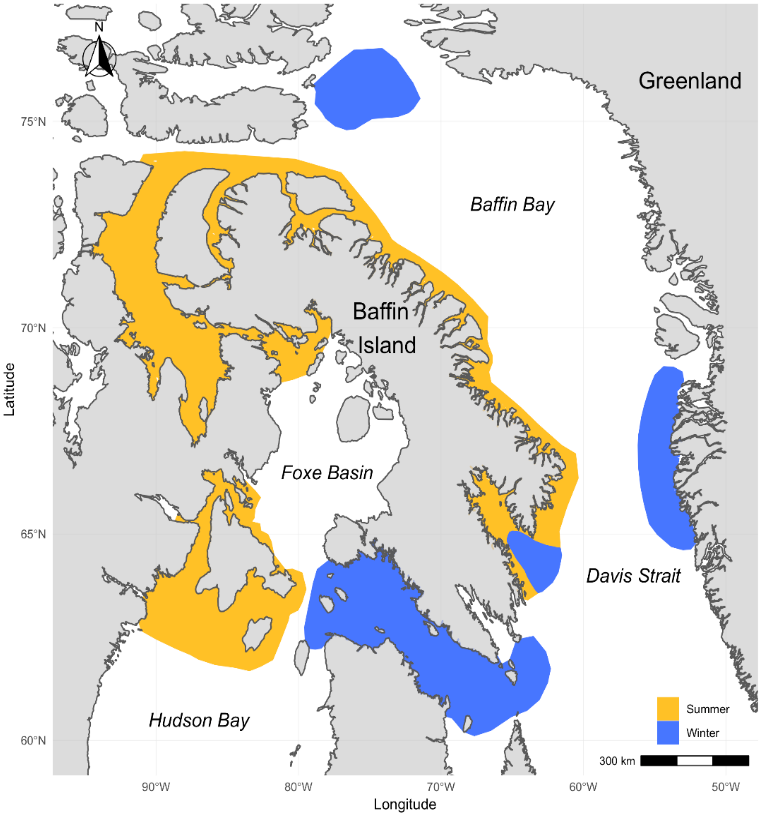

*Figure 27. Eastern Canada-West Greenland Bowhead Whale distributions. Winter distributions (blue) and areas of summer aggregations (yellow) were reproduced from COSEWIC (2005), with modifications after Matthews and Ferguson (2015).*

The global Bowhead population is listed as “Least Concern” by IUCN (Cooke and Reeves 2018), while the EC-WG population is listed as “Special Concern” by COSEWIC (2009), and were classified as the fourth most sensitive Arctic marine mammal to changing habitat, based on a combination of physical and biotic habitat requirements, population size, and geographic range (Laidre et al. 2008). Bowheads are believed to be increasing in number since the termination of commercial whaling (Hay et al. 2000, Richard 2006, COSEWIC 2009, Frasier et al. 2015, Doniol-Valcroze et al. 2015a). Bowhead Whale hunting is an integral part of Inuit culture, and a limited subsistence hunt resumed in Canada in the Nunavut Settlement Area in 1996 and in the Nunavik Marine Region in 2008 (Doniol-Valcroze et al. 2015a). Bowhead harvests in Canada are currently considered sustainable (DFO 2015c) and the EC-WG population can support a total human-induced mortality of 52 whales annually (Doniol-Valcroze et al. 2015a).

### 3.4.4. Bearded Seal (*Erignathus barbatus*)

Bearded Seals are circumpolar, but have patchy distribution and occur at low densities with a population size of roughly 190,000 animals in Canada (Cleator 1996, Bengtson et al. 2005, Cameron et al. 2010). Their range includes nearshore areas along the perimeter of the North Water in Canada and Greenland (Figure 28) (Stephenson and Hartwig 2010, Kovacs 2016a). Due to their remote and broad distribution, information on Bearded Seals is limited. Laidre et al. (2015) summarized known population data for Bearded Seals throughout their range, but described the data available as “poor and outdated”, and there are no reliable quantitative estimates of population trends for the species (NAMMCO 2016). The total number of Bearded Seals using the North Water is unknown. Some historical aerial surveys indicated density was low on the Canadian side and in adjacent Jones Sound (Koski 1980, Kingsley et al. 1985). More recent spring (Heide-Jørgensen et al. 2013) and winter (Heide-Jørgensen et al. 2016) surveys of the eastern North Water estimated approximately 6,000 seals using primarily large ice floe habitat near Inglefield Bredning, Greenland. Residents of Grise Fiord have frequently observed Bearded Seals near the community and nearby fiords, along leads, and at breathing holes (Government of Nunavut 2012, QIA 2018), and have reported increased sightings in recent years (Nunami Stantec 2018).

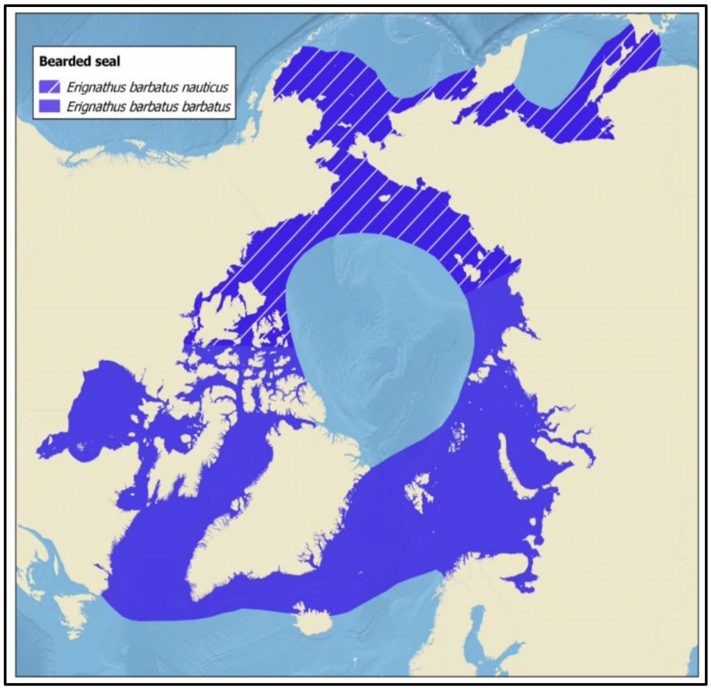

*Figure 28. Global distribution of Bearded Seals (Source: NAMMCO 2016).*

Bearded Seals are strongly associated with sea ice at all life history stages and are primarily benthivores (Thiemann et al. 2008a, Cameron et al. 2010, Kovacs 2016a). Fatty acid signatures found that Bearded Seals were most comparable to Walrus as both are primarily benthic feeders (Thiemann et al. 2008a) although juveniles tend to feed more on fish (Young et al. 2012). A stable isotope model of the North Water trophic food web placed Bearded Seals at an intermediate trophic level of 4.3, suggesting mixed diet with Arctic Cod as the main contributor, but also a large amount of benthic input (Hobson et al. 2002a).

Bearded Seals are sensitive to sea-ice changes, but their large, widely distributed populations, and flexible diet decrease their overall sensitivity to climate change (Laidre et al. 2008). Bearded Seals are listed as “Least Concern” by IUCN due to their large population size, broad distribution, and no evidence of decline (Kovacs 2016a). Stocks in Canada appear to be stable, but are generally data deficient (Cleator 1996).

### 3.4.5. Harp Seal *(Pagophilus groenlandicus)*

Harp Seals are found in the northernmost Atlantic Ocean and parts of the eastern Canadian Arctic and Greenland, and are considered common Arctic summer residents (Figure 29) (Stephenson and Hartwig 2010, DFO 2014b, Kovacs 2015). From July through November the vast majority of the population is in the Arctic, occurring from southeast Greenland, to as far north as Baffin Bay and Lancaster Sound in the Canadian Arctic, and extending as far west as Hudson Bay (Figure 29) (Stenson and Sjare 1997, Stenson et al. 2016). The West Atlantic Harp Seal population was estimated to be 7.6 million (95% CI = 6.6 to 8.8 million) in 2019 and the population appears to be stable (Hammill et al. 2021). There are no abundance estimates for Harp Seals using the North Water, though Koski (1980) observed a low density (0.18 seals/km$^2$) of seals at the entrance to Jones Sound.

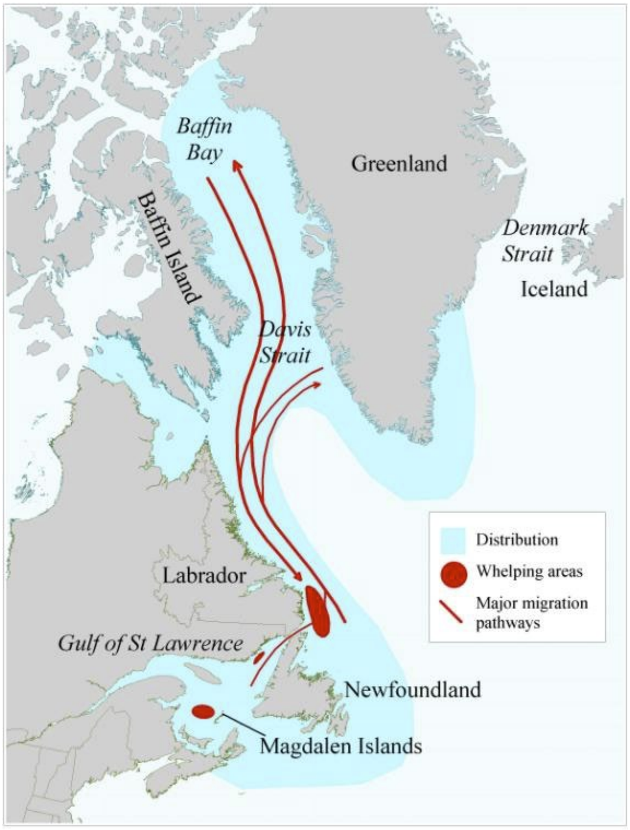

*Figure 29. Distribution of Northwest Atlantic Harp Seals, including whelping areas and migration pathways from the Atlantic to north Baffin Bay (Source: Stenson et al. 2016).*

Harp Seals have a relatively limited geographic distribution during the whelping period, but are highly migratory for most of the year (Figure 29, Stenson and Sjare 1997, Stenson et al. 2016). Historically, residents of Grise Fiord and Greenland settlements near the North Water reported sightings of Harp Seals everywhere along the coast near the community during summer and early fall (Government of Nunavut 2012, QIA 2018). However, residents of Grise Fiord report less Harp Seals over the past five years (L. Audlaluk, Hamlet of Grise Fiord, pers. comm.). Productive Arctic waters provide important foraging habitat for Harp Seals, which are known to feed on pelagic crustaceans (euphausids and amphipods), and small fishes such as Capelin, Atlantic Herring and Arctic Cod, in nearshore areas, and Capelin, Arctic Cod, Sand Lance, and shrimp, in offshore areas (Smith et al. 1979, Lawson and Stenson 1997, Kapel 1995, 2000, Stenson 2013). Inter-annual variability in ice cover can impact key prey species like Arctic Cod and Capelin, and may be one driver of annual changes in Harp Seal occurrence and distributions.

To date, this species has not been assessed by COSEWIC and current harvest levels for this species are low in the Canadian Arctic (DFO 2014b). Harp Seals have a large population size, diverse habitat and dietary requirements, and can adapt to trophic web changes; however, like all of the surveyed pinnipeds, they are sensitive to sea-ice changes (Stenson and Hammill 2014). Specifically, they are highly vulnerable to warming and environmental changes due to their dependence on sea ice for whelping (Kovacs and Lydersen 2008, Kovacs et al. 2011).

### 3.4.6. Hooded Seal (*Cystophora cristata*)

The Hooded Seal is the largest seal species in the Northwest Atlantic. Hooded Seals are found in the North Atlantic Ocean and the Canadian Arctic as far north as the North Water (Figure 30) (Koski 1980, Stephenson and Hartwig 2010, Andersen et al. 2009a, 2013, Kovacs 2016b). The most recent population survey was completed in 2005, and the estimated total Northwest Atlantic (Canadian) population is 593,500 (95% C.I. = 465,600-728,300) (Hammill and Stenson 2006), however there is uncertainty associated with these estimates due to a lack of understanding of the relationship between the Davis Strait, Front and Gulf pupping areas, limited surveys/sporadic monitoring and reproductive data, and uncertain harvest statistics.

Hooded Seals have commonly been sighted in the North Water and Baffin Bay (e.g., Stirling and Holst 2000), however, the overall number of seals using the North Water is unknown. There is a whelping concentration of seals in Davis Strait (Hammill and Stenson 2006), suggesting that the North Water may be an important feeding area both prior to, and following, whelping in March for this segment of the population (G. Stenson, DFO Newfoundland, pers. comm.). However, during the most recent survey (2005) this component of the population was quite small (down to ~ 3,300 pups from ~ 19,000 pups in 1984), though only a single brief survey was conducted in 2005 (Hammill and Stenson 2006). There is limited information on prey selection at various times of the year, but diet studies of adult Hooded Seals indicate they feed primarily on benthopelagic species (Ross 1992, DFO 2008b, 2009). It has been suggested that there could be an overlap in prey preference with other marine mammal species such Beluga, and Narwhal (Richard et al. 1998, Laidre et al. 2003, 2004) in important feeding areas for Hooded Seals during their post-moult migration. Comparisons of seal diets in Newfoundland found very little overlap between Harp Seals and Hooded Seals (Hammill and Stenson 2000, Buren and Stenson 2017), and there is geographic separation between the two species for much of year (Stenson and Kavanagh 1993, Lacoste and Stenson 2000), although these studies were not conducted in the North Water.

After whelping, Hooded Seals return to the pack ice off eastern Greenland to moult during June-July, and then they may remain off the eastern Greenland coast, disperse to the Greenland Sea, or Davis Strait over the summer and fall before returning to their respective breeding areas (Sergeant 1974, Folkow et al. 1996, Hammill 1993, Stenson and Sjare 1997, Andersen et al. 2014). A satellite tracking study of Northwest Atlantic Hooded Seals showed that after moulting in southeast Greenland in July, individuals traveled north through Davis Strait and Baffin Bay along the continental shelf, some reaching as far north as the North Water (in October) before returning to the Labrador Shelf breeding grounds by March (Andersen et al. 2009a, 2014). Anderson et al. (2012) found that males and females are separated on a horizontal scale during annual migration. Females tend to use the Labrador shelf more intensively than males, especially in the autumn/winter season (post-moult and pre-breed) and males use the Baffin

Bay and Davis Strait areas more frequently during autumn/winter, and in spring they spend time in southeast Greenland as well as Davis Strait (Anderson et al. 2012).

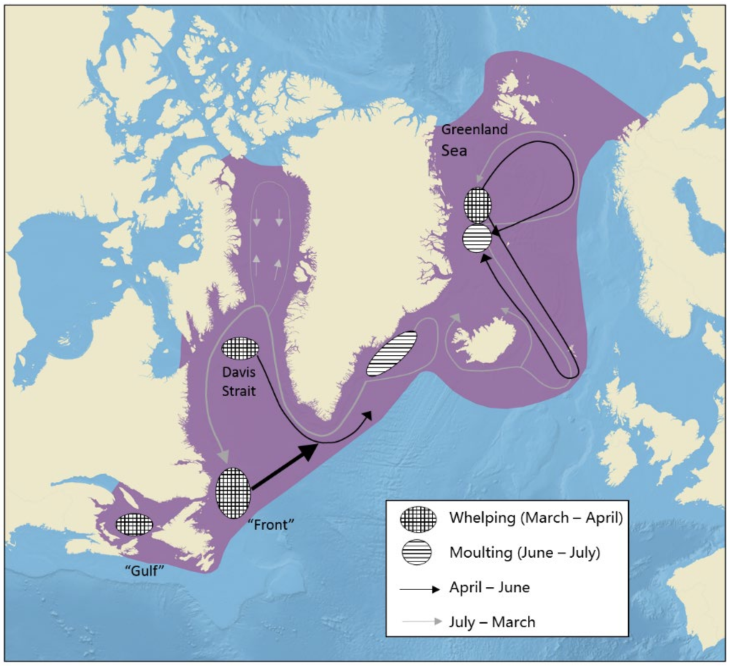

*Figure 30. Distributional range of Hooded Seal in the North Atlantic (Source: NAMMCO 2016).*

Hooded seals are harvested commercially and for subsistence. Historically, the commercial Hooded Seal harvest in Canada has occurred only in Atlantic Canada (Gulf of St. Laurence and Newfoundland) (Stenson 2006). As far as what has been reported, a Hooded Seal hunt has never taken place in Davis Strait, and no harvests have taken place in the Gulf since the mid-1960s. Hooded seals from all three whelping areas in the Northwest Atlantic are harvested for subsistence by Greenland. From 1976 to 1985, catches were estimated to be about 6,000 seals per year (DFO 1996). Tag returns indicate that the spring (pre-moult) hunt along the Greenland coast impacts the Davis Strait component, and may contribute to the apparent decline in pup production in that region (G. Stenson, DFO Newfoundland, pers. comm.). Since 1999, less than 400 hooded seals have been taken annually off the northeast coast of Newfoundland and the Greenland harvest has dropped to around 1,500–2,000 animals since 2011, according to the official Greenland catch statistics. The species is currently assessed as “Not at Risk” by COSEWIC (2019), however an updated population survey is needed. Like all pinnipeds, Hooded Seals have relatively high growth rates, but they are sensitive to sea-ice changes (Johnston et al. 2005), have a relatively limited geographic distribution, show strong site fidelity during whelping, and are highly migratory, ranking them as among the most sensitive of Arctic marine mammals to changing habitat (Laidre et al. 2008).

### 3.4.7. Ringed Seal (*Pusa hispida*)

Ringed Seals are circumpolar and their distributions are closely linked to sea ice (Figure 31) (Kingsley et al. 1985, Stephenson and Hartwig 2010, Lowry 2016a) and have an estimated global population size of 6-7 million animals (Stirling and Calvert 1979, Reeves 1998, Lowry 2016a). All Ringed Seals in Canada are part of the same stock (Palo et al. 2001, Davis et al. 2008, Martinez-Bakker et al. 2013). Kingsley (1987) used the size of the Polar Bear population in Baffin Bay and surrounding waters and their energetic requirements and the energetic contributions per seal to their diet to estimate the population size of Ringed Seals in the area at about 1.2 million, though the proportion using the North Water is largely unknown. An estimated 9,529 seals used large ice floe habitat in the eastern North Water near Inglefield Bredning in early spring 2010 (Heide-Jørgensen et al. 2013). Residents of Grise Fiord have observed Ringed Seals numbering in the tens of thousands year-round throughout Jones Sound, along both coasts and in narrow fiords and inlets (Government of Nunavut 2012, QIA 2018).

Preferred habitat for adult breeding Ringed Seals includes annual ice with deep snow and pressure ridges over shallow water (Kingsley et al. 1985, Barber and Iacozza 2004). They are also one of the few marine mammals that regularly occupy extensive landfast ice (Smith et al. 1991, Tynan and DeMaster 1997, Laidre et al. 2008) but have also been observed to occupy offshore pack-ice habitats for breeding and nursing (Finley et al.1983). Ringed Seals are residents at both the eastern and western margins of the North Water (Born and Knutsen 1989, Born et al. 2004). There is common winter and pupping habitat on the Canadian side of the North Water, which includes the nearshore landfast ice of eastern Ellesmere and Devon Islands (Stephenson and Hartwig 2010). Tagged seals were consistently observed diving along the fast ice edge during its formation in the eastern North Water (Teilmann et al. 1999). During summer, the seals are more common farther offshore throughout the North Water (Stephenson and Hartwig 2010). Ringed Seal movements can be extensive within Baffin Bay (e.g., Ogloff et al. 2021) and the North Water. For example, seals tagged in Wolstenholme Fjord on the Greenland side of the North Water in 1988 remained in the fiord until late June/early July after which some individuals dispersed as far as Coburg Island to the west and northern Smith Sound and Kane Basin to the north (Heide-Jørgensen et al. 1992). Satellite tracking found that the total area covered by the seals during the open-water period (10,300–18,500 km$^2$) represented about 15–25% of the entire North Water (Born et al. 2004). Contrastingly their range was much smaller during winter (2,500–7,000 km$^2$) and spring (800–2,100 km$^2$). Maximum dive depth for these marked seals was shallower (376 m) inside the North Water than when they moved outside of it (greater than 500 m) and sub adult seals generally spent more than 92% of their time in water less than 50 m deep (Born et al. 2004). Seasonal differences in time spent hauled out have been observed in the eastern North Water. Haul-out percentage per month during the winter darkness period ranged from 3.9–15.7% followed by a large increase starting in late March and reaching 57% by the end of June (Born et al. 2002).

Generally, pelagic crustaceans and Arctic Cod are important prey items for Ringed Seals throughout their range with contributions of fish and invertebrates varying by latitude (Bradstreet and Cross 1982, Reeves 1998, Smith and Harwood 2001, Yurkowski et al. 2016b). In turn, Ringed Seals are the main prey of Polar Bears, but may also be preyed upon by Walrus, Killer Whales, and some terrestrial mammals and birds (Reeves 1998). There have been several studies on the diet and biology of Ringed Seals in or near the North Water. In northwest Greenland, Ringed Seal diets were dominated by Polar and Arctic Cod (Siegstad et al. 1998). Holst et al. (2001) compared the diet of seals from the east and west sides of the North Water. In the west, the amphipod *Themisto libellula* and Arctic and Polar Cod were dominant in immature and adult seals, respectively. On the east side, Arctic Cod were dominant prey types in all seals. The observed spatial differences in diet may be due to differences in prey distribution and/or biological productivity and fish biomass between the east and west sides (Holst et al. 2001). Other studies have shown earlier blooms and greater productivity on the Greenland side (see Lower Trophic Levels Section) that could support increased cod reproduction. There was no statistical difference in the trophic level position (from isotope analysis) of seals on either side of the North Water, but the western seals did have a carbon isotopic ratio that indicates a greater dependence on benthic food sources or prey that is more sympatric (i.e., ice-algae associated) (Holst et al. 2001). In another study of eastern North Water seals, Born et al. (2004) reported younger Ringed Seals feeding on ice-associated amphipods and young Arctic Cod and adults feeding on cod and cephalopods at greater depths. In a stable isotope study to model the food web of the North Water, Hobson et al. (2002a) placed Ringed Seals at an intermediate trophic level of 4.5, which suggested they are the main prey of Polar Bears and that they are consuming primarily Arctic Cod, particularly on the Grise Fiord side. There was no difference in trophic levels between seals from the western and eastern sides of the North Water (Hobson et al. 2002a). Fatty acid biomarker studies (Thiemann et al. 2007a, 2008a) and contaminant biomagnification studies (Fisk et al. 2001b) have also shown a primary fish-based diet for seals in the North Water region. In recent years, a similar isotopic trophic level study on Ringed Seals in the North Water (Eulaers et al. 2019) showed a gradual decline in trophic level position since the 1998 results published by Hobson et al. (2002a). Eulaers et al. (2019) attributed this to observed decreases in North Water primary productivity and possible Atlantification/borealization of the Arctic (Møller and Neilsen 2019).

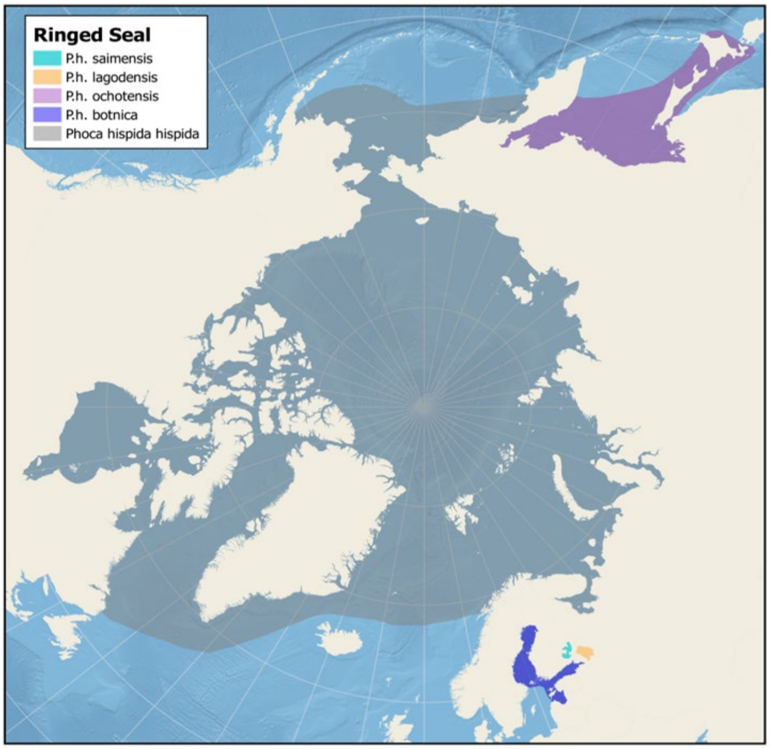

*Figure 31. Circumpolar distribution of Ringed Seals (Source: NAMMCO 2016).*

In general, Ringed Seals in the northern Arctic (such as around Grise Fiord) are larger and heavier than those at the southern periphery of their range (Ferguson et al. 2018, 2020). Spatial differences in Ringed Seal biology are also apparent within the North Water itself. For instance, Holst and Stirling (2002) found that adult seals on the east side were significantly shorter and weighed less than those on the west. In addition, females from the east side had significantly thicker blubber and reached sexual maturity at an earlier average age than western females. In contrast, young of the year (YOY) in the west had significantly thicker blubber than eastern YOY. The authors suggest spatial differences in productivity between the two sides of the polynya are responsible for the observed biological differences between seal populations since the two populations are genetically similar. Longer duration landfast ice on the west side may have lengthened the suckling period and, thus, blubber thickness for YOY on the west side (Holst and Stirling 2002). The greater biological productivity on the east side is thought to have resulted in the earlier age at maturity and thicker blubber in adult females.

Ringed Seals are listed as “Least Concern” by IUCN (Lowry 2016a), are not listed under the *Species at Risk Act* (SARA), and are designated as “Special Concern” by COSEWIC (2019). Laidre et al. (2008) assessed Ringed Seal as one of the least sensitive Arctic marine mammal species to climate change due to its abundance, broad distribution, lack of site fidelity, and high growth rates. However, the authors noted the species is highly sensitive to changes in sea ice where observations of decreased body condition have occurred in the Amundsen Gulf (e.g., Harwood et al. 2015) and declines in abundance and negative demographic responses in Hudson Bay (e.g., Young et al. 2015, Ferguson et al. 2017).

With changing sea ice conditions, Qaanaaq Inughuit hunting techniques for Ringed Seal has evolved too. While seals used to be hunted either from the floe edge in *qajaqs* (*nuigartulerisarpugut)* or from their *allu* (breathing hole), with thinner ice conditions, hunters now often use nets to catch many seals, with an increase to both sales of seal skins and food security for the community (Gearheard et al. 2013).

### 3.4.8. Walrus (*Odobenus rosmarus*)

Walrus have a discontinuous distribution in the central and eastern Canadian Arctic and seven differentiated stocks have been recognized through genetic analysis, satellite telemetry, and trace element studies (Figure 32) (Steward 2008, NAMMCO 2011, Andersen et al. 2014, Wiig et al. 2014, Shafer et al. 2014). Walrus maintain a winter presence in the North Water area (Pikialasorsuaq Commission 2017), but are scarcer during summer (Born et al. 1995). Important local wintering areas include the entrance to Jones Sound at Coburg Island and the entrance to Inglefield Bredning on the Greenland side (Figure 32) (Stewart 2008, Heide-Jørgensen et al. 2017). Small numbers have also been observed scattered throughout the region with concentrations around Coburg Island in the west and around Northumberland Island, Greenland (Koski 1980, Richard et al. 1998b, Stephenson and Hartwig 2010).

Three Walrus stocks, which together make up the High Arctic population (Stewart 2008), occur within or adjacent to the North Water. The Penny Strait-Lancaster Sound (PS-LS) stock inhabits waters from Penny Strait south to Resolute (Cornwallis Island) and east to the entrance to Lancaster Sound and eastern Devon Island in the southwestern limits of the North Water (Stewart 2008, Shafer et al. 2014, Heide-Jørgensen et al. 2017). The Western Jones Sound (WJS) stock range includes the Hell Gate area and the westernmost end of Jones Sound but does not overlap with the North Water. The Baffin Bay (BB) stock ranges from Grise Fiord and Coburg Island north through Smith Sound and across to northwestern Greenland, covering much of the perimeter of the North Water (Stewart 2008, Shafer et al. 2014). The Baffin Bay stock is found year-round in the North Water, but during open water they are largely absent from the Greenland side, concentrating in nearshore Ellesmere Island habitat (Stewart et al. 2014a).The Greenland Walruses migrate west in early to late spring across Smith Sound to summer in coasts and fiords of Ellesmere. DFO surveyed the Baffin Bay stock in 2009 and abundance estimates ranged from 1,249 to 1,251, but the surveys did not cover all potential habitat along eastern Ellesmere Island (DFO 2013, Stewart et al. 2014a). In the same year, the PS-LS stock was estimated at between 661 (CV = 2.08) and 727 (CV = 0.07), and the WJS stock was surveyed in 2008 and was estimated at 503 (CV = 0.07) Walruses; both appear to have been stable for decades (DFO 2013, Stewart et al. 2014b). There is scientific uncertainty surrounding the distributions and movements, and thus current stock delineations, of Canada’s High Arctic walrus population. Walruses tagged in Greenland, from the purported Baffin Bay stock, subsequently moved into Canadian waters and mixed with all three stocks from the High Arctic population (Heide-Jørgensen et al. 2017). Based on this and other genetic evidence (i.e., Shafer et al. 2014), the NAMMCO Walrus Working Group has agreed to operate with the following names for the Greenlandic stocks: Baffin Bay (a subunit of the former North Water population); West Greenland-Southeast Baffin Island (a ‘component’ of the larger Hudson Bay-Davis Strait population); and East Greenland (formerly Northeast Water) (NAMMCO 2018).

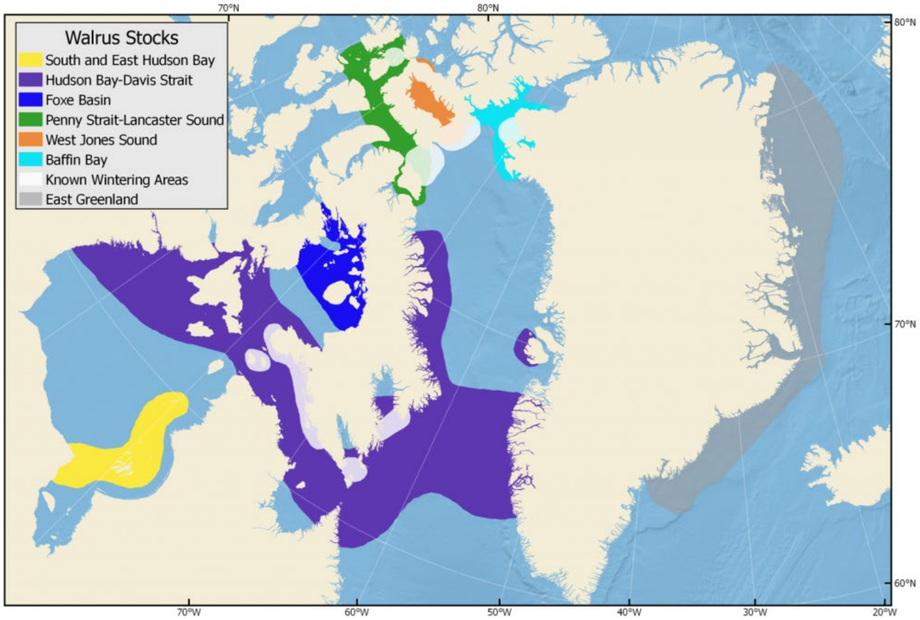

*Figure 32. Summer distributions of Walruses in Greenland and Canada. Known wintering areas shown in white (Source: NAMMCO 2018).*

A spring aerial survey of the North Water in 2009 and 2010 found most Walruses along a band at latitude 73°30’N between Greenland and Ellesmere Island over a variety of depths (Heide-Jørgensen et al. 2013). Walrus are thought to be mostly absent north of 77°, however, in August 2018, eight Walruses were observed during a photographic aerial survey in Archer Fiord (81°), Nunavut, indicating a possible update to the northern range of High Arctic Atlantic population (Yurkowski et al. 2019). Walruses were most frequently observed alone with only a few small groups noted. Historical surveys have been completed for Walrus in the North Water (1978, 1979, and 1993) during winter (see Finley and Renard 1980, Richard et al. 1993). The most recent winter survey of the Greenland side of the North Water estimated a population of 2,544 (95 % CI 1513–4279) Walruses in the area, which is larger than even previous summer estimates (~1,500, Heide-Jørgensen et al. 2013), suggesting a greater importance than initially thought (Heide-Jørgensen et al. 2016). Residents of Grise Fiord indicate the south side of Jones Sound on Devon Island has more Walrus than the north side and they are most common in the area during summer (Figure 42) (Government of Nunavut 2012). Haul-out sites were identified in western Jones Sound and on Coburg Island with males appearing to prefer the westernmost locations and females the east (Government of Nunavut 2012). Walrus migrate eastwards out of Jones Sound during fall towards the North Water (Government of Nunavut 2012).

Walruses that winter in the eastern North Water, where they are typically segregated by gender and age with females and sub adults occurring farther north than adult males, migrate north during spring towards the ice bridge in northern Smith Sound, which prevents further northward movement (Figure 33) (Born et al. 1995). Concentrations of Walrus can be seen in northern Smith Sound during spring (Born et al. 1995), and local knowledge from Qaanaaq has indicated Flagler Bay, in Umimmaat Nunaat, as a Walrus breeding area (Pikialasorsuaq Commission 2017). Movements continue westward across the North Water, spending minimal time in the open water of Smith Sound, to the landfast ice off Ellesmere Island, in its fiords, and the Lancaster Sound floe edge and southeast coast of Devon Island where they spend the summer

(Figure 42) (Born et al. 1995, Stewart et al. 2014a, Higdon and Stewart 2018, Garde et al. 2019). Small numbers can also be seen east of Coburg Island and within Jones Sound (Born et al. 1995). Particularly important summering grounds include fiords and bays on the western side of Kane Basin to the north and Talbot Inlet and Craig Harbour to the south (Heide-Jørgensen et al. 2017). Diving behaviour monitoring of Walrus on both sides of the North Water identified additional important feeding areas in the Alexandra Fiord complex and Princess Mary Bay along southeastern Ellesmere Island (Garde et al. 2018, 2019). Some offshore areas in Smith Sound are also used during spring and fall migrations, but most animals remain near shorelines (Figure 33) (Heide-Jørgensen et al. 2017, Garde et al. 2019). Return fall migrations to Greenland occur during October (Figure 43) (Heide-Jørgensen et al. 2017). A few individuals from Greenland have entered Jones Sound and moved into the supposed boundaries of the WJS and PS-LS stocks. These data suggest that the Walrus population wintering in Greenland is more widely dispersed in Canada during summer than previously thought, which has implications for management (Heide-Jørgensen et al. 2017).

Walruses require productive benthic communities with abundant bivalves, reliable open water and haul-out sites (preferably on ice) near the open water (Lowry 2016b). A stable isotope study to model the trophic food web of the North Water placed Walrus at the lowest trophic level (3.2) of all marine mammals, which suggests a diet of primarily lower trophic level benthic organisms like bivalves, gastropods, and polychaetes (Hobson et al. 2002a). Terrestrial haul-out sites become critically important to Walrus during summer and early fall periods of sea-ice minima (Higdon 2016). There are no known active terrestrial haul-out sites on the eastern side of Smith Sound or along northeastern Ellesmere Island, and only minimal observations from southeastern Ellesmere Island (Heide-Jørgensen et al. 2017, Garde et al. 2019). Smith Sound also has a relatively small shallow water area feasible for benthic feeding and Garde et al. (2018, 2019) suggest this likely limits the carrying capacity to approximately 5,000 individuals. In these areas, the Walrus are more dependant on the presence of summer sea ice for haul-outs, but these features may disappear in the future as the climate warms. Walruses are particularly sensitive to disturbance at haul-out locations and have been known to abandon them for less favourable locations (Higdon 2016, DFO 2019b).

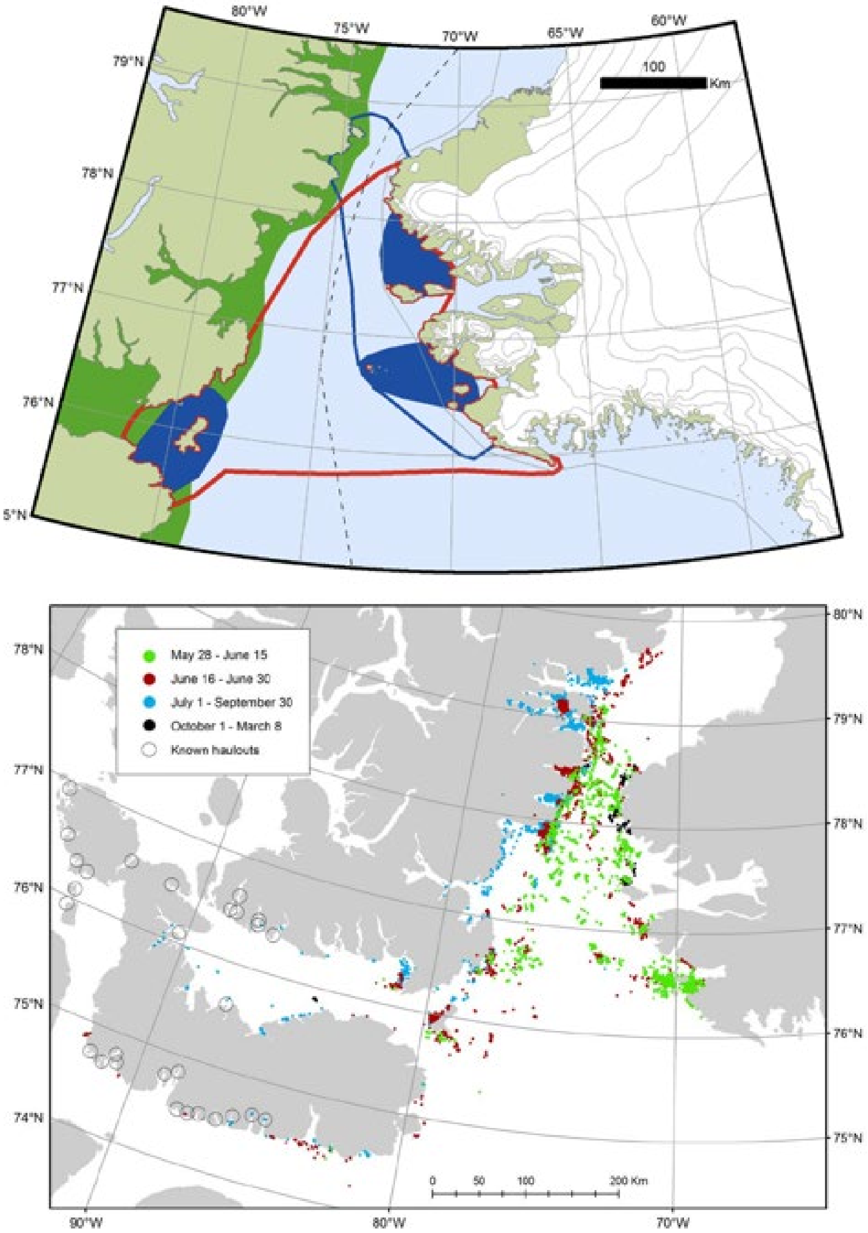

*Figure 33. Top: Distribution and key areas for Walrus; the blue line represents general distribution from Oct-April and blue areas show high density regions for the same time period, the red line denotes distribution from May-June, and green areas the summer distribution from July-Sept (Source: Christensen et al. 2017). Bottom: Seasonal movements of Walrus from satellite tracking data in the North Water region (Source: Heide-Jørgensen et al. 2017).*

Historically, Walrus have been an integral and culturally significant resource for communities surrounding the North Water and adjacent areas (Gotfredsen et al. 2018). In spite of increasingly difficult access due to changing movement patterns, likely induced by climate change, Walrus remain an important component of Inughuit hunting (Born et al. 2017). Walrus tusks remain a valuable commodity and ivory carvings made from Walrus tusks are an important source of income for some communities (Gotfredsen et al. 2018, NAMMCO 2018). Reported catch statistics for Greenland and Canada have been summarized in the NAMMCO

Catch Database. Total Allowable Removal (DFO) for the three stocks are 10–11 animals for BB, 7–8 animals for WJS, and 10–12 animals for PS-LS (DFO 2013, Stewart and Hamilton 2013). Hunters from Qaanaaq, Greenland, reported landing 67 Walruses in 2014 (from a quota of 86); in the three Nunavut locations where this population is harvested (Grise Fiord, Craig Harbour, and Resolute Bay), the average annual take (2007–2011) was 7 (NAMMCO 2013). The species is listed as "Vulnerable" by the IUCN (Lowry 2016b) due to predicted substantial changes to their sea-ice habitat. The Canadian High Arctic population, which includes stocks in or near the North Water was assessed as "Special Concern" by COSEWIC, due to low estimated population numbers (low thousands) and a lack of clarity whether the combined hunting pressure in Canada and Greenland is currently sustainable (Ugarte 2015, COSEWIC 2017). The WJS and PS-LS stocks are considered stable (COSEWIC 2017, Higdon and Stewart 2018). Population dynamics modelling indicates the Baffin Bay stock decreased by approximately 40% from 1960–2005, but has seen recent increases due largely to a decrease in hunting pressure on the Greenland side with the introduction of a quota in 2006 (Wiig et al. 2014, NAMMCO 2018). A better understanding of movement patterns and total hunting pressure is necessary, particularly for the internationally-shared Canada-Greenland stock (DFO 2013). Specifically annual hunt statistics for most Canadian Inuit communities are not available, which poses a challenge for effective management (NAMMCO 2018). While there is cooperation on Walrus research and stock assessment, there is currently no formal Walrus co-management agreement between the two countries (NAMMCO 2018).

### 3.4.9. Polar Bear (*Ursus maritimus*)

Polar Bears have a circumpolar distribution occupying ice-covered seas from Newfoundland to near the North Pole, denning as far south as Akimiski Island in James Bay (COSEWIC 2008, Obbard et al. 2010, Wiig et al. 2015). There are 19 recognized subpopulations of which 13 of occur fully or partially within Canada (Figure 34) (COSEWIC 2008, Obbard et al. 2010, Stephenson and Hartwig 2010, Wiig et al. 2015). Boundaries of the subpopulations have been determined from genetic (Paetkau et al. 1999), telemetry (Stirling et al. 1979, Taylor and Lee 1995, Taylor et al. 2001), dietary (Thiemann et al. 2008b), and traditional knowledge (COSEWIC 2002, 2008) studies. The BB, Lancaster Sound (LS), and Kane Basin (KB) subpopulation ranges all include portions of or are adjacent to the North Water (Aars et al. 2006, COSEWIC 2008, Obbard et al. 2010, Wiig et al. 2015). The LS subpopulation boundary includes all of Devon Island, Jones Sound and the westernmost portion of the North Water (COSEWIC 2008, Obbard et al. 2010). The KB subpopulation boundary includes northern Smith Sound/North Water and associated coastlines on either side of the polynya, while the Baffin Bay subpopulation boundary includes central, southern, and southeastern North Water areas (Taylor et al. 2001, COSEWIC 2008, Obbard et al. 2010).

These three subpopulations form a genetic cluster with three others in the Canadian Archipelago region (Malenfant et al. 2016). There was no significant difference between KB and BB genetics in Malenfant et al. 2016 study however recent work suggests the two subpopulations may be more genetically distinct (Laidre et al. 2018a). This is in contrast with movement data that show little movement between the areas (Taylor et al. 2001). Peacock et al. (2012) identified a noticeable decline in Polar Bear survival rates in Baffin Bay from 1997 onward concurrent with declining sea ice conditions. Rode et al. (2012) also documented a decline in body condition associated with reduced sea ice. A multi-species spring aerial survey of the North Water detected bears on the ice and in the water, but at very low densities for an estimated total abundance of 60 individuals (Heide-Jørgensen et al. 2013). However, multi-species surveys do not result in robust abundance estimates for polar bears so this can be considered biased. Residents of Grise Fiord have identified bears throughout Jones Sound, particularly during winter and spring along the ice edge (Figure 40 and Figure 41) (Government of Nunavut 2012). The north coast of Devon Island was described as an important maternity denning habitat and summer retreat habitat around Hyde Inlet and Philpots Island off eastern Devon Island (Figure 42) (Government of Nunavut 2012, Pikialasorsuaq Commission 2017).

The Baffin Bay and KB subpopulations have been recently reassessed with data collected from 2009–2013 (SWG 2016). Using mark-recapture data (live and dead) from 2012–2013, the Baffin Bay subpopulation size was estimated at 2,826 bears, though this number was not directly comparable to earlier estimates (Taylor et al. 2005) due to differences in sampling design and survey conditions (SWG 2016); the 1990s surveys were geographically-restricted and did not sample entire fiords, likely resulting in an underestimate of abundance. While it is not possible to determine trends in abundance in BB, the observed ranges of the 1990s and 2000s subpopulations showed a reduction in range size in the 2000s in all seasons and a shift northward due to loss of annual sea ice and changes to the timing of breakup (Laidre et al. 2018a). Baffin Bay bears were also less likely to emigrate from Baffin Bay into Davis Strait or Lancaster Sound in the 2000s than in the 1990s due to reduced sea ice. The updated mark-recapture estimate of abundance for KB was 357 bears and the evidence suggests a stable or increasing subpopulation. Reduced access to certain portions of the KB subpopulation, due to loss of sea ice, may have reduced harvest pressure on the Greenland-side. KB range use has moderately expanded since the 1990s due to changes in the sea ice regime from multi-year to annual, but the overall range of the subpopulation is still largely the same.

Changes in habitat use have also been observed for the Baffin Bay and KB populations (SWG 2016, Laidre et al. 2018ab). Baffin Bay female summer movement rates have declined since the 1990s due to the disappearance of offshore and archipelago summertime ice, and overall habitat has shifted to lower sea-ice concentrations. Bears remained closer to land in all months in the 2000s except at the end of breakup and there was an increase in the observations of long-distance swimming events (especially in 2011) (Laidre et al. 2018b, Laidre et al. 2020). Baffin Bay bears arrived on land on Baffin Island about a month earlier in the 2000s and no longer arrive on Devon or Ellesmere islands. Maternity den use was of shorter duration in the 2000s and the dens were typically at higher elevations (Escajeda et al. 2018). Estimates of total survival for females (0.90) in the Baffin Bay from 2011–2013 are likely too low to support a stable population over the long-term but also may include bias (SWG 2016). There was little evidence of change in litter size (cubs-of-the-year or yearlings) in the BB, but there was a decrease in cub recruitment likely related to earlier spring breakup, though there was no similar temporal trend in yearling recruitment. From 1993–2013 there was a decline in body condition of Baffin Bay bears strongly associated with ice-free period and sea-ice transition dates (Laidre et al. 2020). Habitat in KB has shifted to a more seasonal ice ecoregion being completely ice-free in the summer and the KB bears have responded with movement and use patterns more similar to those in other seasonal sea-ice ecoregions such as very low emigration and overall movement rates within their range. Data on KB litter size indicated similarities with other subpopulations in the archipelago, but trends could not be detected due to low sample size. Similarly, recruitment trends could not be identified due to insufficient data. Body condition in KB improved in the 2010s relative to the 1990s and may reflect natural variation or long-term trends in sea-ice changes (e.g., increased productivity of annual vs. multi-year sea ice).

Using stable isotopes to model the North Water food web, Hobson et al. (2002a) placed Polar Bears at the highest trophic level of any sampled animal (5.5) with the results suggesting that their diet consists primarily of Ringed Seals. Fatty acid markers have also been used to assess Polar Bear subpopulation diets (Thiemann et al. 2007b, 2008b, Galicia et al. 2015). Although Ringed Seals were dominant in all 10 subpopulations sampled by Thiemann et al. (2008b), Baffin Bay and LS bears consumed greater proportions of Beluga and, in LS, greater proportions of Bearded Seal than most other areas. Galicia et al. (2015) observed similar results with Bearded Seals and Beluga important in both subpopulations and Harp Seals contributing to Baffin Bay diets. A greater overall diversity observed in the Baffin Bay diet relative to other subpopulations was attributed to the variety of marine mammals attracted to the nutrient-rich waters of the North Water and surrounding areas (Galicia et al. 2015). Age and sex-specific foraging has also been noted for LS and Baffin Bay bears using fatty acid biomarkers though the differences were not significant as they were for other subpopulations (Thiemann et al. 2007b, 2008b, Galicia et al. 2015). Large adult male bears were the primary predators of Bearded Seals and Walruses; however, the predation rates on these two species in Baffin Bay were much lower than in other surveyed areas in the western Canadian Arctic and the Hudson Bay/Foxe Basin region (Thiemann et al. 2007b). In BB, adult females consumed primarily Ringed and Bearded Seals while adult males and sub adult males and females most frequently preyed upon Ringed and Harp Seals and Beluga (Galicia et al. 2015).

Globally, Polar Bears are listed under *Appendix II* of both the *Convention on International Trade in Endangered Species of Wild Fauna and Flora* (CITES 2017) (UNEP WCMC 2021) and the *Convention on the Conservation of Migratory Species of Wild Animals* (CMS 2020). The IUCN listed Polar Bears as “Vulnerable” (Wiig et al. 2015) due to a predicted population reduction of over 30% within three generations as ice cover recedes and open-water periods increase (Schleibe et al. 2008, Wiig et al. 2015). In addition to being highly specialized Arctic predators, Polar Bears have low reproductive rates and long generations, making facultative adaptations to the rapid changes in sea-ice habitat unlikely. If current trends continue, extirpation across much of their range within 100 years appears likely (Schleibe et al. 2008, Wiig et al. 2015). In Canada, Polar Bears were designated as “Special Concern” by COSEWIC to ensure protection across their entire range (COSEWIC 2018). This designation has recently been debated, both nationally and internationally, due to the absence of climate change considerations in the assessment and concerns raised by the Government of Nunavut (Peacock et al. 2011). The LS subpopulation has shown some signs of a decline, but is considered data deficient as the most recent demographic data are more than 20 years old (Obbard et al. 2010). The trend in the Baffin Bay subpopulation could not be assessed, while the KB subpopulation is likely stable or possibly increasing (SWG 2016).

Residents of Qaanaaq and Savissivik had a long tradition of traveling west onto the sea ice with specialized dog teams to hunt Polar Bears during February through April. However, since the 1990’s, Inughuit have noted that the bears’ behaviour has changed – they now come close to the settlements as the sea ice is forming (October–December), and the old spring hunting platform of sea ice is not safe to use. Bears are therefore hunted near the settlements now, and their presence often causes problems for personal safety and destruction of overwinter country food caches (Gearheard et al. 2013). Inuit in Qikiqtarjuaq, Pond Inlet, Clyde River, and Grise Fiord have observed an increase in bear numbers near their respective communities (Dowsley 2005, 2007, Dowsley and Wenzel 2008, QIA 2018). Possible explanations for the discrepancy between these observations and scientific estimates include: immigration from adjacent populations (e.g., Lancaster Sound), an underestimation of the population in scientific studies, and increased bear densities along the coast (Dowsley 2007). Grise Fiord residents have also observed an increase in Polar Bear numbers in Kane Basin (Government of Nunavut 2017). Laidre et al. (2020) provides evidence of a range expansion for the KB subpopulation, likely driven by a shift from thick, multiyear ice to thinner, seasonal ice with higher biological productivity. Increased presence of seals near glaciers also points to increased primary production linked to glacial inputs (SWG 2016). Coastal areas and glacial fronts are hypothesized to be key breeding habitat for seals and feeding areas for Polar Bears and Narwhals (e.g. Lydersen et al. 2014, Laidre et al. 2016, Freitas et al. 2018). This could also be true for eastern Kane Basin, however, the extent to which shallow, productive habitats may occur and support prey is unknown, and more information is needed for this region.

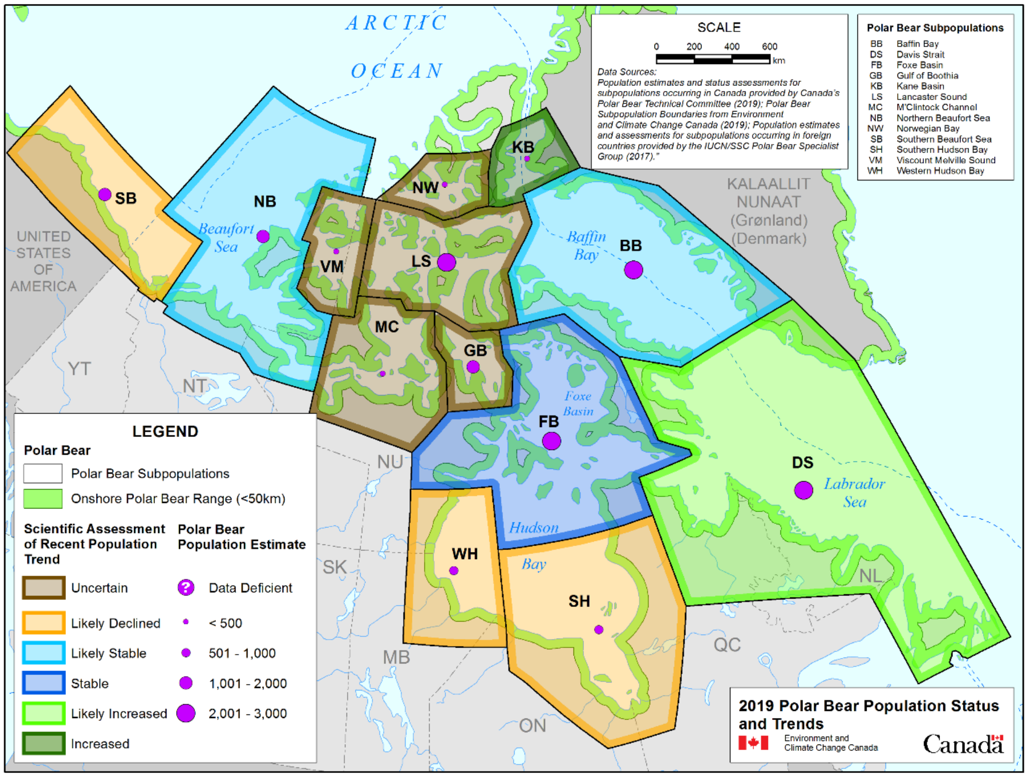

*Figure 34. Circumpolar Polar Bear population status and trends. Polar Bears inhabiting the North Water and adjacent areas belong to the Lancaster Sound (LS), Baffin Bay (BB), and Kane Basin (KB) subpopulations (Source: International Union for the Conservation of Nature's Polar Bear Specialist Group).*

### 3.4.10. Summary of Marine Mammals: Knowledge Gaps and Climate Impacts

In a highly dynamic ecosystem like the North Water, marine mammals can act as sentinels for areas of high productivity (Boyce et al. 2015) and help identify conservation areas or 'hotspots' (Yurkowski et al. 2019, Christensen et al. 2017). Unfortunately, demographic and long-term data on movement and population trends for most Arctic marine mammals is lacking or incomplete, and the North Water is no exception. There is also an overall lack of knowledge in the stock structure, distribution, numbers, and ecology of most marine mammal species that occur in the North Water region, and limited understanding of the biological importance of potential foraging habitats. Specifically, there are still data gaps related to the seasonal habitat use and movements (specifically winter) of populations of Narwhal and Beluga using Jones Sound, Smith Sound, and Inglefield Bredning. Due to this lack of understanding of stock delineation, more research is needed to improve understanding of Greenland-Canada shared Narwhal/Beluga stocks for management purposes. There is considerable uncertainty surrounding the distribution and movement, and thus current stock delineation, of Canada's High Arctic Walrus population. Data on Ringed Seal habitat use in the North Water as well as Bearded Seal, life history, movement, and foraging ecology (during all seasons) are also lacking.

The coastal fiord and floe edge environment around the North Water in winter and spring is especially important for Inuit hunting of marine mammals. These protected regions can provide sanctuary for many species and are crucial feeding sites for Walrus, Polar Bears, Beluga, Narwhal, and Bowhead Whales (Heide-Jørgensen et al. 2013). High densities of ice seals are often correlated with productive annual ice over the continental shelf (< 300 m), ice edge features, or polynyas (Stirling 1997). The shelf and fiords of the North Water region are known to be important for Greenland Halibut (DFO 2020) and the slope between 400–600 m are important for adult (age-1+) Arctic Cod (Bouchard et al. 2018). There is a general lack of knowledge of marine mammal use of coastal fiord systems and inlets in the North Water, however, Murchison Sound, Wolstenholme Fjord, and the entrance to Inglefield Bredning and Jones Sound have been highlighted as important coastal areas for many marine mammals year-round (Christensen et al. 2017). Current data gaps and uncertainties are largely due to the high costs and logistical challenges of monitoring populations in large remote areas like the North Water. In many locations in the Canadian Arctic, local harvest data, and Indigenous knowledge of fishes and marine mammals represent the longest ecological records (Niemi et al. 2019), and coastal communities may be most equipped to observe marine mammals on a seasonal and annual basis. For example, Polar Bear traditional ecological knowledge surveys have been conducted extensively in West Greenland through interviews of over 60 hunters in all municipalities (Born et al. 2011), and continue to be a valuable independent resource to researchers, as well as management and decision makers.

Changes and variability in sea ice conditions (i.e., reductions in sea ice, loss of the perennial ice cover) are having impacts on habitat availability, diet, competition and predation, and causing shifts in migrations and distributions of endemic Arctic species, primarily in the eastern Canadian Arctic. The impacts of climate change and sea ice retreat on the distribution, population size, and biology of Arctic marine mammals are not totally known, and the health/sustainability of these species will likely vary by region and population. Belugas have strong site fidelity (typically small core summer and winter habitat) and low population growth rates, making them potentially vulnerable to changes in the system (Laidre et al. 2008). Physiological specializations for prolonged diving and navigating ice habitat may also make them more sensitive to climate change (Choy et al. 2019). Residents of Grise Fiord indicated that there had been fewer Belugas in Jones Sound than in the past, particularly during summer (Nunavut 2012). However in the summer of 2019, residents saw an increase in the number of Belugas near the community (L. Audlaluk, Hamlet of Grise Fiord, pers. comm.), suggesting high variability in seasonal habitat use. Data collected from Narwhal wintering grounds south of the North Water, showed a decreasing trend in the availability of open water and increased annual variability in sea ice cover (Laidre and Heide-Jørgensen 2005). Similar to Beluga, high site fidelity can make Narwhal more susceptible to ice entrapment (Laidre and Heide-Jørgensen 2005, Laidre et al. 2008). If the availability of open water decreases in the winter (perhaps due to changes in the formation and duration of the polynya), entrapments may become more common in the North Water.

The shift to a more seasonal ice cover in this region will impact ice associated species (e.g., Polar Bears, Walrus, Ringed Seals, and Hooded Seals) that rely on a stable and consistent multiyear ice platform for resting, feeding, and birthing/whelping. In West Greenland, Walruses have not been using terrestrial haul-outs for the last 50 years, however in 2018, the first sign of a terrestrial walrus haul-out was found near the Thule Air Base/ Pituffik (Yurkowski et al. 2019). This occurrence requires further study, as it may be a response to the sea ice becoming thinner in this region and providing Walrus with less opportunities to find suitable haul-outs. Walrus health and distribution appears to be impacted by changing climatic conditions and climate-induced loss of sea ice across the Arctic (Fischbach et al. 2009, Born et al. 2017). However, Laidre et al. (2008) ranked Walrus as moderately sensitive to change as they are sensitive to sea ice changes, but adaptable to trophic web changes. Walrus are, however, very sensitive to human disturbance (DFO 2019b), and may be highly vulnerable to any reductions in sea ice which provide more opportunities for shipping in the region.

Being highly specialized Arctic predators, Polar Bears are particularly sensitive to sea ice and trophic web changes, and have been categorized as the second most sensitive Arctic marine mammal species to a changing habitat (Laidre et al. 2008). Critical habitat loss, caused by long-term reductions in sea ice (including earlier break-up and later freeze-up), will likely reduce prey availability causing declines in body condition and a shifting Polar Bear demography. Polar Bears also have low reproductive rates and long generations, making facultative adaptations to the rapid changes in sea-ice habitat unlikely. As such, the population status of Polar Bears in areas of the North Water will be dependent on the availability of sea ice habitat. Stern and Laidre (2016) documented long-term declines in the number of ice covered days in KB, BB, and LS with decreases of -14.1, -12.7 and -10.6 days per decade respectively, from 1979–2014. Hamilton et al. (2014) projected a loss of sea-ice habitat (ice concentration, thickness and snow depth) important for Polar Bears in the Canadian Arctic Archipelago, including the KB subpopulation. It is expected that Lancaster Sound will shift primarily from multi-year to annual ice, and much of this subpopulations range outside of Jones Sound will experience critical habitat loss by 2050. Kane Basin is largely an annual ice-covered region and this is not expected to change by 2100; however, there is expected to be a 2–4 month ice-free season by 2100 and < 100% sea ice coverage in 2080–2090 (Hamilton et al. 2014). Starvation of 2–3% of adult male bears can occur at 120 days ice-free and 9–21% at 180 days (Hamilton et al. 2014). In addition, a decline in Polar Bear prey (i.e., ice associated seal species) quality and availability may increase their reliance on terrestrial habitats in the North Water, resulting in greater foraging by bears at seabird colonies and eventual reductions in body condition. Earlier breakup dates are projected to increase the rates of reproductive failure and may cause much of Baffin Bay to become unsuitable by 2050 (Hamilton et al. 2014).

These far-reaching ecosystem changes and environmental stressors may also cause shifts in diets for other important species in the North Water. Specifically, adjustments to local food web changes, such as changes in prey availability and a temporal shift in forage species (e.g., Capelin, Sand Lance), have been observed in Hudson Bay (e.g., Kelley et al. 2010, Yurkowski et al. 2017), the Beaufort Sea (e.g., Loseto et al. 2018, Choy et al. 2020), and Cumberland Sound (e.g., Marcoux et al. 2012). Shifts in diet may come with other direct or indirect negative effects, such as contaminant accumulation (McKinney et al. 2012) and/or a change in the quality and quantity of nutrients (Leu et al. 2011, Marcoux et al. 2012), which can lead a decline in body condition (Choy et al. 2017). In addition, specialized feeders, such as Bowhead Whales that depend on endemic Arctic copepods in the North Water region, may be more vulnerable to climate change and shifts in prey species abundance and distribution (Pomerleau et al. 2012). Bowhead Whales may be flexible to sea-ice changes, however their population growth rates are low and generation lengths are long, presenting uncertainties as to how the species will respond to increasing environmental change and human activities in the Arctic (COSEWIC 2009). They also undertake annual long-distance migrations following specific routes, increasing their potential sensitivity to anthropogenic change (Laidre et al. 2008).

As prey species of marine mammals shift northwards due to warming ocean temperatures, the diversity of mammals in the North Water could also increase (Hansen et al. 2018). For example, large numbers of Pilot Whales (*Globicephala melas*), White-beaked Dolphins (*Lagenorhynchus albirostris*), and Harbour Porpoises (*Phocoena phocoena*) have been observed in Inglefield Bredning (Teilman and Dietz 1998) and coastal Greenland from Disko Bay to the southern shore (Hansen and Heide-Jørgensen 2013). Although only Pilot Whales have been observed north of this region (as far north as Upernavik to the southeast of the North Water), all three species prefer highly productive inshore and offshore areas with abundant pelagic and demersal fish. Sperm Whales have also been observed as far as Eclipse Sound, Nunavut, in recent years (S. Ferguson, DFO Winnipeg, pers. comm.). In other eastern Arctic regions, sea ice reductions have increased the temporal access for southern predators such as Killer Whales. Although documentation of Killer Whale presence in the North Water is currently limited, a northward expansion is possible, and could lead to greater predation pressures on other large Arctic mammals, such as Narwhal, Beluga and seals.

## 3.5. BIRDS

Each year, millions of seabirds migrate to areas surrounding the North Water to breed and feed in the open waters of the polynya (Figure 35). Seasonally important areas for seabirds are highlighted in Figure 40-Figure 43 and appendix 5 lists species that have been reported using habitat in or near the North Water study area. Distribution and habitat use maps for many of the species found in the North Water region are also been provided in Appendix 5. Martec Ltd. (1982) also provides habitat use maps of several bird species which use the North Water.

The North Water region represents vital breeding and nesting habitat for important seabirds, such as the Ivory Gull, Dovekie, and Thick-billed Murre, Black-legged Kittiwakes, and Common Eiders. In terms of conservation, the most important bird species found in the North Water EBSA (Canada) is the endangered Ivory Gull. The Dovekie (also known as Little Auks) is the most abundant seabird in the North Water, supporting an estimated 80% of the world's population (Boertmann and Mosbech 1998). The Thick-billed Murre also breeds in large colonies around the North Water, despite decreasing numbers in other areas of Greenland. Black-legged Kittiwakes and Common Eiders (*Somateria mollissima*), both breed along the east coast of Ellesmere Island, and Common Eiders are found on the northwestern coast of Greenland (Martec Ltd. 1982, CAFF 1997). Radiocarbon dating of sediment suggests that the Common Eider has nested in this area for the last 5,500 years (Davidson et al. 2018).

We discuss the most abundant seabirds in the North Water region in the sections below, and describe climate impacts and vulnerable species in the summary section at the end; highlighting knowledge gaps and data uncertainties. Seabirds have been an important food source for indigenous people living near the North Water for millennia. Historically, the arrival of seabirds to the North Water in spring, at a time when few resources were available, often prevented starvation (Ekblaw 1919). Of the seabirds using the North Water and adjacent waterbodies, the Dovekie, Thick-billed Murre, Black Guillemot, eiders, Glaucous Gull, Ivory Gull, Black-legged Kittiwake, Common Eider, Northern Fulmar, and the Long-tailed Duck have been historically harvested (Ekblaw 1919, Davidson et al. 2018, Mosbech et al. 2018). Specifically for the people of Nunavut, the west side of the North Water and surrounding areas of Ellesmere Island, have been identified as key marine and terrestrial habitat sites for birds (Beckett et al. 2008).

### 3.5.1. General Seabird Distribution and Diet

On the Canadian side of the North Water, along the southeast coast of Ellesmere Island, breeding populations of Northern Fulmar, Glaucous Gull, Arctic Tern (*Sterna paradisaea*), Thayer's Gull (*Larus thayeri*), Black-legged Kittiwake, and Sabine's Gull (*Xema sabini*) have been documented (Figure 35); however, the relative abundance of these species is not known (Brown et al. 1975, Blomqvist and Elander 1981, Gerson and Gerson 1986). An estimated 6,000 Black Guillemots nest on the coast of Ellesmere Island (Gaston et al. 2012), and an observed increase in colonies on the Greenland coast north of Savissivik (Pikialasorsuaq Commission 2017). Seventeen seabird, ten shorebird, and seven waterfowl species were recorded from the Thule district in northwest Greenland by Vaughan (1988) in the early 1980s, with several of these species having established breeding colonies. Currently, there are 14 seabird species regularly breeding in the North Water region (Mosbech et al. 2019).

Boertmann et al. (1996) reported 77 seabird colonies in northwest Greenland, but also speculated there were many more unrecorded. These colonies are largely made up of

Dovekies, Thick-billed Murre (*Uria lomvia*) and Common Eider; however, the area supports an additional 5,000 breeding Northern Fulmars, 65 pairs of Sabine's Gull, 600 pairs of Glaucous Gull, 20 individual Razorbill (*Alca torda*), 5,500 individual Black Guillemot, and an unknown number of Thayer's Gulls (Boertmann et al. 1996). Kampp (1990) reported 14,000 breeding pairs of Black-legged Kittiwakes in northwest Greenland in 1987. More recent surveys (2007) suggest the population is much larger, reporting 35,666 occupied nests in the same area (Figure 36) (Labansen et al. 2010, Christensen et al. 2017).

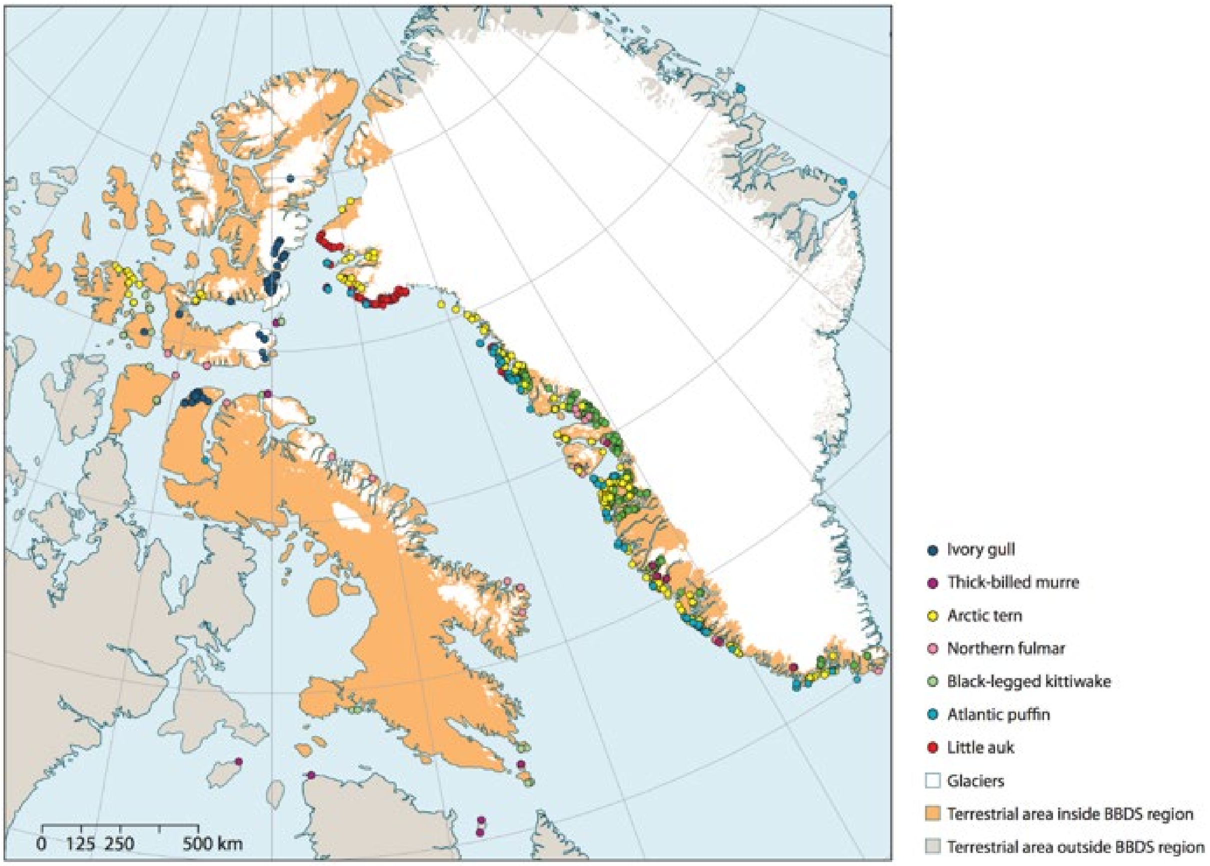

*Figure 35. Distribution of breeding colonies of key bird species in the Baffin Bay-Davis Strait (BBDS) and North Water region. Note the high density of Little Auk (Dovekie) colonies along the northwest Greenland coast adjacent to the area of the North Water (Data from the Greenland Seabird Colony Register and Seabirds.net: Circumpolar Seabird Data Portal) (Source: AMAP 2018).*

Coburg Island, Nunavut, is a particularly important nesting site for birds and as such, has been identified as a separate EBSA by DFO (DFO 2011). Coburg Island is one of the few known breeding sites for Atlantic Puffins in the Arctic, with a colony estimated at 14 pairs (Robards et al. 2000). The Atlantic Puffin has also been reported breeding in northwestern Greenland, with an estimated 200 individuals (Brown et al. 1975, Boertmann et al. 1996). In particular, a colony of 110 individuals has been documented on the Carey Islands (Burnham and Burnham 2010). In addition, approximately 30,000 pairs of Black-legged Kittiwakes, representing 16% of the Canadian population, nest at Cambridge Point on Coburg Island (Figure 36) (Nettleship 1980).This is an increase from a 1973 survey which estimated the population at 1,000+ birds (Gaston et al. 2012). In 1971, it was estimated that 3,000 pairs of Northern Fulmars bred on the Island; however, 1998 estimates ranged between 250 and 300 breeding pairs (Gaston et al.

2006). The Island supports an additional 175 pairs of Black Guillemots, and 60–80 pairs of Glaucous Gulls (Robards et al. 2000).

The east coast of Ellesmere Island also supports breeding populations of shorebirds including, Red Knot (*Calidris canutus*), Red Phalarope (*Phalaropus fulicarius*), and Ruddy Turnstone (*Arenaria interpres*) (Brown et al. 1975, Robards et al. 2000, Davidson and Piersma 2009, Oceans North Conservation Society et al. 2018). The Red-throated Loon (*Gavia stellata*) nests inland on Ellesmere Island but uses its coasts to feed and support its young (Barr et al. 2000, Oceans North Conservation Society et al. 2018). Snow geese (*Chen caerulescens*) and Brant (*Branta bernicla*) have been documented in the North Water, and the Brant is known to breed along Ellesmere Island and Greenland coasts (Oceans North Conservation Society et al. 2018). Parasitic Jaeger (*Stercorarius parasiticus*) are known to breed on Ellesmere and Coburg Islands and, although these birds remain inland during breeding, they are dependent on polynya habitat during spring migration (Martec Ltd. 1982, Wiley and Lee 1999). Not all species of bird that use the North Water breed in the area. Long-tailed ducks (*Clangula hyemalis*) congregate along the coast of Ellesmere Island and within bays at the south end of Coburg Island, arriving in late June (Martec Ltd. 1982, Robards et al. 2000). Other, largely terrestrial, species have been observed in the North Water, including the Gyrfalcon (*Falco rusticolus*) (Robards et al. 2000, France and Sharp 1992).

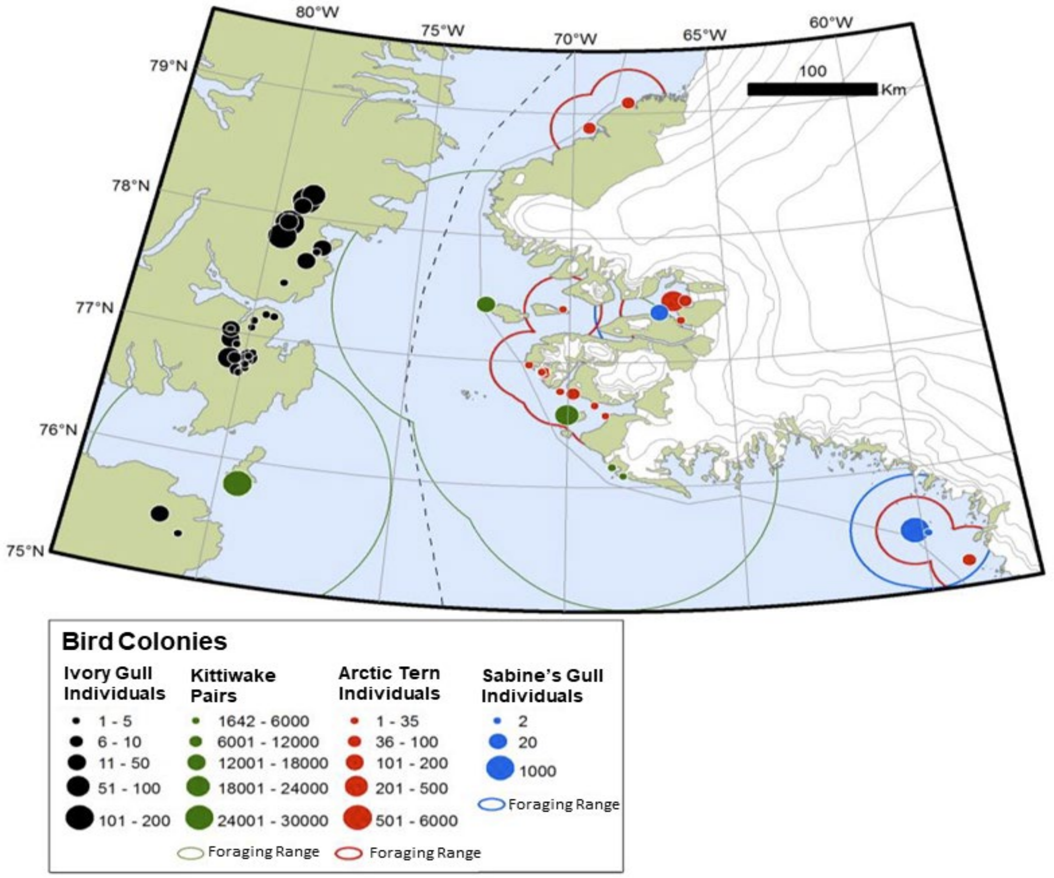

*Figure 36. Breeding colonies and foraging ranges for Kittiwake (green), Arctic Tern (red), Sabine's Gull (blue) and Ivory Gull (black) – foraging range for Ivory Gull is very large and not shown on map (Source: Christensen et al. 2017).*

Additional breeding colonies of seabirds occupy areas surrounding the North Water, but feed within its boundaries. Residents of Grise Fiord have identified eiders, nesting along the coastlines of Jones Sound, and Black-legged Kittiwake, Atlantic Puffins (*Fratercula arctica*), and Northern Fulmar on Coburg Island (Government of Nunavut 2012, Christensen et al. 2017). Eiders, kittiwakes, guillemots, murres, gulls, and Dovekies have also been reported from the coast and at the ice edge of northeastern Baffin Island with some species nesting on nearby cliffs (Government of Nunavut 2018, QIA 2018). The majority of seabirds are present in the North Water during the spring and summer months, with the exception of Black Guillemots, some of which overwinter in the area (Vaughan 1988, Butler and Buckley 2002, Davidson et al. 2018). Renaud and Bradstreet (1980) estimated this overwintering population at 3,900 individuals during aerial surveys conducted in 1978 and 1979. The highest densities of these birds were recorded along the edges of landfast ice where open water is most consistently available (Renaud and Bradstreet 1980).

Invertebrates such as mysids, copepods, and amphipods make up a large percentage of the diets of adult seabirds using the North Water, and these birds often occupy a lower trophic level than elsewhere in the Arctic (Hobson et al. 2002b). However, seabird feeding habits in the North Water are often seasonal and shift with prey availability (Karnovsky et al. 2008). Karnovsky and Hunt (2002) estimated that a total of 100,000 Northern Fulmar, 50,000 Glaucous Gull, 60,000 Black-legged Kittiwake, 2,000 Ivory Gull, 3–6,000,000 Dovekies, 1,000,000 Thick-billed Murre, and 100,000 Black Guillemot feed within the North Water. Black Guillemot eat Arctic Cod early in the breeding season and other fish later in the year (Gerson and Gerson 1986). Northern Fulmar eat a wide variety of invertebrates and feed Arctic Cod to their young (Gerson and Gerson 1986). Hobson et al. (2002b) studied the differences in diet of seabirds nesting on the west and the east sides of the North Water. They found that chicks of seabirds on the east side generally occupied lower trophic positions than their conspecifics on the west, possibly due to the lower availability of Arctic Cod (Hobson et al. 2002b). Atlantic Puffin chicks on Coburg Island have been observed feeding on fish, including Sand Lance (*Ammodytes* sp.) and juvenile Capelin (Robards et al. 2000).

There has been a temporal shift in seabird trophic level positions in recent years, coinciding with observed changes to primary production in the North Water. An isotopic trophic level study of several seabird species feeding in the North Water conducted in 2013–2015 (Eulaers et al. 2019) showed a steady decline in trophic position when compared with similar data from 1998 (Hobson et al. 2002b) such that all sampled species, except Northern Fulmar and Glaucous Gull, currently feed an entire trophic position lower than they did in 1998. Eulaers et al. (2019) suggested that the apparent increased dietary specialization and lower trophic level foraging indicated by their findings may provide evidence of decreasing species diversity and carrying capacity in the North Water associated with decreased primary production and potential Atlantification of the Arctic.

### 3.5.2. Ivory Gull (*Pagophila eburnea*)

Ivory Gulls nest in close proximity to areas of ocean that are partially free of ice in late May and early June, where they feed on small fish and invertebrates near the surface around edges of ice flows or marine terminating glacier outlets (Divoky 1976, Mallory et al. 2008, NOAA 2019). Because of this habitat requirement, best known nesting locations for the species are associated with polynyas (COSEWIC 2006). Within Canada, Ivory Gulls are known to nest in only five locations: Ellesmere Island, Devon Island, Cornwallis Island, Seymour Island, and the Brodeur Peninsula of northern Baffin Island (Figure 37) (Gilchrist et al. 2008, Environment Canada 2014). Breeding colonies form in May on southeast Ellesmere Island, within 50–90 km of the North Water, and on Devon Island, within 30–50 km (COSEWIC 2006). Renaud and

McLaren (1982) conducted surveys of breeding colonies on Ellesmere Island in 1978 and estimated densities of 0.5–1.5 birds/km$^2$. Other surveys of the Island conducted prior to 1985 documented colonies of 20–287 individuals (Thomas and MacDonald 1987, Gilchrist and Mallory 2005). However, the same colonies were made up of between zero and ten individuals in 2002 and 2003 (Gilchrist and Mallory 2005). Surveys conducted between 2002 and 2003 discovered some new, small colonies on Ellesmere Island, each containing fewer than 20 individuals; however, there was a significant overall decline in the number of Ivory Gulls in the region over an approximately 20-year period (Gilchrist and Mallory 2005). A few new colonies have been discovered on Ellesmere Island more recently that may represent significant contributions to the overall population. In 2004, a new site with between 92 and 131 gulls was documented (Robertson et al. 2007). In 2006, an additional seven new colonies were found, accounting for 697 Ivory Gulls, or 83% of the total number of birds observed that year (Robertson et al. 2007). This was the largest number of Ivory Gulls in any count since 2002 (Robertson et al. 2007). The 2009 population estimate of Makinson Inlet, Ellesmere Island, was approximately 700 birds (Environment Canada 2014).

Despite the apparent recovery of breeding colonies on Ellesmere Island, populations on Devon Island continue to decline. Aerial surveys conducted between 1976 and 1979 recorded significant concentrations of the Ivory Gull at glacial fronts along the coast (Renaud and McLaren 1982). Offshore densities ranged from 0.0 to 0.14 birds/km$^2$, peaking later (late September through mid October) during fall (Renaud and McLaren 1982). Inland surveys conducted in 1982 discovered four colonies of Ivory Gulls on Devon Island, comprising an estimated 91 birds, although breeding was not confirmed (Frisch 1983). Surveys in the 2000s of the Devon Island colonies yielded only six gulls in 2002, none in 2003 or 2004, five in 2005, and one in 2006 (Gilchrist and Mallory 2005, Robertson et al. 2007). Population viability analyses suggest that colonies on Devon Island are not expected to persist if current conditions continue (Robertson et al. 2007). More recent surveys suggest they are now absent on Baffin and Devon Islands (G. Gilchrist, ECCC, pers. comm.)

At-sea surveys have also documented a decrease in the number of Ivory Gulls in northern Canada. Ivory Gulls were observed within the North Water and surrounding areas in surveys conducted in 1993; however, none were observed in 2002 (Chardine et al. 2004). Further observations from residents of Grise Fiord indicate that the number of Ivory Gulls has decreased over the last 25 years (Mallory et al. 2003). As a result of declining populations throughout its range, the Ivory Gull was listed as “Endangered” in Canada in 2006 (COSEWIC 2006) and the global population was designated as “Near Threatened” by the IUCN in 2005 (BirdLife International 2018).

The decline of the species highlights the importance of the North Water. As of 2009, the range of Ivory Gulls had contracted northward, such that almost all of the extant colonies were located on eastern Ellesmere Island, adjacent to the North Water (Environment Canada 2014). Given the observed rate of decline in other locations, this may be the only site where Ivory Gulls continue to breed in the future (Robertson et al. 2007). Ivory Gulls require ice edges to access food sources, which the North Water provides (Karnovsky et al. 2009). Ivory Gulls largely feed on cod (mostly larvae and juveniles) and invertebrates, but are opportunists and have been documented consuming other fish species and small mammals (Karnovsky et al. 2009). Ivory Gulls are also known scavengers and are often associated with kills of whales and seals (Renaud and McLaren 1982, Chardine et al. 2004). Ivory Gulls generally arrive at the North Water in May and use the open water for feeding during the breeding season (Karnovsky et al. 2009). The North Water may also act as an important food source for Ivory Gulls that do not nest in the immediate area. Spencer et al. (2014) tracked an Ivory Gull to the North Water, likely for foraging, during its pre-breeding migration to the Seymour Island colony (approximately 600 km away). In August and September, fledglings leave the nests on Ellesmere Island, leading to an increased number of gulls within the North Water and along its borders (Renaud and McLaren 1982, Karnovsky et al. 2009). These gulls move out of the North Water in October to wintering areas between Greenland and Newfoundland/Labrador (Renaud and McLaren 1982, Karnovsky et al. 2009, Environment Canada 2014).

Although the causes of Ivory Gull declines are unknown, possible threats include hunting, disturbance at some breeding locations, and climate change (COSEWIC 2006). Stenhouse et al. (2004) found that Ivory Gulls have a relatively low adult survival rate compared with other species of gull. They may also experience high post-fledgling mortality (Mallory et al. 2008). As a scavenger, Ivory Gulls may be particularly susceptible to contaminants in the food chain; see section on environmental stressors (COSEWIC 2006, Braune et al. 2006, Mallory et al. 2015). A recovery strategy for the Ivory Gull was prepared by Environment Canada, with the goal of maintaining the population numbers on eastern Ellesmere Island at 2009 levels, approximately 700 birds, over a five-year average (Environment Canada 2014).

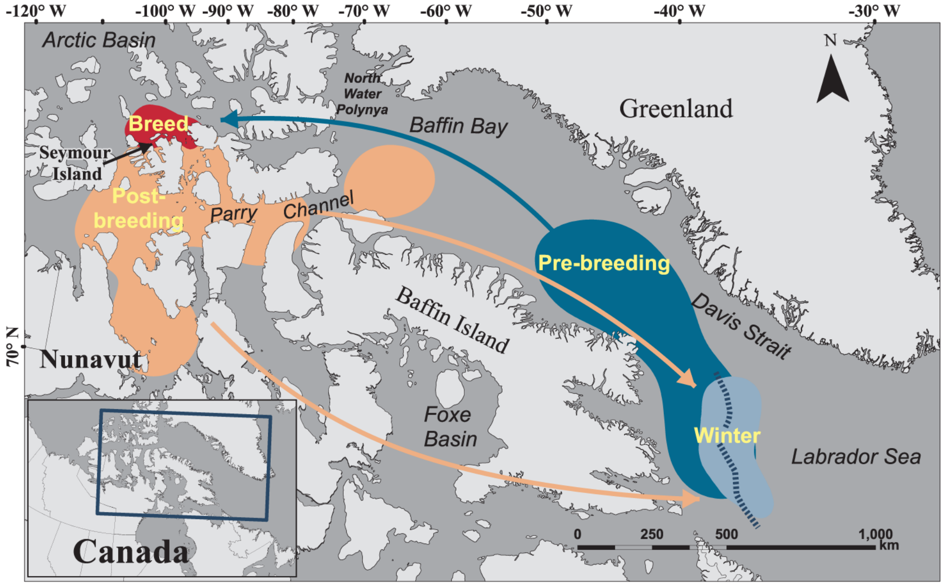

*Figure 37. Annual distribution of the Canadian Ivory Gull (Source: Spencer et al. 2014).*

### 3.5.3. Dovekie/Little Auk *(Alle alle)*

Radiocarbon dating of sediment along Greenland's northwest coast suggests that the Dovekie has nested in this area for the last 4,400 years (Davidson et al. 2018). The Dovekie nests in crevices on scree slopes, rubble at the foot of cliffs of coastal mountains, on the sides of fiords, and on rocky outcrops surrounded by glaciers (Montevecchi and Stenhouse 2002).

The Dovekie arrives at the North Water in May in large numbers, exceeding 1,700 birds km$^2$ on the eastern side of the North Water (Karnovsky and Hunt 2002). Dovekie numbers are highest on the Greenland side of the North Water; the breeding population of the Dovekie in the Thule District in northwest Greenland is the largest known population of the species, representing an estimated 80% of the world population (Nettleship and Evans 1985, Boertmann and Mosbech 1998). In 1958, the population was estimated at 30 million birds and subsequent estimates have ranged between 20 and 33 million breeding pairs (Boertmann and Mosbech 1998, Egevang et al. 2003).These birds all breed within a range of 325 km along the coast (Figure 38) (Møller et al. 2019) and are common in coastal areas new Qaanaaq (Pikialasorsuaq Commission 2017). Mosbech et al. (2017a) estimated the density of active nests in northwest Greenland at between

1.06 and 1.63 per m$^2$ in 2012 and 2013. The density of breeding Dovekies on Hykluyt Island within the North Water was estimated at 1.8 birds per m$^2$ in 1996/1997 (Kampp et al. 2000). The North Water is such an important Dovekie breeding area largely due to chick feeding opportunities, as it provides suitable prey throughout the entire breeding season (Møller et al. 2018). Although they use the full extent of the North Water for feeding, the Dovekie is not known to breed on the Canadian side of the polynya (Finley and Evans 1984). Given their importance to the ecosystem, Mosbech et al. (2019) recommends using Dovekies as an indicator species, along with murres, for monitoring future changes in the North Water.

The Dovekie's energy demands account for 92–96% of all seabirds feeding in the North Water (Karnovsky and Hunt 2002). Karnovsky et al. (2008) found that the diet of the Dovekie is highly seasonal, feeding at the lowest trophic level in the spring and at a higher level in the fall. Their diet is composed largely of female *Calanus* copepods in May and June, smaller stages of *Calanus* copepods and amphipods in July, and amphipods and juvenile Arctic Cod in August and September (Pedersen and Falk 2001, Karnovsky and Hunt 2002, Montevecchi and Stenhouse 2002). Chicks feed largely on *Calanus* copepods and amphipods, but are also fed decapods and small fish (Evans 1981, Roby et al. 1981, Bradstreet and Brown 1985). The Dovekie uses different parts of the North Water seasonally, generally feeding near nesting areas early in the year, but using the entirety of the North Water during the chick-rearing period when energy demands are highest (Karnovsky and Hunt 2002). It is this combination of suitable nesting sites and an abundance of adequate *Calanus* prey during the chick-rearing period that makes northern Baffin Bay such an important breeding area for Dovekies (Møller et al. 2018, 2019). In 2010, chick diets from the south-eastern margin of the North Water contained the highest proportion of lipid-rich *Calanus hyperboreus* for any Dovekie colony ever reported (Frandsen et al. 2014). Sea ice may also play a role in the distribution of the Dovekie in the North Water, as the presence of sea ice along coastal areas may force the birds to feed further offshore (Heide-Jørgensen et al. 2013). Mosbech et al. (2019) suggest that Dovekies are adaptable to seasonally and annually variable zooplankton abundance and distribution and sea-ice conditions, but the northward expansion of zooplanktivores, such as the Capelin, may pose the largest potential future threat to North Water colonies.

Tagging studies have shown that the Dovekie alternates between short (2 hours, ~ 9 km) and long (13 hours, ~ 65 km) foraging trips to the North Water (Mosbech et al. 2016). During breeding season, the Dovekie averages 9.1 feedings per chick per day (Mosbech et al. 2017a). It is likely that the short trips serve to maintain the high feeding rates of chicks, and the longer foraging trips to more productive feeding grounds serve to replenish adult energy reserves (Mosbech et al. 2017b). The Dovekie has been referred to as an "ecosystem engineer", transporting vast amounts (> 3,500 tonnes per year) of nutrients from sea to land, transforming coastal areas into lush vegetated habitat used by terrestrial grazers (González-Bergonzoni et al. 2017, Mosbech et al. 2018, 2019). Unlike other shorebirds, Dovekie colonies extend up to 11 km inland, and thus they fertilize (through their droppings) a large area of terrestrial and freshwater habitat (Mosbech et al. 2018). Mosbech et al. (2018) estimated that the Dovekie transports 3,645 tonnes of nitrogen per year from the sea to the land (Mosbech et al. 2018).

The Dovekie is an important source of food and has been harvested by indigenous people in northwestern Greenland for millennia (Boertmann and Mosbech 1998, Dietz et al. 2018, Mosbech et al. 2018). Dietz and Heide-Jørgensen (in Boertmann and Mosbech 1998) estimated the total catch in the Thule District in 1984 to be in the range between 250,000 and 500,000 birds. Between 1993 and 2013, hunters in northwest Greenland adjacent to the North Water reported harvests of approximately 22,599 Dovekie (Dietz et al. 2018). The harvest also has important cultural significance, especially in Savissivik, where the Dovekie's arrival marks the beginning of new community hunting activities and a different social rhythm (Mosbech et al.

2018). Currently, there are no limits or regulations for the harvest of the Dovekie in northwest Greenland; however, the season is limited to the period when birds are present, between May and August (Boertmann and Mosbech 1998).

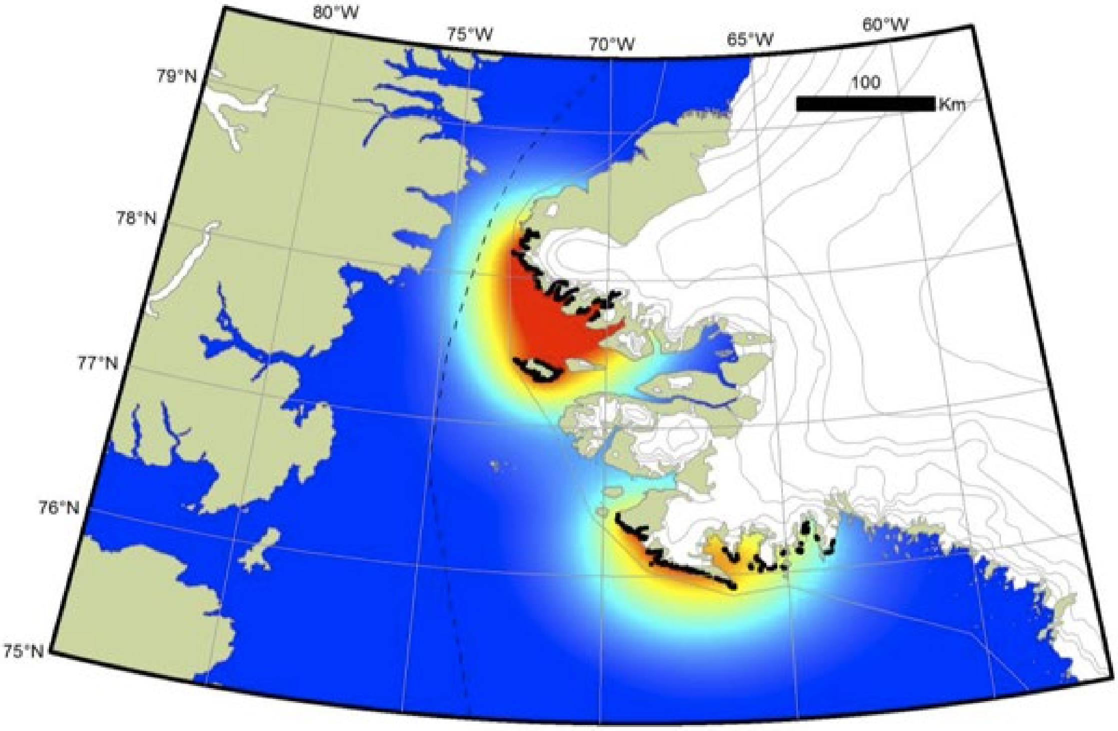

*Figure 38. Dovekie/Little Auk colonies (black dots) in the North Water region and west coast of Greenland. The colour gradients in the marine areas indicate a theoretical, relative density (red-high, blue- low) of birds on the sea, calculated by distributing the number of breeding birds from the individual colonies within a foraging radius of 105 km (as identified by GPS tracking of breeding birds from the North Water) (Source: Christensen et al. 2017).*

### 3.5.4. Thick-billed Murre *(Uria lomvia)*

Radiocarbon dates show that the Thick-billed Murre have been present in the area of the North Water for at least 5,500 years (Davidson et al. 2018). Thick-billed Murres breed on cliff ledges, from about 5 m asl (above sea level) to the top of cliffs (Birkhead and Nettleship 1981, Gaston and Hipfner 2000). The North Water is considered a globally important breeding area for the species (Mosbech et al. 2019). Currently, over 350,000 pairs of Thick-billed Murre nest in colonies around the margins of the North Water and an additional > 250,000 pairs nest in nearby Lancaster Sound (Figure 39) (Gaston and Hipfner 2000, Falk et al. 2001). In Canada, Coburg Island supports 160,000 pairs (Figure 39), or about 12% of the Canadian population (Gaston 1980, Nettleship 1980). In 1973, the population estimate in this area was 200,000 pairs (Gaston et al. 2012). The Thick-billed Murre colonies along the Greenland coast of the North Water (Figure 39) were estimated at 214,000 breeding pairs in 1987, approximately 50% of the Greenland Murre population (Kampp 1990). Between 2006 and 2011, the breeding population was estimated at 308,000 birds (or around 216,000 pairs), totaling 68% of the Greenland population (Merkel et al. 2014).

Thick-billed Murres forage in the North Water, feeding largely on amphipods (especially *Themisto libellula*) and some copepods and Arctic Cod (Gerson and Gerson 1986, Gaston and Bradstreet 1993). Murres largely feed Arctic Cod to their young (Birkhead and Nettleship 1981, Gerson and Gerson 1986, Hobson et al. 2002b), as smaller prey are energetically unsuitable for successfully raising chicks (Mosbech et al. 2019). Murres are highly specialized for deep diving (Gaston 2004), so they likely feed at a different trophic level than other seabirds. Breeding murres from the Canadian side (Coburg Island) and Greenland side (Hakluyt Island) of the North Water were found to forage in different areas. Birds from Coburg Island took longer trips, foraged at shallower depths and focused feeding effort at a different time of day than birds from Hakluyt Island, which suggests that foraging conditions differ on each side of the North Water (Falk et al. 2002). Chicks from Coburg Island were also found to feed at a higher trophic level, eating more Arctic Cod, than chicks from Hakluyt Island, which fed more frequently on sculpin (Hobson et al. 2002b). The North Water is also an important feeding area for post-fledgling murres, who stage in the polynya before migrating to wintering areas (Falk et al. 2001). Adult female murres may migrate south earlier than males who accompany flightless chicks to wintering areas (Frederiksen et al. 2016).

Although harvested in small numbers, the Thick-billed Murres remain a food source for local people. Between 1993 and 2013, hunters in northwest Greenland adjacent to the North Water harvested approximately 1,200 Thick-billed Murres (Dietz et al. 2018). Numbers in west Greenland were decreasing in the 1970s and 1980s, largely due to hunting and bycatch (Falk and Durinck 1991, Gaston and Elliot 1991, Kampp et al. 1994). However, the bycatch slowed in the late 1980’s (Falk and Durinck 1991) and the *Game Act* came into effect in 1988 prohibiting hunting at most colonies from June through August (Gaston and Elliot 1991). As the most numerous seabird breeding in eastern Canada, the status of the Thick-billed Murre is a good indicator of the health of seabird populations in general (Gaston 1980). Thick-billed Murre populations are sensitive to human activities including gillnetting (as incidental captures), hunting, and pollution, especially oil spills (Gerson and Gerson 1986).

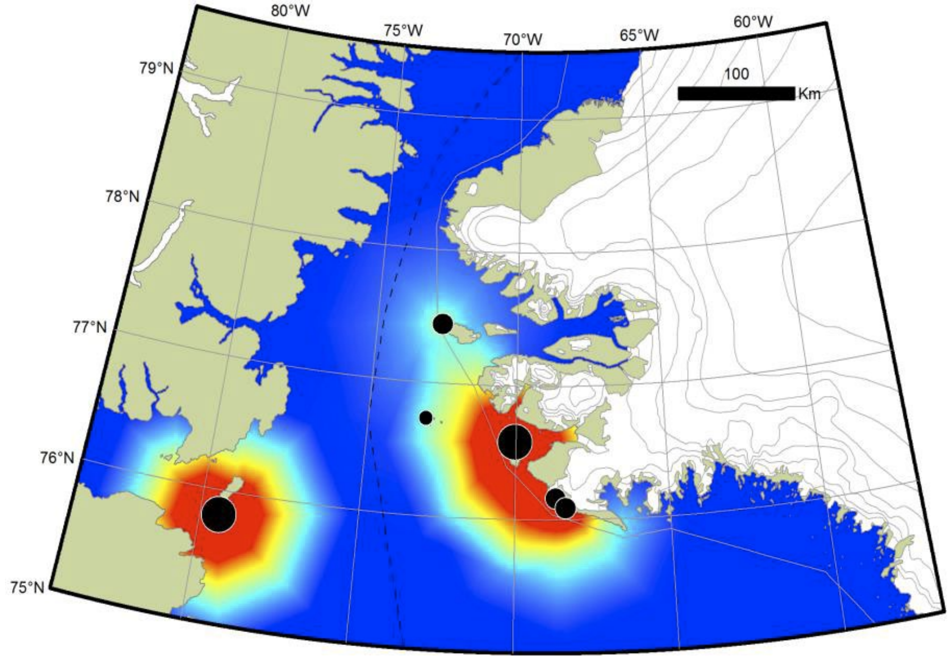

*Figure 39. Thick-billed Murre colonies (black dots) in the North Water region. The colour gradients in the marine areas indicate a theoretical, relative density (red-high, blue-low) of birds on the sea, calculated by distributing the number of breeding birds from the individual colonies within a foraging radius of 114 km (as identified by GPS tracking of breeding birds from the North Water) (Source: Christensen et al. 2017).*

### 3.5.5. Black-legged Kittiwake (*Rissa tridactyla*)

Black-legged Kittiwakes have a circumpolar distribution, but maintain large breeding colonies in the vicinity of the North Water, particularly on Coburg Island (~ 30,000 pairs; Brown et al. 1975, Nettleship 1980, Mallory and Fontaine 2004, Gaston et al. 2012) and in the Qaanaaq area (~ 35,000 pairs in 2007; Labansen et al. 2010). They nest on steep cliffs in coastal areas, though many non-breeders use offshore areas in summer (Boertmann and Mosbech 2017). Most of the major kittiwake colonies in the Arctic are co-located with Murre colonies (Mallory and Fontaine 2004). They leave their breeding areas in September-October and return when open water appears in the spring (Frederiksen et al. 2012).

Kittiwake feeding habitat requirements change throughout the year. Along the west coast of Greenland during the breeding season, they use both offshore areas (up to 75 km from the colony) and shallow bays, including glacial fronts (Frederiksen et al. 2017). Kittiwakes along the coast of Ellesmere and Devon Islands have been observed to be gather more densely along edges of glaciers than off the regular coastline (Mallory and Fontaine 2004); this habitat is likely important for foraging. Tidewater glacier bays have been identified as foraging hotspots for kittiwakes in other Arctic locations (Urbanski et al. 2017). At high latitudes, kittiwakes eat mainly Arctic Cod, copepods, pteropods and amphipods (Gerson and Gerson 1986, Reiertsen et al. 2014). Diet studies from the North Water are scarce, though one study, using birds sampled in the North Water in 1998 and 1999, identified *Themisto libellula* and Arctic Cod (*B. Saida*), as primary prey items in the spring and summer, and found that trophic level declined in the fall as the consumption of the pteropod, *Limacina limacine*, increased (Karnovsky et al. 2008). More recently, stable isotope analysis of muscle tissue from kittiwakes collected in 2013–2015 in the North Water showed that kittiwakes, along with several other seabird species, were feeding an entire trophic position lower than they did in 1998 (Eulaers et al. 2019).

Within Canada, the kittiwake breeding population is concentrated in two areas: the eastern Arctic, and Atlantic Canada. Recent estimates suggest there are approximately 100,000 breeding pairs within the eastern Canadian Arctic (Gaston et al. 2017) with the largest colonies located on Coburg Island (~ 30,000 pairs) (Brown et al. 1975, Nettleship 1980, Mallory and Fontaine 2004, Gaston et al. 2012). The Canadian Arctic population appears to have increased at a slow rate (~ 1% annually; Mallory et al. 2009, Gaston et al. 2012), though population trends in this region are difficult to estimate given the lack of historic information (Gaston et al. 2017). The largest colonies in Greenland are in the Qaanaaq area (~ 35,000 pairs in 2007; Labansen et al. 2010). Earlier estimates of ~ 14,000 breeding pairs in the area (Kampp 1990) are thought to be underestimated and number of breeding birds in Qaanaaq area is considered relatively stable (Merkel et al. 2007). In contrast, the breeding population further south has declined significantly, due to reductions in some colonies and the complete abandonment of others (Burnham et al. 2005, Boertmann 2006). For instance, by 2007, the number of breeding pairs in Upernavik, Uummannaq, and Disko Bay had decreased by 39%, 79% and 76%, respectively, compared to earlier surveys (Boertmann et al. 1996, Labansen et al. 2010), though it is unclear precisely when this occurred (Burnham et al. 2005, Boertmann 2006). These declines occurred despite recent observations of much higher breeding success at colonies in Upernavik than those near Qaanaaq (Frederiksen and Merkel 2017). Globally, the kittiwake population has seen a decline of 40% since 1975, with accelerated declines occurring since the 1990s (Descamps et al. 2017, CAFF 2020). These trends highlight the importance of the stable populations around the North Water for the preservation of the species. The Arctic Council working group Conservation of Arctic Flora and Fauna (CAFF) considers the kittiwake to be a species of conservation concern and an action plan has recently been developed by CAFF's Seabird Expert Group (CAFF 2020). The kittiwake is categorized as vulnerable (VU) on the Greenland Red List (Boertmann and Mosbech 2017).

Black-legged Kittiwakes are subject to hunting pressure in Greenland; adults, eggs, and chicks are harvested (Boertmann et al. 1996, Merkel and Barry 2008). This is a possible contributor to the population decline in Greenland (Labansen et al. 2010), though the direct linkage is not as clear as for other seabirds in Greenland (Nyeland 2004). Poor feeding conditions are believed to be another contributing factor (Labansen et al. 2010). Globally, trends in the kittiwake population have been linked to trends in spring sea-surface temperature (Descamps et al. 2017), likely due to associated ecosystem shifts and altered productivity. However, in Svalbard, where Arctic food resources have already begun to be replaced by Atlantic ones, kittiwakes have shown an ability to replace diet items (Vihtakari et al. 2018), suggesting they may have some resiliency to certain changes in the North Water as well. Fisheries, pollutants, predation, tourism, increased shipping, are also factors of concern throughout the Arctic (CAFF 2020).

### 3.5.6. Common and King Eiders (*Somateria mollissima* and *S. spectabilis*)

Both Common and King Eiders (*Somateria mollissima* and *S. spectabilis*), breed along the East coast of Ellesmere Island and within the North Water (Martec Ltd. 1982, CAFF 1997). Local hunters have noted large congregations of eiders within Princess Marie and Buchanan bays of Ellesmere Island (Brown and Fast 2012). Bays at the south end of Coburg Island are used by moulting Common Eiders, a few of which also breed in the area, arriving in early May (McLaren and McLaren 1982, Robards et al. 2000). Common Eiders also breed along the northwestern coast of Greenland (CAFF 1997), with several known colonies near Qaanaaq (Boertmann and Mosbech 2017). Common and King Eiders moult in the late-Summer/early-Autumn, often within 100km of the breeding site (Mosbech et al. 2006). Moulting areas are particularly sensitive as birds are unable to fly and are thus very vulnerable (Boertmann and Mosbech 2017) The breeding population in northwest Greenland overwinters in the coastal waters south of Disko Bay (Lyngs 2003, Mosbech et al. 2007) while breeders from Arctic Canada overwinter in Atlantic Canada or southwest Greenland (Mosbech et al. 2006).

Like most seabirds, Eiders are reliant on open water for feeding. They require relatively shallow feeding areas along coasts and skerries because they are benthic feeders, capable of diving to depths of ~ 10 m to target mussels, crustaceans, and polychaetes (Merkel et al. 2007). As such, the thriving benthic community in the North Water area is critical for the species. This specialization enables them to feed without competition from other seabirds within the North Water (Eulaers et al. 2019). Their habitat requirements mean most eider colonies form on small islands and skerries separated from the mainland, though breeding may shift to other islands if Arctic Foxes are left on the island when the ice disappears (A. Mosbech, Aarhus University, pers. comm.). As with other seabirds, longer periods of open water may initially benefit the species. For instance, in East Greenland, Common Eiders have expanded their breeding range northward by hundreds of kilometers as the open water period has increased (Boertmann and Nielsen 2010). However, in recent years Polar Bear predation has become more common in Arctic Eider colonies (Iverson et al. 2014), including those in the North Water (A. Mosbech, Aarhus University, pers. comm.) and this is expected to impact the population. Additionally, their reliance on benthic food sources makes them particularly vulnerable to oil spills if hydrocarbons become concentrated at the seafloor (Boertmann and Mosbech 2017).

Paleoecological evidence indicates Common Eiders have been in the North Water area for at least 5900 years (Davidson et al. 2018). Between 1960 and 2000, the breeding population of Common Eider in western Greenland was reduced by approximately 80% due largely to overharvesting (Merkel 2004). By 1998, the population of northwestern Greenland was estimated at 5,000 pairs (Christensen and Falk 2001). Harvest regulations were put in place in 2001, which significantly reduced the catch along the west coast of Greenland, from over 6000 birds/year to ~1,000 birds/year (Boertmann and Mosbech 2017), resulting in a general population increase (Merkel 2010) to an estimated 25,000–30,000 breeding pairs in the Qaanaaq District by 2009 (Burnham et al. 2012). From 2009–2013 the harvest numbers increased an average of 3,955 birds/year (Boertmann and Mosbech 2017). Currently, the population of Common Eiders that breed in the North Water area of northwestern Greenland (several large colonies in Wolstenholme Fjord) represents about 30–50% of the total west Greenland breeding population (Burnham et al. 2012, Christensen et al. 2017). Common Eiders are listed as vulnerable in Greenland (Boertmann and Mosbech 2017).

### 3.5.7. Summary of Birds: Knowledge Gaps and Climate Impacts

The North Water provides important seasonal habitat and foraging opportunities for millions of seabirds that range throughout the broader region. Many of these species are ecologically, culturally, and nutritionally important throughout the region. There is limited knowledge on the population structure, distribution, numbers, and ecology of many seabird species that occur in the North Water. For instance, there is lack of data available on the winter behavior and potential winter grounds of the Ivory Gull, and the trend of the Dovekie breeding population is unknown. Additionally, the relative abundance for many other species with breeding populations within the North Water region, including the Northern Fulmar, Glaucous Gull, Arctic Tern, Thayer's Gull, Black-legged Kittiwake, and Sabine's Gull, is still unknown. Additional information is required to support conservation and sustainable use of seabirds in the North Water region.

Since 2009, the range of the Ivory Gull has contracted northward, such that almost all of the extant Canadian colonies are located adjacent to the North Water (Environment Canada 2014). Reasons for this decline are unknown, but could be linked to hunting, disturbance at breeding locations, climate change, or high susceptibility to contaminants. Low adult survival rate, high post-fledgling mortality, and restrictive habitat requirements may also be key contributors that highlight the importance of the North Water. The high proportion of the world's population of Dovekies and Thick-billed Murres that use the North Water also highlight its importance. Basin-scale climatic shifts have been linked to declines in other Thick-billed Murre populations (Irons et al. 2008, Descamps et al. 2013, Fluhr et al. 2017). Currently, the area of western Greenland adjacent to the North Water is the only area in Greenland where the Thick-billed Murre population is not in decline (Gaston and Elliot 1991, Davidson et al. 2018, Mosbech et al. 2019). These climate sensitivities may exist at breeding and/or post-breeding locations (Frederiksen et al. 2016). There is also evidence that climate change is increasing contaminant levels in some murre populations due to dietary shifts associated with changes to sea ice (McKinney et al. 2015).

Climate change, and the associated instability of the Smith Sound ice bridge, will significantly alter the ecosystem and could have a particularly strong influence on the foraging efficiency of nesting birds in the North Water. However, the magnitude and mechanisms of these influences remain knowledge gaps. These gaps generally stem from uncertainties regarding the effects of climate change on potential prey type, abundance, timing, and distribution. For instance, changes in oceanographic conditions could result in a shift towards smaller zooplankton species that are less rich in lipids than the high Arctic species. These shifts have been observed in other seasonally ice-covered areas (i.e., southern Baffin Bay, Labrador Sea, and Disko Bay) and could have cascading effects on the energetics of higher trophic levels, including seabirds, but the full effects are unknown. Causey et al. (2019) identified similar widespread changes in the diets of seabirds in coastal northwest Greenland and hypothesized that increased freshwater input from melting glaciers and associated oceanographic changes have also played a role in the observed ecological shifts. Some seabird species, like the Dovekie, may be adaptable to seasonally and annually variable zooplankton abundance and distribution and sea ice conditions, but the northward expansion of zooplanktivores, such as Capelin, may pose a large potential future threat. Seabirds themselves are useful indicators of ecosystem change since they congregate at areas of increased productivity and so can be used to identify hotspots. In particular, Dovekies and murres would be useful indicator species for monitoring future changes in the North Water. The decline in trophic level position for many seabird species in the North Water may already be evidence of decreasing species diversity and carrying capacity in the North Water associated with decreased primary production and potential Atlantification of the Arctic.

# 4. SEASONALLY IMPORTANT AREAS

In the section we present work completed by Christensen et al. (2017), which outlines core areas of biodiversity, specifically identifying potential sensitive areas within the North Water study area. For this analysis, the North Water region (both Canada and Greenland) was examined spatially and temporally to show the variation in biological significance throughout the seasons. Data used to derive these maps were compiled from research and analyses carried out in connection with the eastern Baffin Bay Strategic Environmental Assessment (Boertmann and Mosbech 2017), and supplemented by recent literature where relevant and available. From the Canadian side, data used in the past assessments of the North Water EBSA was used (Stephenson and Hartwig 2010, Kenchington et al. 2011, Cobb 2011, DFO 2015), as well as available data from the Conservation of Arctic Flora and Fauna (CAFF) Circumpolar Seabird Data Portal, and historical ship-based bird surveys (Gjerdrum et al. 2012).

Christensen et al. (2017) conducted a GIS-based overlay analysis of 58 seasonal distribution maps of 24 key species (marine mammals and birds), habitat types, and ecosystem components (details can be found in Chapter 3). The overlay analysis involved both a differential weighting of the different species/ecosystem components (based on the criteria used in Christensen et al. 2017) and of different parts of the seasonal distribution of the individual species/ecosystem components (based on best available knowledge). The resulting maps described below (Figure 40–Figure 43) are colour-shaded in 5% percentiles (20 colour shades) on a scale from dark blue (low values), over yellow, to dark red (high values). The darkest red shading identifies the 5% of the area with the highest overlay score at the date indicated in the legend. Dark red tends to highlight areas where many different species overlap (high biodiversity) or areas where important individual species have an extremely high relative abundance. Based on the criteria used, the highest biological significance occurs from May to August, when productivity is the highest and migratory species are present in the North Water (Christensen et al. 2017). The maps are relative and cannot be directly compared across seasons (i.e., dark red areas in summer tend to have higher abundance and diversity than dark red areas in winter). It should be noted that the assessment of these areas is primarily based on regions of biological significance to seabirds and marine mammals, such as Walrus, Beluga, and Narwhal, and largely excludes fishes, and important physical features, oceanographic and/or sea ice processes within the polynya.

Below, we contribute to the work of Christensen et al. (2017) by synthesizing information presented in this document, to enhance our understanding of the North Water ecosystem in different seasons. Specifically, we use the maps as a starting point to help guide future discussion, needed for both selecting important (trans-boundary) ecological areas within the North Water region, as well as highlighting where more data may be required. In addition, as distribution of species changes, important and sensitive areas may lose their significance, and/or be more accessible/exposed to human stressors (see Stressors section).

## 4.1. WINTER

Walrus are present in the North Water throughout the year, but occur in much more concentrated areas during winter (Born et al. 1995). As such, during the winter (December to early March), the most important areas within the North Water are the three main wintering areas for Walrus in Murchison Sound, west of Wolstenholme Fjord, and the entrance to Jones Sound at Coburg Island (Figure 40, dark orange areas). The area of importance along the Greenland continental slope is primarily due to overlapping distribution areas for Narwhal, Walrus, Beluga, and Bearded Seal. The north-western side of the polynya in Canada, is primarily critical wintering habitat for Belugas (Figure 40, orange-red) (Remnant and Thomas 1992, Richard et al. 1998b, Heide-Jørgensen et al. 2013, 2016, Higdon 2017). Approximately 15% of the Somerset Island Beluga Whales are estimated to migrate through the North Water to wintering areas further south along the west Greenland coast (Richard et al. 2001, Heide-Jørgensen et al. 2003a). It has also been suggested that most Belugas overwintering in the North Water are solitary adults (Richard et al. 1998b, Heide-Jørgensen et al. 2013).

Narwhals overwinter in central parts of the North Water and Northern Baffin Bay (arriving in late November). Narwhal consistently select deeper water in the winter, regardless of sea-ice concentration, thickness, and floe size in Baffin Bay (Kenyon et al. 2018). This is thought to correspond to high densities of their preferred prey, Greenland Halibut (Laidre et al. 2004a,b, Richard et al. 2014),

The Baffin Bay (BB), Lancaster Sound (LS), and Kane Basin (KB) subpopulations of Polar Bear all use portions of or range adjacent to the North Water (Aars et al. 2006, COSEWIC 2008, Obbard et al. 2010, Wiig et al. 2015). Residents of Grise Fiord have identified Polar Bears throughout Jones Sound, particularly during winter, as seen by the red zone on the south-west side of the North Water (Government of Nunavut 2012). During this winter period, it was noted that it is the propagation of the land-based ice that affects the spatial distribution of the species, thus causing minor changes in the delimitation of the important areas (Christensen et al. 2017).

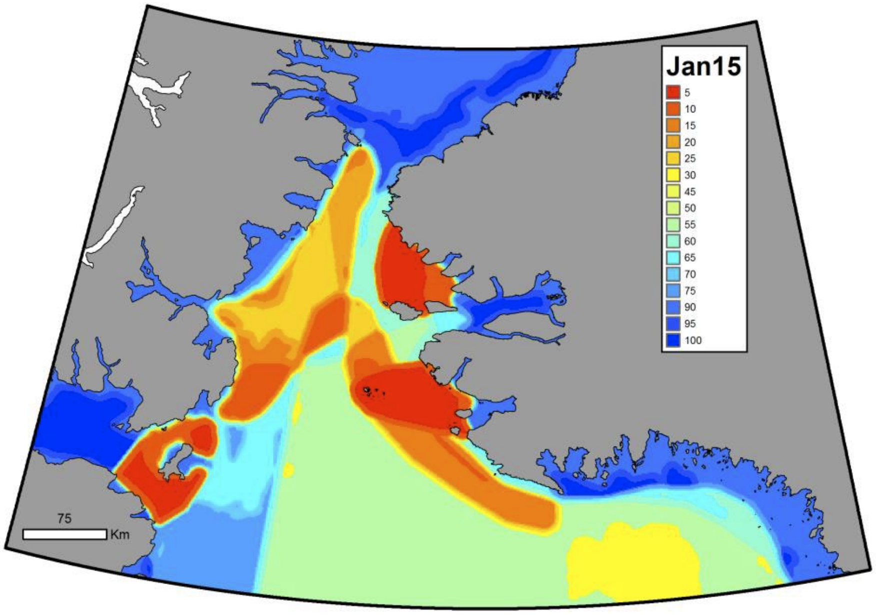

*Figure 40. Map of biologically important areas in mid-January, as indicated by a GIS overlay analysis of the distribution of important species (marine mammals and birds) and ecosystem components. The map is colour-shaded in 5% percentiles on a scale from dark blue (lowest values), over yellow, to dark red (highest values). This map is characteristic of much of the winter period, from the early December to early March. During this period, the most important areas in red are the three main wintering areas for Walrus in Murchison Sound, west of Wolstenholme Fjord and around Coburg Island (see Figure 2). The dark orange area along the Greenland shelf-break results primarily from overlapping distributions of Narwhal, Walrus, Beluga, and Bearded seal. In the northwest part of North Water (Canadian coast), the orange area reflects the main winter distribution of Beluga Whales (Source: Christensen et al. 2017).*

## 4.2. SPRING

Marine mammals (Narwhal, Beluga, Bowhead and seals) and seabirds begin to arrive at the polynya as the sea ice retreats in April–May, however there is no knowledge of particular pre-breeding concentration areas during this time, therefore seabirds have no influence of the spatial configuration of important areas yet (Christensen et al. 2017). Similar to the winter, high use areas for Walrus dominated the scoring for early-spring (Figure 41A). However, Polar Bears begin to arrive at the eastern side of Baffin Bay in April (orange areas), including the outer reaches of Melville Bay, along the Greenland side (Figure 41). In Canada, residents of Grise Fiord have identified bears throughout Jones Sound, particularly during winter and spring along the ice edge (Government of Nunavut 2012). During early spring, when the Greenland side of the North Water has more open water, Belugas have been observed in greater numbers off the northwest coast of Greenland and into the central North Water (Heide-Jørgensen et al. 2013). In Canada, the entrance to Jones Sound has been identified as calving and feeding habitat (Remnant and Thomas 1992), and an east-west spring migration route along both shores of the sound and the south shore of Devon Island (Government of Nunavut 2012).

Phytoplankton productivity is particularly high in the spring and lasts approximately 6 months until the sun angle limits light availability in the fall (Booth et al. 2002, Klein et al. 2002, Garneau et al. 2007). The increase of primary production is gradual, with an early emerging algae bloom observed in the centre of the polynya (shown as light yellow, Figure 41). As such, the North Water is predictable and presumably important for early spring foraging by Bowhead Whales (Dueck and Ferguson 2008). Narwhals appear to show greater use of the Greenland side of the North Water in the spring, especially at the entrance to Inglefield Bredning (Heide-Jørgensen et al. 2013, 2016). IQ from Grise Fiord indicates that Narwhals follow the floe edge at eastern Jones Sound during spring, mating at the entrance to Jones Sound and feeding along its coast and in its fiords during late spring and summer (Remnant and Thomas 1992, Stewart et al. 1995, Stewart 2001). These spring maps also begin to show the dispersal of Walrus. During the open water season Baffin Bay Walrus are largely absent from the Greenland side, concentrating in nearshore Ellesmere Island habitat (Stewart et al. 2014a, Heide-Jørgensen et al. 2017). In addition, Greenland Walruses tend to migrate west in early to late spring across Smith Sound to summer in coasts and fiords of Ellesmere.

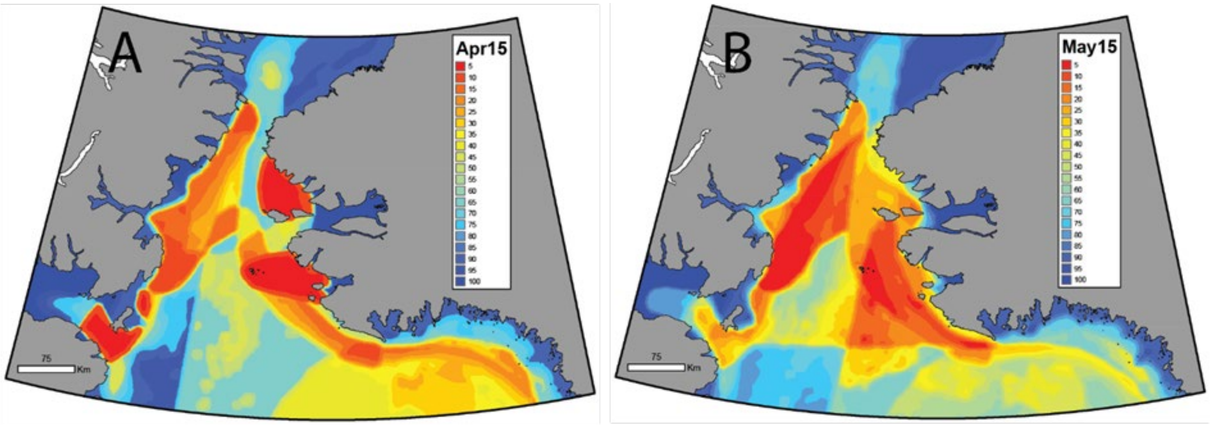

*Figure 41. Map of biologically important areas in spring (April 15/May 15) as indicated by a GIS overlay analysis of the distribution of important species (marine mammals and birds) and ecosystem components. The map is colour-shaded in 5% percentiles on a scale from dark blue (lowest values), over yellow, to dark red (highest values). A) In mid-April, the Walrus wintering areas still dominate the map (red areas), as does the main Beluga wintering area in orange in the Canadian part of the North Water. However, the general biodiversity related to the fast-ice edges of the polynya begins to show up (in orange), as does the emerging spring algae bloom in the centre of the polynya (light yellow shades). B) By mid-May, a triangular area in the Greenlandic part of the North Water is highlighted as important (red/dark orange). This is driven by overlapping spring distributions of Walrus, Narwhal, Beluga, and Bowhead Whale. The elongated important area off the Canadian coast highlights overlapping distributions of Beluga, Walrus, Narwhal, and Polar Bear, and the colour shades in the central parts of the North Water reflects the spring algae bloom. Note: Large species distribution shifts occur in May, and the important areas in map B should therefore be seen only as a snapshot in the middle of a dynamic transition period. Also note that millions of seabirds arrive to the area in April–May, but as there is no knowledge of particular pre-breeding concentration areas, they have no influence of the spatial configuration of import areas yet (Source: Christensen et al. 2017).*

## 4.3. SUMMER

By the summer, a drastic change in species occurrence and distributions can be observed, and as a result, the areas of importance expand and show more variability than the spring (Figure 42 A/B). At this time, millions of seabirds arrive to coastal areas surrounding the North Water to breed and feed in the open waters and coastal/fiord areas (Figure 35 and Figure 36). Bird 'hotspots' in Canada and Greenland tend to be more concentrated/localized during this time, specifically the Thick-billed Murre, Sabine's Gull, Arctic Tern and Dovekie/Little Auk colonies (shown mostly in red/orange areas, Figure 42A). Marine mammals, such as Walrus and Narwhal, contribute to the important areas but do not contribute significantly to the red zones (Christensen et al. 2017). Harp, Hooded, and Ringed Seals are also considered common summer residents throughout the North Water (Ringed Seals are present throughout the year). Core summering areas for Beluga are outside the North Water, principally around Somerset Island, but also in Lancaster Sound (and adjacent waterbodies) and Jones Sound (Koski 1980, Richard et al. 2001, Stewart 2001, Stephenson and Hartwig 2010, COSEWIC 2016). Terrestrial Walrus haul-out sites in Canada become critically important during summer and early fall periods of sea-ice minima (Figure 42B) (Higdon 2016). We see important areas shift to the coast of Ellesmere Island, and Polar Bears begin to concentrate in overlapping areas during the summer (Christensen et al. 2017). In Canada, the north coast of Devon Island has been described as Polar Bear summer retreat habitat around Hyde Inlet and Philpots Island off eastern Devon Island (Government of Nunavut 2012, Pikialasorsuaq Commission 2017). However, there have also been observed changes in habitat use within both the BB and KB subpopulation ranges (SWG 2016). Polar Bear summer range also includes western and northern North Water coastal areas (Stephenson and Hartwig 2010). Due to the disappearance of offshore and archipelago summertime ice, Polar Bear habitat has shifted to lower sea-ice concentrations and resulted in bears remaining closer to land (Hamilton et al. 2014), suggesting that the terrestrial habitat may become more important.

Preferred summer habitat for Narwhal includes deep, steep-sided inlets with partial ice cover, presumably to provide protection from Killer Whales (Kingsley et al. 1994, Petersen et al. 2011, Breed et al. 2017). In Greenland, Melville Bay and Inglefield Bredning both are more important in the summer than winter or spring, due to the occurrence of Narwhals, which use this region for foraging and breeding (Pikialasorsuaq Commission 2017). Bird colonies continue to be important throughout the summer months, as are the moulting areas along the coast of Greenland, where Common and King Eider congregate in late summer/early fall after the breeding season (Christensen et al. 2017).

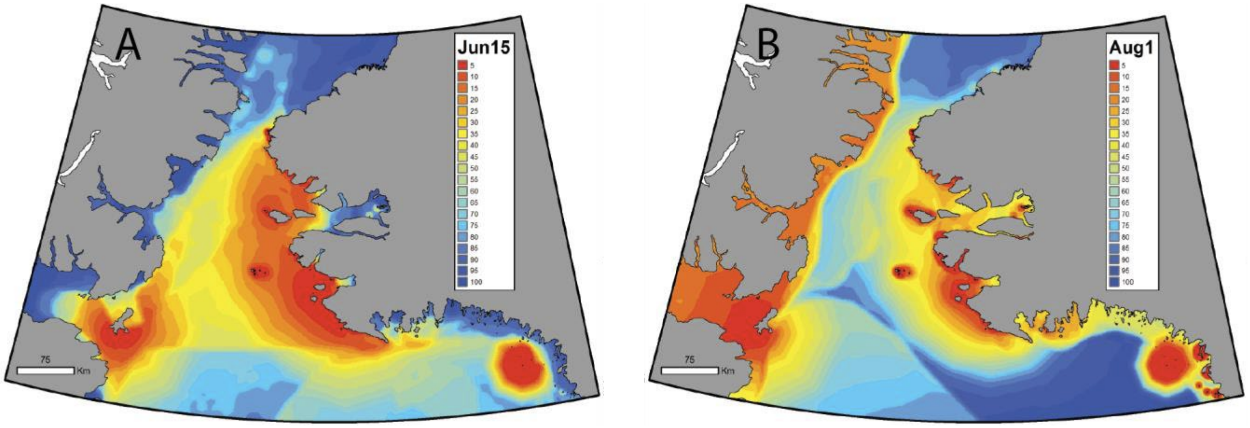

*Figure 42. Map of biologically important areas in summer (June 15/August 1) as indicated by a GIS overlay analysis of the distribution of important species (marine mammals and birds) and ecosystem components. The map is colour-shaded in 5% percentiles on a scale from dark blue (lowest values), over yellow, to dark red (highest values). A) By mid-June, millions of seabirds are actively breeding in large colonies around the North Water, and the foraging ranges around these colonies, where many birds are concentrated, now dominate the relative distribution of important areas. The large red areas are primarily driven by Thick-billed Murre, Dovekie/Little Auk, and Common Eider colonies. The large red dot in Melville Bay reflects a large and unique Sabine's Gull (and Arctic Tern) colony. B) In early August, the foraging habitats around large seabird colonies are still highlighted as the most important areas (in red), as are Common and King Eider moulting areas along Greenland coasts. However, compared to map A, much of the relative weight/importance has shifted to the Canadian coast, where Narwhal, Walrus and Polar Bear now concentrate (large orange area). Inglefield Bredning and Melville Bay also have higher relative importance due to Narwhal, and Narwhal and Polar Bear concentrations, respectively (Source: Christensen et al. 2017).*

## 4.4. FALL

By fall, the western side of Smith Sound and the North Water are covered with rubble and multiyear ice, with thin-medium first year ice throughout the remainder of the North Water and Baffin Bay (Mundy and Barber 2001). The Canadian side of the North Water remains an important region for Walrus, Polar Bear, and Narwhal (Figure 43, red areas). During fall, there is an observable shift from coastal summering areas (Figure 43A) into offshore habitats (Figure 43B), both on the west and east side of north Baffin Bay. This is primarily due to the overlap between the Beluga Whale migration route, and the northern portion of key Narwhal habitat, as they move into their wintering area (dark yellow/ orange band, cutting west-to-east across the study area). Satellite tracking of EHA-BB Belugas tagged shows a rapid early fall movement east towards Devon Island and into the southern limits of the North Water (Figure 43, orange) (Barber et al. 2001b, Richard et al. 2001). During late fall and early winter, Belugas move into the North Water, where most will remain until they begin westward spring migrations (Stewart et al. 1995, Richard et al. 1998a, 2001, QIA 2018). This movement may be driven by Arctic Cod, an important prey species for marine mammals and birds, which are known to spawn in late fall and early winter underneath ice shelves.

Additionally, most seabirds finish breeding by late summer and breeding locations are abandoned. Along the coast of Greenland, the Eider and King Eider moulting areas are still clearly visible, but are typically abandoned by the end of September. Again, Inglefield Bredning and Melville Bay on the Greenland side have relatively high values, primarily due to the distribution of Narwhal, and Melville Bay remains important for Polar Bear use.

By mid-November, Walruses will concentrate in the same three key wintering areas (Figure 43B). Local knowledge from Qaanaaq describes the ice formation period as a time when Narwhals and Polar Bears start migrating south (Pikialasorsuaq Commission 2017). Narwhal leave their summering habitat (along the Canadian coast, in Inglefield Bredning and Melville Bay) to winter in the central parts of the North Water and Northern Baffin Bay (arrival late November). As ice begins to form along the Canadian coast and in Melville Bay, Polar Bears disperse, and are more widespread throughout the regions (also contributing to the orange-yellow bands in Figure 43B).

In Canada, the north coast of Devon Island and areas within Jones Sound are important for Polar Bear denning (Stephenson and Hartwig 2010, Government of Nunavut 2012, Pikialasorsuaq Commission 2017). However, in BB, the denning season appears to be beginning later; denning was an average of 27 days shorter in the 2000s than the 1990s, due primarily to late entry in the fall (Escajeda et al. 2018).

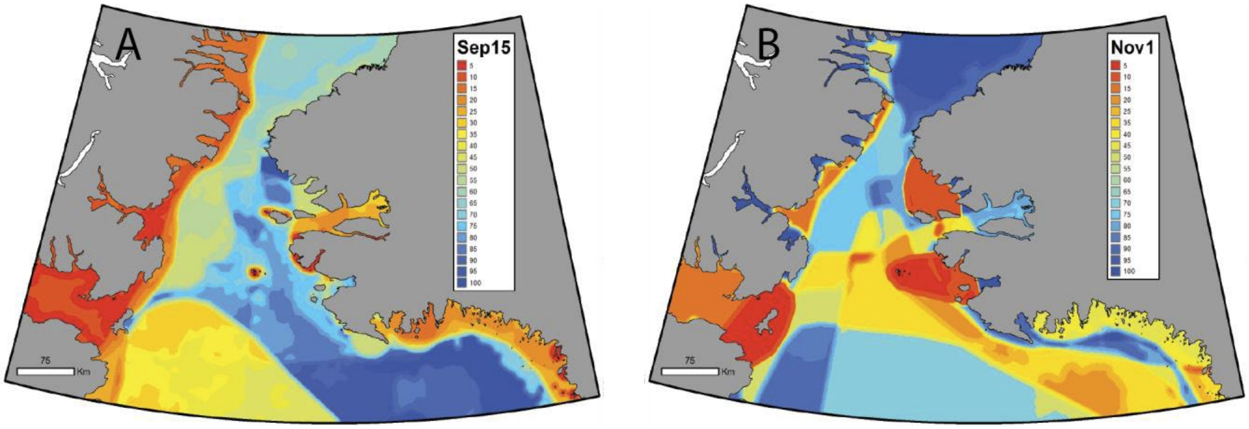

*Figure 43. Map of biologically important areas in fall (September 15/November 1) as indicated by a GIS overlay analysis of the distribution of important species (marine mammals and birds) and ecosystem components. The map is colour-shaded in 5% percentiles on a scale from dark blue (lowest values), over yellow, to dark red (highest value). A) By mid-September, the seabird breeding season is over and most birds have left the area. However, Common and King Eider moulting areas along Greenland coasts are still highlighted as important. The Canadian coastal areas are very important due to overlapping distributions of Walrus, Polar Bear and Narwhal. Inglefield Bredning and Melville Bay also have relatively high importance due to Narwhal and Narwhal and Polar Bear concentrations, respectively. B) By late October/early-November, Walruses start to concentrate in their wintering areas (the three red areas). Narwhals gradually move from their coastal summering areas (along the Canadian coast, in Inglefield Bredning and Melville Bay) to winter in the central parts of the North Water. Here they overlap with the Beluga fall migration and Polar Bears which gradually disperse from the Canadian coasts and Melville Bay as sea ice expands. Note: Large species distribution shifts occur during fall, and the important areas in maps should therefore be seen only as snapshots in a dynamic transition period (Source: Christensen et al. 2017).*

# 5. ANTHROPOGENIC STRESSORS

## 5.1. TRANSBOUNDARY OR PERVASIVE STRESSORS

The issue of pollutants and other long-range anthropogenic stressors from outside the Arctic resulting in significant impacts within the region is not a recent phenomenon. Canada, Greenland, and Denmark already prioritize monitoring and collaboration within the Arctic Council. Scientists and government officials have been active in monitoring through the Arctic Monitoring and Assessment Programme (AMAP), one of six working groups under the Arctic

Council. Under this program, other sub-networks, such as the AMAP Contaminants Programme, produce high quality reports and related communication products that detail the status of the Arctic with respect to pollution issues. Recent AMAP reports include the Arctic Ocean Acidification Assessment (AMAP 2019a), Biological Effects of Contaminants on Arctic Wildlife and Fish (AMAP 2019b), and Chemicals of Emerging Arctic Concern (AMAP 2017). The most recent assessment of trends in Arctic contaminants and their effects on wildlife and fish (AMAP 2019b) concluded that contaminants, including polychlorinated biphenyls (PCBs) and mercury, continue to pose a significant risk to some Arctic biota. After entering the marine system, many contaminants go through biomagnification (Bard 1999).

Within the North Water, there is evidence of strong linkages between higher concentrations of persistent organic pollutants (POPs) and higher trophic levels; confirming biomagnification in the food web (Fisk et al. 2001b, c). The threats contaminants pose to wildlife are different in the North Water than some other regions, partly because contaminants can be directly deposited into the open water (Bargagli et al. 2005), and partly because of the high biological activity in this area (Hobson et al. 2002). In particular, top predators including Polar Bears, Killer Whales, seals and various species of birds are at continuing risk from exposure to these contaminants. Furthermore, as new contaminants enter the Arctic system (e.g., plastics), the magnitude of the problem is expected to increase.

A recent transboundary issue has also been noted in regards to the release of residual hydrazine fuel contained in Russian rocket stages that regularly come down in Baffin Bay and the North Water region (Byers and Byers 2017). The potential impacts from Hydrazine within the North Water are unclear and volatility of hydrazine in cold water is also unknown. The effects on the North Water ecosystem which could result from the continued releases of rocket stages in the region is of concern.

### 5.1.1. Contaminants and Trace Elements

The North Water is not the most exposed site for POPs transported to the Arctic (AMAP 2015, Dietz et al. 2018) and only has a few local sources of contaminants (Bard 1999). Nonetheless, there is mounting evidence that contaminants (e.g., mercury) are in the North Water and pose threats to marine mammals and birds, as well as the northern communities that rely these species as part of a traditional diet (Fisk et al. 2001b,c, Campbell et al. 2005, Dietz et al. 2009, AMAP 2015, Dietz et al. 2018, Barber et al. 2019). There are two groups of contaminants of major concern: POPs (e.g., polychlorinated biphenyls (PCBs), dichlorodiphenyltrichloroethane (DDT) and hexachlorocyclohexane (HCH), hexachlorobenzene (HCB), and chlordane) and trace metals (e.g., mercury, cadmium, zinc, and lead) (Braune et al. 2005). The amount of 'current-use pesticides' and other emerging contaminants (e.g., polyfluorinated and polybrominated contaminants, crude oil and associated contaminants) entering the North Water system are of new concern as they are expected to increase over time (Morris et al. 2016).

#### 5.1.1.1. Sources and pathways of contaminants

The POPs and metal contaminants present in the North Water are transported from their source regions in mid- and low-latitudes (mainly Asia, North America, and Europe), after which they are incorporated into food webs where they bioaccumulate (a process by which toxins enrich in animals at high trophic levels of the food chain) (Figure 44 and Figure 45) (Kirk et al. 2012). The major transport routes include atmospheric transport, riverine transport, oceanic circulation, sea ice motion, as well as migration of birds, marine fish and mammals (Figure 44) (Blais et al. 2005, Outridge et al. 2008, Durnford et al. 2010, Wang et al. 2017). Coastal erosion and melting of permafrost and glaciers may also release stored toxins (Outridge et al. 2008, Stern et al. 2011, AMAP 2015). International conventions regulating emissions of certain contaminants (e.g., mercury and many POPs) has stabilized, or even decreased, the concentrations in the Arctic atmosphere since the mid-1970s (Li et al. 2009, Hung et al. 2010), although some POPs, such as HCB, may increase in the Arctic air due to the rising world usage of certain pesticides (Hung et al. 2010).

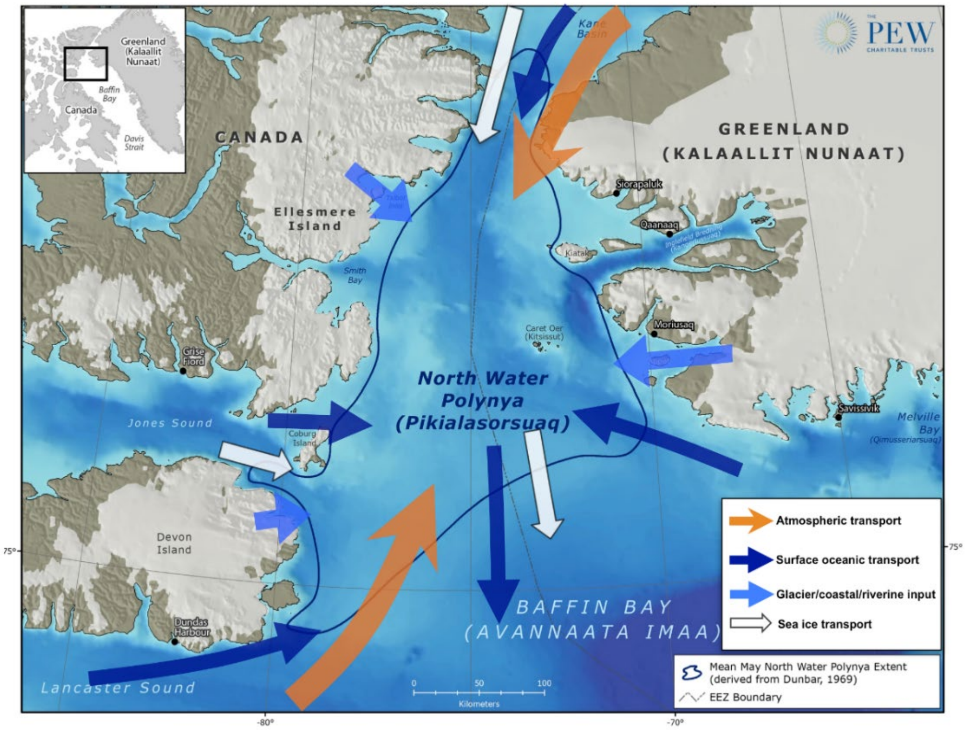

*Figure 44. The major pathways of contaminant transport to the North Water region (Source: Modified from Oceans North: The PEW Charitable Trusts).*

The atmospheric circulation patterns suggest that contaminants entering the North Water in winter and summer are mainly from Eurasia and North America, respectively (Macdonald et al. 2000). During winter and early spring, the atmosphere does not deposit contaminants efficiently to the Arctic Ocean because the surface is covered by snow and sea ice. The North Water is an exception, because the open water allows for direct air-seawater exchange. This makes the North Water especially susceptible to mercury deposition because mercury depletion events occur in the spring, which deposit large amounts of the metal on land and sea surfaces (Schroeder et al. 1998). Since this happens at a time when primary productivity in the North Water starts to increase, it could provide a rapid route for the entry of mercury (and other contaminants) to the local food web (Campbell et al. 2005).

Ocean currents primarily affect persistent contaminants that remain soluble over very long (millennial) time scales (Macdonald et al. 2000). In addition, rivers can transport contaminants that are deposited throughout their watersheds to the North Water; this could be of particular importance during the spring melt season. In the context of global warming, release of stored contaminants by the melting of glacier ice and permafrost is of increasing concern (Stern et al. 2011). The motion of sea ice can also transport contaminants by atmospheric deposition and sediment entrainment (Outridge et al. 2008, Wang et al. 2017). Migration of animals is another way of contaminant transport to terrestrial and coastal Arctic ecosystems (Blais et al. 2005), although its contribution to marine ecosystems such as North Water is unlikely to be major.

#### 5.1.1.2. Movement of contaminants and trace elements through the food web

Migration, scavenging, and biotransformation (biological processes that alter the forms of a chemical) can also influence the accumulation of these contaminants in animals. Similar to many POPs, the organic form of mercury, methylmercury, also biomagnifies in the North Water food web (Campbell et al. 2005). Most metal contaminants (e.g., cadmium, lead), however, do not biomagnify, and tend to have higher concentrations in zooplankton than in seabirds and marine mammals as a result of bioconcentration from seawater (Campbell et al. 2005). Conversely, seabirds and marine mammals have higher biomagnification factors than fish, due to their greater energy requirement and feeding rates (Fisk et al. 2001c). Most of the mercury in the Arctic is transported from Asia followed by *in situ* monomethyl mercury production in marine waters, so the North Water is relatively sheltered from the effects observed in the western Arctic (Kirk et al. 2012, AMAP 2015, Dietz et al. 2018). Monthly and annual mercury intake in humans from northwest Greenland are six and eleven times the tolerable levels, respectively, and concentrations have been increasing since the 1990s (Dietz et al. 2018). Mercury exposure primarily comes from traditional food, consisting of mainly of seabirds and marine mammals (Figure 46) (Dietz et al. 2018). It is thought that the higher selenium in select marine mammal tissues may offer some protection against elevated mercury levels, but the trend remains a concern. In addition, a diet of seals, which is high in vitamin D, calcium, phosphorus, zinc, selenium, and protein, likely counteracts potential damage from high cadmium levels.

##### 5.1.1.2.1. Zooplankton, benthos, and fishes

As an important link in the North Water food web, zooplankton is likely a significant contributor to the transfer of organic pollutants and mercury to higher trophic levels (Braune et al. 2005). Organic pollutants tend to be lower in zooplankton from the North Water and eastern Canadian Arctic region than the western Arctic due to the atmospheric and oceanic transport of these chemicals from Asian sources (Fisk et al. 2003a). The most common organic pollutants present in zooplankton from northern Baffin Bay and Smith Sound are polychlorinated biphenyls (PCBs) and hexachlorocyclohexanes (HCHs) (Fisk et al. 2001a, 2003a, Borgå et al. 2005, Braune et al. 2005), but overall levels are generally lower than in higher trophic levels or in benthic organisms (Fisk et al. 2003b, Braune et al. 2005). More specifically, Borgå et al. (2005) reported that *Calanus* copepods had the highest HCH concentrations and pelagic *Themisto libellula* had the highest levels of PCBs. Total mercury measured in zooplankton from northern Baffin Bay was also relatively low overall (Campbell et al. 2005, Braune et al. 2005). In addition, concentrations of mercury and other trace elements were low in ice algae from the North Water and were comparable to observations from other regions (Campbell et al. 2005).

Benthic invertebrates can be important contributors to contaminant cycling in Arctic food webs, but concentrations are highly variable across taxa due to the wide range of ecological niches occupied by benthic species (Fisk et al. 2003b, Braune et al. 2005). Relatively high levels of organic contaminants, particularly PCBs, have been found in some bivalves and the scavenging amphipod *Anonyx nugax* in northern Baffin Bay with some indication that proximity to harbours increases concentrations (Fisk et al. 2003b). Baseline toxicity surveys completed in 2005 characterized the sediment within Smith Sound as not toxic to benthos (Canário et al. 2013), so contamination levels should remain relatively low when compared with other Arctic regions.

As an important component in Arctic marine food webs, Arctic Cod represents a key link in the transfer of contaminants and mercury to higher trophic levels. There have been few direct observations of contaminants in cod from the North Water region. Similarly low total mercury concentrations have been reported in Arctic Cod from Lancaster Sound (Atwell et al. 1998) and northern Baffin Bay (Campbell et al. 2005). Fisk et al. (2002) and Borgå et al. (2005) noted that

PCBs, dichlorodiphenyltrichloroethane (DDT), and chlordanes, were among the dominant contaminants found in cod from northern Baffin Bay.

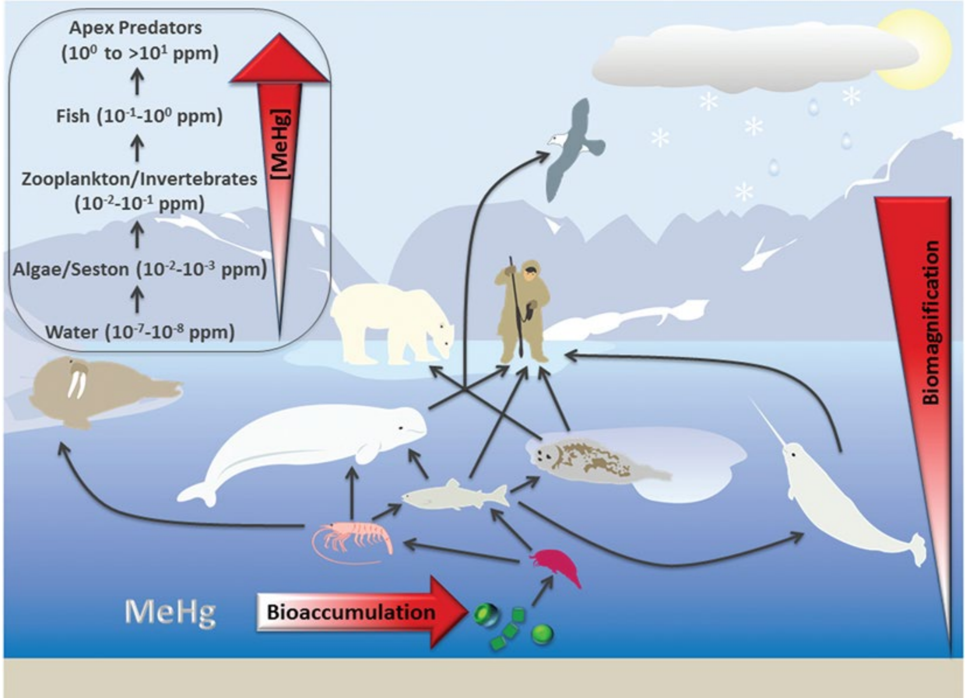

*Figure 45. The bioaccumulation and biomagnification of methylmercury in a typical Arctic marine food web (Source: Lehnherr 2014).*

#### 5.1.1.2.2. Marine Mammals

As the marine mammal occupying the highest trophic position in Arctic food webs, Polar Bears are very susceptible to bioaccumulation of organic contaminants and mercury (Figure 46). Dietz et al. (2011) analysed hair samples from Polar Bears taken over a long period of time (1892–2008) from northwest Greenland and found that mercury levels increased about 1.6–1.7% annually, such that the most recent samples had concentrations 23–27 fold higher than the oldest. The authors also reported that approximately 96% of the observed increase was anthropogenic in origin and predicted up to a 92-fold increase in concentrations by the year 2100, which could have significant effects on the health of bears. Rush et al. (2008) observed little change in the concentrations of most trace elements in Polar Bear livers in Canada and Greenland over time, but did identify levels of cadmium and mercury that exceeded thresholds correlated with pathological effects in laboratory animals. Samples analyzed by Rush et al. (2008) included bears from the LS and BB subpopulations. LS bears had some of the highest concentrations for several essential and non-essential elements among all sampled subpopulations while BB from NW Greenland had among the lowest.

In contrast to observed trends in trace elements, many of the legacy contaminants (i.e., older chemicals that have been banned for many years) have decreased by as much as 72% in Polar Bears in recent years (Muir and Norstrom 2000, Verreault et al. 2005, McKinney et al. 2011). McKinney et al. (2011) sampled a large number of POPs in 11 subpopulations, including LS and BB bears, from 2005–2008. Concentrations of most contaminants in the LS subpopulation were typically lower than in other surveyed Canadian subpopulations. The BB subpopulation had moderate contaminant levels, most similar to the Davis Strait bears, but usually lower than Hudson Bay bears. However, in some subpopulations (including LS) some contaminants, such as PCBs, remain above levels known to cause additional harmful effects (e.g., liver lesions, decreased cellular, and humoral immunity) in seals and sled dogs, but with unknown effects to bears (Nuijten et al. 2016). There is also evidence that climate change is increasing contaminant levels in some populations of Polar Bears due to shifts in diet associated with changes to sea ice (McKinney et al. 2015).

Contaminant and trace element levels in Ringed Seals have received attention due to the species' importance in Polar Bear and human diets in the Arctic. Feeding ecology appears to play an important role in total mercury (THg) and cadmium levels in Ringed Seals (Brown et al. 2016), and there is also evidence that climate change is increasing contaminant levels in some populations of Ringed Seals due to dietary shifts associated with changes to sea ice (McKinney et al. 2015, Ferguson et al. 2017). Mercury levels in the liver and kidneys of Ringed Seals from Grise Fiord have been found to be lower than levels found in seals sampled in the western Canadian Arctic, but higher overall than Arctic regions of the United States and Europe (Riget et al. 2005; Braune et al. 2005, Brown et al. 2016). Ringed Seals sampled in Grise Fiord typically have among the lowest concentrations of muscle THg compared to other communities in the Canadian Arctic (Braune et al. 2015, Brown et al. 2016). One study on found that the concentrations of contaminants such as PCB, DDT, and chlordane in Ringed Seals increased with age, but were not significantly different in Ringed Seals from the east and west sides of the North Water (Fisk et al. 2002). HCH was found to vary across the food web because of the biotransformation capacity of different species (Moisey et al. 2001). Braune et al. (2005) found that HCH and PCB concentrations in the Grise Fiord area are typically higher and lower, respectively, than in the southern Canadian Arctic. Cadmium levels in seals from northwest Greenland are among the highest measured in the Arctic; however, there are no apparent histopathological effects from such high concentrations (Sonne-Hansen et al. 2002).

Similar to seals, concentrations of Hg and Cd in cetaceans are driven by dietary selection (Dehn et al. 2015). Bowhead Whales feed at a low trophic position and yet have higher Cd concentrations than other top-level Arctic consumers (e.g., Polar Bear and Arctic fox (*Alopex lagopus*) (Bratton et al. 1997, Ballard et al. 2003, Woshner et al. 2001a, Woshner et al. 2001b). Concentrations of PCBs and toxaphene in Belugas from the Jones Sound region were generally lower than in other areas of the Canadian Arctic (Braune et al. 2005). Liver mercury levels measured across the Canadian Arctic from 1981–2002 were almost universally higher than the Canadian consumption guide and there were indications of an increasing trend over time (Lockhart et al. 2005). Regionally, Belugas sampled from the Grise Fiord region had among the lowest of measured mercury concentrations with no apparent trend between 1984 and 2001, though overall sample size was low (Lockhart et al. 2005). Studies on contaminants in Narwhal from the North Water region are limited, however, concentrations of PCBs in Narwhal harvested by Grise Fiord hunters were generally lower than in other areas of the Canadian Arctic (Braune et al. 2005). Walrus tend to have lower mercury concentrations in their tissue, when compared to other marine mammals, due to their lower trophic level (Wagemann et al. 1996, Braune et al. 2005).

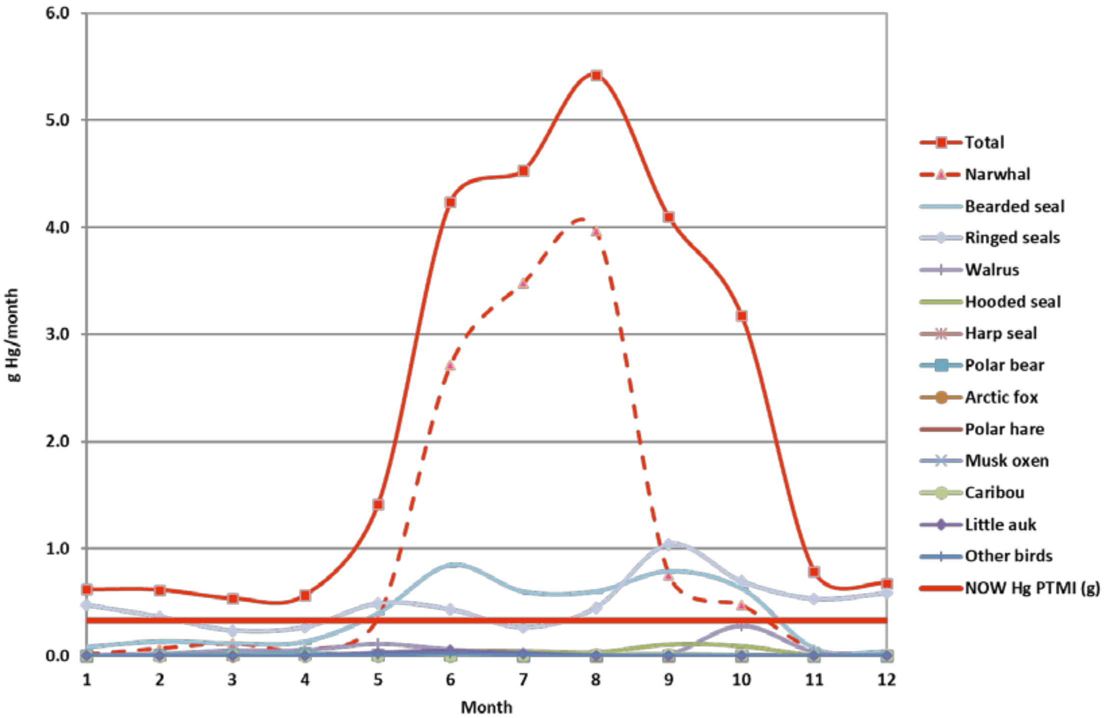

*Figure 46. Seasonal Hg load in the hunted game of Avanersuaq, Greenland, based on average hunt from 1994 to 2014 and average Hg loads in muscle tissue from the present study and published and unpublished contaminant studies in Greenland (Source: Dietz et al. 2018).*

#### 5.1.1.2.3. Seabirds

Trace elements and organic contaminants are of concern in Arctic marine bird populations, as well as for human health in communities that harvest birds on both sides of the North Water (AMAP 2015, Dietz et al. 2018, Barber et al. 2019). Greater energy requirements for seabirds account for relatively higher contaminant concentrations than in marine mammals or fish (Braune et al. 2005). Provencher et al. (2014) suggested that although most Canadian Arctic seabirds currently have sub-toxic mercury levels, they are already among the highest in the pan-Arctic region, and are particularly susceptible to increasing levels associated with climate change. Campbell et al. (2005) examined total methylmercury and other trace elements in eight species of seabirds in the North Water in 1998 and found significant biomagnification, particularly for liver arsenic concentrations. Mercury concentrations were highly correlated with trophic position, and were highest in Glaucous Gulls (Braune et al. 2005, Campbell et al. 2005). Dovekies, had significantly lower mercury concentrations than all other seabirds, probably because of their comparatively low trophic position.

Organochlorine concentrations and dynamics were measured in the liver and fat of seven Arctic seabird species collected in northern Baffin Bay in 1998 (Fisk et al. 2001b, Buckman et al. 2004). PCBs were the most common organic contaminant observed in all seabird species and, along with most of the other organic contaminant groups, reached the highest concentrations in gulls (Glaucous and Ivory Gulls, Black-legged Kittiwakes) and Northern Fulmars (Braune et al. 2005). These species are primarily scavengers and/or feed on other seabirds, and, therefore, occupy higher trophic levels. In contrast, Common Eiders in the Canadian Arctic generally had low concentrations of organic pollutants, particularly relative to European eider species and sympatric species (Mallory et al. 2004). Tittlemier et al. (2002) examined levels of halogenated dimethyl bipyrroles (HDBPs) in four seabird species (Dovekie, Black Guillemot, Black-legged

Kittiwakes, and Glaucous Gulls) collected in northern Baffin Bay, and HDBPs were detected in all of the samples studied from within the North Water region. This study represented the first time a naturally produced halogenated compound had been measured in Arctic species.

High levels of organic pollutants, including organochlorides and PCBs, have been measured in Ivory Gulls collected in the North Water (Fisk et al. 2001c, Buckman et al. 2004, Braune et al. 2005). Ivory Gulls were found to have higher concentrations of cadmium, selenium, and total mercury, than similar species from the Barents Sea in Europe (Campbell et al. 2005). Furthermore, Ivory Gull eggs have the highest total mercury recorded for any Arctic marine seabird (Braune et al. 2006). Testing of feathers collected over long periods of time in Arctic Canada and western Greenland showed that methylmercury concentrations increased over time without concurrent changes in foraging behaviour (Bond et al. 2015, Mallory et al. 2015). In addition, mercury concentrations were much higher in Ivory Gulls than in other Arctic seabirds with similar dietary isotope signatures, including Glaucous Gulls (Mallory et al. 2015) and higher than in Ivory Gulls from Arctic Europe (Lucia et al. 2015). Braune et al. (2006) suggested that observed elevated concentrations in Ivory Gulls may be due to a combination of feeding at a higher trophic position and the species' need for greater food intake to meet its relatively high daily metabolic requirements. Furthermore, most of the analyzed Ivory Gull eggs from Seymour Island displayed mercury levels above a threshold thought to negatively affect successful development (Braune et al. 2006). Concentrations of other contaminants in these eggs were below published toxicological thresholds, but sub-lethal or cumulative effects cannot be ruled out (Braune et al. 2007).

### 5.1.2. Microplastics

Plastic (macro and micro) ingestion by various species has recently been recognized as a potential stressor in Arctic marine ecosystems and can be considered another form of contamination. Obbard et al. (2014) found concentrations of microplastics frozen in Arctic sea ice that were several times greater than in highly contaminated surface waters (e.g., Pacific Gyre) and suggested that the risk of contamination from these legacy plastics increases as ice melts. Although there are limited published results from the North Water region, increased ice transport through this area could increase the exposure of microplastics to the food web and environment. Similar observations in other Arctic regions with comparable fauna have recently been reported. Stomachs of two of 72 juvenile Arctic Cod sampled from Svalbard contained microplastic (Kühn et al. 2018). Off eastern Greenland, 34% of Bigeye Sculpin (*Triglops nybelini*) and 18% of Arctic Cod surveyed had consumed microplastics, with the difference likely due to species-specific feeding behaviour and habitat preferences (Morgana et al. 2018). Although levels in Arctic marine fish remain low compared to Arctic seabirds (e.g., Trevail et al. 2015), the results of these studies show that contamination of a key trophic link such as Arctic Cod is possible and warrants additional monitoring.

Trevail et al. (2015) also found that 87.5% of Northern Fulmars sampled from Svalbard had plastic in their stomachs. In the Canadian high Arctic, Poon et al. (2017) found plastic in the stomachs of four species of seabirds with higher levels in surface feeders (Fulmars and Kittiwakes) than pursuit divers (murres and guillemots). Although recently-measured levels in Arctic birds generally remain lower than in birds farther south, the presence of plastic in these relatively remote bird populations highlights the ubiquity of this pollutant, even away from direct human marine impact.

### 5.1.3. Ocean Acidification

When the ocean absorbs $CO_2$, it reduces the magnitude of the greenhouse effect; however, this process results in major changes to ocean chemistry. Increases in $CO_2$ cause decreases in pH through the process of ocean acidification (OA). As the ocean becomes more acidic, the shells of many marine species (made of calcium carbonate) become more brittle and dissolve due to the excess acid in the seawater (Doney et al. 2009, AMAP 2013). If waters of the North Water become more acidic (decrease the pH), there could be negative effects on marine life inhabiting the region. They will need to adapt to the new chemistry of their environment, impacting their survival and creating a domino effect up through the food chain. OA is a significant concern throughout the Arctic, as cold water is more efficient at absorbing $CO_2$ than warm water.

The rates of air-sea $CO_2$ exchange have been measured to understand the role of the North Water within the global carbon cycle. Whether the North Water is an overall source or sink of $CO_2$ has implications on the marine ecosystem but also for atmospheric $CO_2$ levels, eventually affecting the global climate (Arrhenius 1896) and determining rates of OA both within the North Water and downstream in Baffin Bay. Air-sea exchanges of dimethyl sulfide (DMS) also play a major role in the global sulfur cycle. They have the potential to influence global climate through the production of new aerosol particles and cloud condensation nuclei (water bonds to these and precipitation forms) (Charlson et al. 1987). In addition, sustained observations now show that the Pacific inflow to the Arctic via the Bering Strait has become more acidic, highlighting the connectivity of stressors between oceans (Niemi et al. 2020). Scientific studies to better understand gas fluxes in the North Water and their relation to the acidification of connected waterbodies, are required in the North Water region, and more broadly throughout the Arctic.

## 5.2. LOCALIZED IMPACTS AND STRESSORS

There are currently only about 1000 people living next to the North Water (Boertmann et al. 2019). Despite the remoteness, the local Inuit and Inughuit population living here are already seeing the effects of global anthropogenic pollution (Dietz et al. 2018), and have raised concerns regarding the current and potential new pressures of non-climatic stressors on the North Water ecosystem. Changing sea ice is also a serious issue affecting safety, travel, food security, and costs for Indigenous peoples. For all coastal Arctic communities, human access to sea ice and the coastal marine environment is critical for hunting and other land use activities, including subsistence and small-scale fisheries. Subsistence hunting in the region is generally considered sustainable. However, the hunting pressure on Narwhals (Heide-Jørgensen et al. 2020) and Walruses can be high on the Greenland side of the North Water, and catches have been at times higher than the scientific advice from the North Atlantic Marine Mammal Commission (NAMMCO) and Joint Commission on Narwhal and Beluga (JCNB). An overview of anthropogenic stressors and their overall impact in the North Water is provided in (Table 4).

*Table 4. Overview of anthropogenic stressors, including climate change, and their overall impact currently in the North Water and future implications (Source: Boertmann et al. 2019).*

| **Anthropogenic Stressor** | **Current impact** | **Future impacts** |
|---|---|---|
| Subsistence hunting and fishing | Low | No significant changes * |
| Commercial (large-scale) fishing | Low | Potential to increase |
| Industrial activity (i.e., mineral extraction and hydrocarbon activities) | Low | Potential to increase |

| Anthropogenic Stressor | Current impact | Future impacts |
|---|---|---|
| Commercial shipping (e.g., movement of material and use of icebreakers) | Low | Potential to increase in polynya and southern regions |
| Tourism | Low | Potential to increase |
| Pollution | Local - Low<br>Long Range - Of Concern | No change |
| Climate change | Strong | Significant effects |

* With continued co-management of sensitive stocks

### 5.2.1. Industrial activity and commercial shipping

Seismic data suggests that Baffin Bay and the surrounding region may support gas, but that the potential for oil is low, particularly in northern Baffin Bay (Maclean et al. 1990). Frisch (1988) examined the Precambrian geology of southeastern Ellesmere Island and Devon Island and found that the primary metallic mineral deposits were copper and iron sulphides forming lenses and layers in gneiss. They appeared to be abundant in the northern part of the area, but no deposits of commercial significance had been discovered to date. Sea ice decline and the lengthening of the open water season in the North Water region has the potential to encourage more oil and gas exploration, shipping, industrial activity, and tourism; although the impact of these stressors is currently low (Table 4) (AMAP 2018). There is some potential for these activities to increase in the near future, with a significant increase in the amount of ship-based export from active mines in the eastern Canadian Arctic (e.g., Baffinland 2019) and proposed activity for a mine close to the North Water on west Greenland (Government of Greenland 2020). Other potential risks from any resource extraction activity in or near to the North Water include, construction impacts, seismic activity during oil and gas exploration, the risk of large spills (including hydrocarbon), and underwater noise from shipping.

The extended ice-free season is already increasing not only commercial marine traffic within the Canadian Arctic region, but also tourism vessels, cruise ships, and pleasure crafts. With a longer ice free season, the frequency, type, and number of vessels are expected to grow, with cascading impacts to the marine environment, such as noise pollution and risk of invasive species. The use of commercial vessels for seismic testing and ice breaking in particular can generate extensive anthropogenic noise, which overlaps with the frequency range many marine species use to communicate, and can disturb sensitive bird and marine mammal habitat (PAME 2019). For example, Walrus are known to be particularly sensitive to human disturbance, specifically disturbance at haul-out locations, where they have been known to abandon sites for less favourable locations (Higdon 2016, DFO 2019b). Recent telemetry research from Resolute Bay, Nunavut, also found that both Arctic Cod and Shorthorn Sculpin (*Myoxocephalus scorpius*) altered their home range and movement in the presence of vessels, even when the vessels were stationary (Ivanova et al. 2018, 2020). However, in general very little is known about the impact of noise on fish and invertebrates in the Arctic (PAME 2019).

Despite documentation of many of the negative impacts on marine mammals during seismic surveys (e.g., see Kavanagh et al. 2019, and references within), the full extent of impacts are not fully understood, especially in this region (Kyhn et al. 2019). A recent seismic exposure study from the inner part of the Scoresby Sound in East Greenland, revealed a negative effect of the airgun pulses to Narwhal behaviour, resulting in deeper/longer dives and less foraging (GINR in press). Loud pulses/sounds caused by seismic could have serious effects on marine mammals during migration, potentially leading to entrapment and/or inhibit the calls of certain low-frequency species, such as Bowheads (Blackwell et al. 2013, Heide-Jørgensen et al. 2013). Local accounts from the community of Savissivik, Greenland, describe seeing Narwhals more agitated after seismic testing, and observed the whales staying further from land (Pikialasorsuaq Commission 2017). A comprehensive review of the impacts of underwater noise on marine mammals and fishes in the Canadian Arctic was recently presented in a state of knowledge report (PAME 2019). Despite being a pan-Arctic review, many of the key findings are also applicable to the North Water.

### 5.2.2. Commercial (large-scale) fishing

The impact of commercial fishing in the North Water is currently low (Table 4), as most activities occur in the waters south of the North Water. However, these large-scale offshore fishing operations may benefit from an extended open-water season and licenses to fish further north may be approved in the future. This would increase the fishing pressure on currently fished areas and possibly create new opportunities in areas that were previously inaccessible for too much of the year to be of interest. Of particular concern, harmful fishing practices, such as the use of longlines and bottom trawling equipment, are known to produce bycatch and can damage the sea floor structure and sensitive benthic communities (Jørgensen et al. 2016). A large expansion of summer fisheries and trawling activities in the North Water has the potential to substantially impact the local biodiversity, as well as important food sources that top predators depend on during winter in the polynya (Yurkowski et al. 2019). However, limited expansion of fisheries into the North Water may also represent an opportunity for northern communities, especially if operations are owned and/or managed locally.

## 6. CONCLUSION

While the North Water region has been intermittently studied over the years since 1867, many knowledge gaps exist and present challenges when evaluating long-term trends for the region. As described in this report, there are a number of themes that are lacking significantly in data (e.g., ice-associated algae, unique ice habitats, fiord/coastal interactions, and climatic projections). This can be attributed, in part, to the highly remote location of the North Water, high degree of connectivity and complexity within the system, and at times, jurisdictional challenges. As a result, sporadic research programs and varied sampling effort between Canada and Greenland, have resulted in short time-series and uncertainty in terms of the comparability of datasets, as technology and collection methods have evolved. Additionally, collection methods and availability of published knowledge (Indigenous/local and scientific) can vary between Canada and Greenland, resulting in different recommendations and/or monitoring actions by each country. It has been acknowledged that some historical scientific data may not be useful for our current thinking of the North Water ecosystem and its long-term health, and these data may be more appropriate when considering episodic impacts or short-term changes in the system.

The North Water is a system highly sensitive to changes in the physical environment, driven both by natural fluctuations and climatic influences. Yet, whether local changes being observed in this region are part of natural variability or if it is an emerging trend resulting from climate change is not fully understood. In the North Water, high inter-annual variability can be attributed to differences in year-to year ice cover, and a balance between oceanographic (i.e., ocean currents and temperature) and climatic forcings, with longer and shorter blooms during years of low and high ice cover, respectively. These observations have resulted in many uncertainties related to the actual degree/extent and timing of productivity in response to these changes, and overall biodiversity within the region. In addition, it remains unknown how these cascading changes in biophysical conditions will impact lower trophic levels up to higher trophic levels.

Some of the major uncertainties and knowledge gaps outlined in this report should help to inform future research priorities for the North Water region and facilitate informed future policy decisions. However, these research priorities will require longer timelines to properly account for any meaningful change in this complex system. It is expected that some of the uncertainties can and will be filled by future IQ collected in the region. Future collection of IQ and local/hunter knowledge, together with scientific knowledge, will lead to the most holistic understanding of the North Water system that addresses priorities of mutual importance. Inuit and local users of the region have an intimate connection and knowledge of the area and wildlife, including a historical understanding of the local system changes. As such, local communities are uniquely positioned to carry out year-round, sustained monitoring of the North Water (e.g., through Inuit Stewardship program, QIA 2020), which among other things, can lead to a better understanding of seasonality and long-term ecosystem change that is not achievable through short term periodic studies.

In collaboration with the governments of Greenland and Denmark, Fisheries and Oceans Canada organized a Canadian Science Advisory Secretariat (CSAS) meeting to review the state of knowledge of the North Water and surrounding area; this meeting was held on January 22–24, 2020, in Winnipeg, Manitoba, Canada. Participants were invited from Canada, Greenland, and Denmark, and were asked to review and contribute to this report, as well as provided scientific advice for a Science Advisory Report (DFO 2021). This document is intended to be a useful resource for future consultations with partners, and help to guide co-development of research priorities between Inuit of the region and international researchers. Although we note fundamental biological, oceanographic, and cultural differences between the two sides of the North Water region that occur within the jurisdictions of Canada, Greenland, and the Kingdom of Denmark, this review is intended to be information applicable to the whole region, and can be considered when making management decisions either jointly or under each jurisdiction.

The continued development of spatial mapping exercises/databases and hotspots analyses for the North Water (e.g., Christensen et al. 2017) will be an important tool in providing baseline measures to help guide future discussion of important and vulnerable areas, and can easily be expanded on in the future (i.e., updated layers, sources of information). As our understanding of the overall changing Arctic system continues to expand, so must our understanding of the links between regional dynamics, and global climate change and variability. It is important to document and understand the changes that are already occurring, as the future of the North Water is uncertain.

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# APPENDIX 1: LIST OF PHYTOPLANKTON, ICE ALGAE, AND PLANKTONIC PROTIST TAXA REPORTED FROM MARINE WATERS OF THE NORTH WATER

*Table A1. List of known phytoplankton, ice algae, and planktonic protist taxa reported from marine waters of the North Water.*

| **Taxonomic Nomenclature[1]** | **Authority[2]** | **Source(s)** |
|---|---|---|
| Bacillariophyta | | |
| *Actinocyclus curvatulus*[3] | Janisch in A. Schmidt | Grøntved and Seidenfaden (1938), Lovejoy et al. (2002) |
| *Actinocyclus tenuissimus* | Cleve | Lovejoy et al. (2002) |
| *Amphora* spp. | - | Lovejoy et al. (2002) |
| *Amphora laevis* var. *laevissim* | (Gregory) Cleve | Lovejoy et al. (2002) |
| *Arcocellulus cornucervis* | Hasle, von Stosch, and Syvertsen | Lovejoy et al. (2002) |
| *Asteromphalus robustus* | Castracane | Grøntved and Seidenfaden (1938) |
| *Attheya* sp. | T. West | Lovejoy et al. (2002) |
| *Attheya septentrionalis*[4] | (Østrup) Crawford | Grøntved and Seidenfaden (1938), Lovejoy et al. (2002) |
| *Bacterosira bathyomphala*[5] | (Cleve) Syvertsen and Hasle | Grøntved and Seidenfaden (1938), Lovejoy et al. (2002) |
| *Brockmanniella* sp. | Hasle, von Stosch and Syvertsen | Lovejoy et al. (2002) |
| *Chaetoceros* spp. | - | Lewis et al. (1996) |
| *Chaetoceros* cf. *affinis* | Lauder | Lovejoy et al. (2002) |
| *Chaetoceros atlanticus* | Cleve | Grøntved and Seidenfaden (1938), Lovejoy et al. (2002) |
| *Chaetoceros borealis* | Bailey | Grøntved and Seidenfaden (1938), Booth et al. (2002) |
| *Chaetoceros brevis* | Schütt | Lovejoy et al. (2002) |
| *Chaetoceros compressus* | Lauder | Grøntved and Seidenfaden (1938) |
| *Chaetoceros concavicornis* | Mangin | Grøntved and Seidenfaden (1938), Lovejoy et al. (2002) |
| *Chaetoceros convolutus* | Castracane | Grøntved and Seidenfaden (1938), Lovejoy et al. (2002) |
| *Chaetoceros debilis* | Cleve | Grøntved and Seidenfaden (1938), Lovejoy et al. (2002) |
| *Chaetoceros decipiens* | Cleve | Grøntved and Seidenfaden (1938), Lovejoy et al. (2002), Caron et al. (2004) |
| *Chaetoceros densus* | Cleve | Grøntved and Seidenfaden (1938) |

| **Taxonomic Nomenclature[1]** | **Authority[2]** | **Source(s)** |
|---|---|---|
| *Chaetoceros diadema* | (Ehrenberg) Gran | Grøntved and Seidenfaden (1938), Lovejoy et al. (2002) |
| *Chaetoceros fragilis* | Meunier | Grøntved and Seidenfaden (1938) |
| *Chaetoceros furcellatus* | Bailey | Grøntved and Seidenfaden (1938) |
| *Chaetoceros gelidus* | - | Joli et al. (2018) |
| *Chaetoceros glacialis* | Schütt | Grøntved and Seidenfaden (1938) |
| *Chaetoceros hyalochaete* | - | Mostajir et al. (2001), Acuña et al. (2002) |
| *Chaetoceros karianus* | Grunow | Grøntved and Seidenfaden (1938), Lovejoy et al. (2002) |
| *Chaetoceros laciniosus* | Schütt | Grøntved and Seidenfaden (1938), Lovejoy et al. (2002) |
| *Chaetoceros mitra* | (Bailey) Cleve | Lovejoy et al. (2002) |
| *Chaetoceros neogracile* | - | Joli et al. (2018) |
| *Chaetoceros radicans* | Schütt | Lovejoy et al. (2002) |
| *Chaetoceros* cf. *simplex* | Ostenfeld | Lovejoy et al. (2002) |
| *Chaetoceros socialis* | Lauder | Grøntved and Seidenfaden (1938), Borstad and Gower (1984), Mostajir et al. (2001), Acuña et al. (2002), Lovejoy et al. (2002), Caron et al. (2004) |
| *Chaetoceros* cf. *tenuissimus* | Meunier | Lovejoy et al. (2002) |
| *Chaetoceros teres* | Cleve | Grøntved and Seidenfaden (1938), Lovejoy et al. (2002) |
| *Chaetoceros wighamii* | Brightwell | Grøntved and Seidenfaden (1938), Lovejoy et al. (2002) |
| *Coscinodiscus asteromphalus* | Ehrenberg | Lovejoy et al. (2002) |
| *Coscinodiscus centralis* | Ehrenberg | Grøntved and Seidenfaden (1938), Lovejoy et al. (2002) |
| *Coscinodiscus radiatus* | Ehrenberg | Lovejoy et al. (2002) |
| *Coscinosira polychorda* | Gran | Grøntved and Seidenfaden (1938) |
| *Cylindrotheca closterium*[6] | (Ehrenberg) Lewin and Reimann | Grøntved and Seidenfaden (1938), Lovejoy et al. (2002) |
| *Dactyliosolen fragilissimus* | (Bergon) Hasle | Lovejoy et al. (2002) |
| *Detonula* sp. | - | Booth et al. (2002) |
| *Detonula confervacea* | (Cleve) Gran | Grøntved and Seidenfaden (1938), Lovejoy et al. (2002) |

| **Taxonomic Nomenclature[1]** | **Authority[2]** | **Source(s)** |
|---|---|---|
| *Ditylum brightwellii* | (West) Grunow in Van Heurck | Lovejoy et al. (2002) |
| *Entomoneis* cf. *alata* | (Ehrenberg) Poulin and Cardinal | Lovejoy et al. (2002) |
| *Eucampia groenlandica* | Cleve | Lovejoy et al. (2002) |
| *Eucampia zoodiacus* | Ehrenberg | Grøntved and Seidenfaden (1938) |
| *Fallacia* sp. | - | Lovejoy et al. (2002) |
| *Fossula arctica* | Hasle, Syvertsen and Quillfeldt | Bouillon et al. (2002), Lovejoy et al. (2002), Caron et al. (2004) |
| *Fragilaria* spp. | - | Grøntved and Seidenfaden (1938), Lewis et al. (1996) |
| *Fragilaria islandica* | Grunow | Grøntved and Seidenfaden (1938) |
| *Fragilaria oceanica*[7] | Cleve | Grøntved and Seidenfaden (1938) |
| *Fragilariopsis cylindrus*[7,8] | (Grunow) Krieger in Helmcke and Krieger | Borstad and Gower (1984), Lovejoy et al. (2002), Caron et al. (2004) |
| *Fragilariopsis cylindrus/oceanica*[7] | - | Bouillon et al. (2002) |
| *Fragilariopsis oceanica*[7,9] | (Cleve) Hasle | Borstad and Gower (1984), Lovejoy et al. (2002) |
| *Lennoxia faveolata* | Thomsen and Buck | Lovejoy et al. (2002) |
| *Leptocylindrus danicus* | Cleve | Grøntved and Seidenfaden (1938), Lovejoy et al. (2002) |
| *Manguinea* sp. | Paddock | Lovejoy et al. (2002) |
| *Melosira* spp. | - | Lewis et al. (1996) |
| *Melosira arctica* | Dickie | Grøntved and Seidenfaden (1938), Lovejoy et al. (2002), Caron et al. (2004) |
| *Minidiscus* sp. | Hasle | Lovejoy et al. (2002) |
| *Minutocellus* sp. | Hasle, von Stosch and Syvertsen | Lovejoy et al. (2002) |
| *Navicula* spp. | - | Lewis et al. (1996), Lovejoy et al. (2002) |
| *Navicula directa* | (W. Smith) Ralfs | Lovejoy et al. (2002) |
| *Navicula granii* | (Jorgensen) Gran | Grøntved and Seidenfaden (1938), Lovejoy et al. (2002) |
| *Navicula impexa*[10] | Hustedt | Lovejoy et al. (2002) |
| *Navicula* cf. *obtusa* | Cleve | Lovejoy et al. (2002) |

| **Taxonomic Nomenclature**[1] | **Authority**[2] | **Source(s)** |
|---|---|---|
| *Navicula pelagica* | Cleve | Bouillon et al. (2002), Lovejoy et al. (2002) |
| *Navicula septentrionalis* | (Grunow) Gran | Grøntved and Seidenfaden (1938), Lovejoy et al. (2002) |
| *Navicula transitans* var. *derasa* f. *delicatula* | Heimdal | Lovejoy et al. (2002) |
| *Navicula vanhoeffenii* | Gran | Grøntved and Seidenfaden (1938), Lovejoy et al. (2002) |
| *Nitzschia* spp. | - | Lewis et al. (1996) |
| *Nitzschia arctica* | Cleve | Lovejoy et al. (2002) |
| *Nitzschia* cf. *dissipata* | (Kützing) Grunow | Lovejoy et al. (2002) |
| *Nitzschia frigida* | Grunow | Grøntved and Seidenfaden (1938), Lovejoy et al. (2002), Caron et al. (2004) |
| *Nitzschia frigida/neofrigida* | - | Bouillon et al. (2002) |
| *Nitzschia longissima* | Brébisson (Kützing) Ralfs in Pritchard | Lovejoy et al. (2002) |
| *Nitzschia promare* | Medlin | Lovejoy et al. (2002) |
| *Pauliella taeniata*[11] | (Grunow) Round and Basson | Grøntved and Seidenfaden (1938), Bouillon et al. (2002), Lovejoy et al. (2002) |
| *Plagiotropis* cf. *longa* | (Cleve) Kuntze | Lovejoy et al. (2002) |
| *Pleurosigma*spp. | - | Grøntved and Seidenfaden (1938), Lovejoy et al. (2002) |
| *Porosira glacialis* | (Grunow) Jørgensen | Grøntved and Seidenfaden (1938), Bouillon et al. (2002), Lovejoy et al. (2002) |
| *Pseudogomphonema articum* | (Grunow) Medlin | Lovejoy et al. (2002) |
| *Pseudo-nitzschia* spp. | - | Booth et al. (2002), Lovejoy et al. (2002), Joli et al. (2018) |
| *Pseudo-nitzschia delicatissima* | (Cleve) Heiden in Heiden and Kolbe | Lovejoy et al. (2002) |
| *Pseudo-nitzschia granii* | (Hasle) Hasle and Syvertsen | Lovejoy et al. (2002) |
| *Pseudo-nitzschia seriata* f. *seriata*[12] | (Cleve) H. Pergallo in H. and M. Pergallo | Grøntved and Seidenfaden (1938), Lovejoy et al. (2002) |
| *Rhizosolenia* sp. | - | Booth et al. (2002) |
| *Rhizosolenia hebetata* f. *hebetata* | Bailey | Lovejoy et al. (2002) |

| **Taxonomic Nomenclature**[1] | **Authority**[2] | **Source(s)** |
|---|---|---|
| *Rhizosolenia hebetata* f. *hiemalis* | (Bailey) Gran Gran | Grøntved and Seidenfaden (1938) |
| *Rhizosolenia hebetata* f. *semispina* | (Bailey) Gran (Hensen) Gran | Grøntved and Seidenfaden (1938) |
| *Rhizosolenia imbricata* v. *Schrubsolei* | (Bailey) Gran (Cleve) Schroeder | Grøntved and Seidenfaden (1938) |
| *Skeletonema costatum* | (Greville) Cleve | Lovejoy et al. (2002) |
| *Synedropsis hyperborea* | (Grunow) Hasle, Medlin, and Syvertsen | Lovejoy et al. (2002), Caron et al. (2004) |
| *Thalassiosira* spp. | - | Lewis et al. (1996), Mostajir et al. (2001), Booth et al. (2002) |
| *Thalassiosira angulata* | (Gregory) Hasle | Lovejoy et al. (2002) |
| *Thalassiosira anguste-lineata* | (A. Schmidt) Fryxell and Hasle | Lovejoy et al. (2002) |
| *Thalassiosira antarctica*[13] | - | Acuña et al. (2002), Lovejoy et al. (2002) |
| *Thalassiosira bioculata* | (Grunow) Ostenfeld | Grøntved and Seidenfaden (1938), Acuña et al. (2002), Lovejoy et al. (2002) |
| *Thalassiosira bulbosa* | Syvertsen | Lovejoy et al. (2002) |
| *Thalassiosira gravida* | Cleve | Grøntved and Seidenfaden (1938) |
| *Thalassiosira hyalina* | (Grunow) Gran | Lovejoy et al. (2002), Caron et al. (2004) |
| *Thalassiosira* cf. *poroseriata* | (Ramsfjell) Hasle | Lovejoy et al. (2002) |
| *Thalassiosira nordenskioeldii* | Cleve | Grøntved and Seidenfaden (1938), Lovejoy et al. (2002), Caron et al. (2004) |
| *Thalassiothrix longissima* | Cleve and Grunow | Grøntved and Seidenfaden (1938), Lovejoy et al. (2002), Caron et al. (2004) |
| Pyrrophycophyta | | |
| Dinoflagellate species | - | Lewis et al. (1996) |
| *Achradina* sp. | Lohmann | Lovejoy et al. (2002) |
| *Actiniscus pentasterias* | (Ehrenberg) Ehrenberg | Lovejoy et al. (2002) |
| *Alexandrium* sp. | Halim | Lovejoy et al. (2002) |
| cf. *Alexandrium* cysts. | - | Lovejoy et al. (2002) |
| Amphidinium spp. | Claparéde and Lachmann | Lovejoy et al. (2002) |
| *Amphidinium* aff. *carterae* | Hulburt | Lovejoy et al. (2002) |

| **Taxonomic Nomenclature**[1] | **Authority**[2] | **Source(s)** |
|---|---|---|
| *Amphidinium sphenoides* | Wülff | Lovejoy et al. (2002) |
| Calciodinellaceae aff. *Scrippsiella* spp.[14] | Taylor; Balech ex Loeblich III spp. | Lovejoy et al. (2002) |
| *Ceratium* sp. | - | Grøntved and Seidenfaden (1938) |
| *Ceratium arcticum* | (Ehrenberg) Cleve | Grøntved and Seidenfaden (1938), Booth et al. (2002), Lovejoy et al. (2002) |
| *Ceratium fusus* | (Ehrenberg) Dujardin | Lovejoy et al. (2002) |
| *Ceratium horridum* | (Cleve) Gran | Lovejoy et al. (2002) |
| *Ceratium lineatum* | (Ehrenberg) Cleve | Lovejoy et al. (2002) |
| Cochlodinium spp. | Schütt | Lovejoy et al. (2002) |
| Corythodinium sp. | Loeblich Jr. and Loeblich III | Lovejoy et al. (2002) |
| Cysts, dinoflagellate spp. (not identified) | - | Lovejoy et al. (2002) |
| *Dicroerisma psilonereiella* | Taylor and Cattell | Lovejoy et al. (2002) |
| *Dinophysis arctica* | Mereschkowsky | Grøntved and Seidenfaden (1938) |
| *Dinophysis norvegica* | Claparéde and Lachmann | Grøntved and Seidenfaden (1938) |
| *Dinophysis acuminata* | Claparéde and Lachmann | Grøntved and Seidenfaden (1938), Lovejoy et al. (2002) |
| *Diplopsalis lenticula*[15] | Bergh | Grøntved and Seidenfaden (1938), Lovejoy et al. (2002) |
| *Glenodinium danicum* | Paulsen | Grøntved and Seidenfaden (1938) |
| *Gonyaulax* spp. | Diesing | Lovejoy et al. (2002) |
| *Gonyaulax catenata* | (Levand.) Kofoid | Grøntved and Seidenfaden (1938) |
| *Gonyaulax grindleyi* | Reinecke | Lovejoy et al. (2002) |
| *Gonyaulax scrippsae*[16] | Kofoid | Grøntved and Seidenfaden (1938) |
| *Gonyaulax spinifera* | (Claparéde and Lachmann) Diesing | Lovejoy et al. (2002) |
| *Gonyaulax triacantha* | Jørgensen | Grøntved and Seidenfaden (1938) |
| *Gymnodinium* spp. | Kofoid and Swezy | Lovejoy et al. (2002) |
| *Gymnodinium arcticum* | Wülff | Lovejoy et al. (2002) |
| *Gymnodinium aureolum* | (Hulburt) Hansen | Lovejoy et al. (2002) |
| *Gymnodinium* aff. *dentatum* | Larsen. | Lovejoy et al. (2002) |
| *Gymnodinium elongatum* | Hope | Lovejoy et al. (2002) |
| *Gymnodinium galeatum* | Larsen | Lovejoy et al. (2002) |

| **Taxonomic Nomenclature[1]** | **Authority[2]** | **Source(s)** |
|---|---|---|
| *Gymnodinium gracile* | Bergh | Lovejoy et al. (2002) |
| *Gymnodinium* aff. *octo* | Larsen | Lovejoy et al. (2002) |
| *Gymnodinium simplex* | (Lohmann) Kofoid and Swezy | Lovejoy et al. (2002) |
| *Gymnodinium* aff. *instriatum* | Fredudenthal and Lee | Lovejoy et al. (2002) |
| *Gymnodinium* aff. *minutulum* | Larsen | Lovejoy et al. (2002) |
| *Gymnodinium* aff. *parvum* | Larsen | Lovejoy et al. (2002) |
| *Gymnodinium* aff. *pseudonoctiluca* | Pouchet | Lovejoy et al. (2002) |
| *Gymnodinium/Gyrodinium* spp. | - | Lovejoy et al. (2002) |
| *Polarella* glacialis | Montresor et al. | Lovejoy et al. (2002) |
| *Polarella* cysts | Montresor et al. | Lovejoy et al. (2002) |
| *Gyrodinium* sp. | - | Mostajir et al. (2001), Joli et al. (2018) |
| *Gyrodinium* aff. *esturiale* | Hulburt | Lovejoy et al. (2002) |
| *Gyrodinium flagellare* | Schiller | Lovejoy et al. (2002) |
| *Gyrodinium helveticum* | - | Joli et al. (2018) |
| *Gyrodinium lachryma* | (Meunier) Kofoid and Swezy | Lovejoy et al. (2002) |
| *Gyrodinium pepo* | (Schütt) Kofoid and Swezy | Lovejoy et al. (2002) |
| *Gyrodinium pingue* | (Schütt) Kofoid and Swezy | Lovejoy et al. (2002) |
| *Gyrodinium spirale* | (Bergh) Kofoid and Swezy | Lovejoy et al. (2002), Joli et al. (2018) |
| Gymnodiniales | - | Joli et al. (2018) |
| *Heterocapsa rotundata* | (Lohmann) Hansen | Lovejoy et al. (2002) |
| *Heterocapsa triquetra* | (Ehrenberg) Stein | Lovejoy et al. (2002) |
| *Katodinium* sp. | Fott | Lovejoy et al. (2002) |
| *Katodinium glaucum* | (Labour) Loeblich | Lovejoy et al. (2002) |
| *Lingulodinium polyedrum*[17] | (Stein) Dodge | Lovejoy et al. (2002) |
| *Mesoporos perforatus* | (Gran) Lillick | Lovejoy et al. (2002) |
| *Micracanthodinium claytonii* | (Holmes) Dodge | Lovejoy et al. (2002) |
| *Nematodinium* sp. | - | Joli et al. (2018) |
| *Oxyphysis* sp. | Kofoid | Lovejoy et al. (2002) |
| *Oxytoxum gracile* | Schiller | Lovejoy et al. (2002) |

| **Taxonomic Nomenclature[1]** | **Authority[2]** | **Source(s)** |
|---|---|---|
| *Peridinium triquetrum* | (Ehrenberg) Lebour | Grøntved and Seidenfaden (1938) |
| *Phalacroma rotundatum* | Claparéde and Lachmann and Kofoid and Michener | Grøntved and Seidenfaden (1938) |
| *Pronoctiluca pelagica* | Fabre-Domergue | Lovejoy et al. (2002) |
| *Prorocentrum balticum* | (Lohmann) Loeblich III | Lovejoy et al. (2002) |
| *Prorocentrum minimum* | (Pavillard) Schiller | Lovejoy et al. (2002) |
| *Prorocentrum scutellum* | Schröder | Lovejoy et al. (2002) |
| *Protoceratium spinulosum* | (Murray and Whitting) Schiller | Lovejoy et al. (2002) |
| *Protherythropsis vigilans* | Marshall | Lovejoy et al. (2002) |
| *Protoperidinium* sp. | Bergh | Lovejoy et al. (2002) |
| *Protoperidinium acrcticum*[18] | - | Grøntved and Seidenfaden (1938) |
| *Protoperidinium bipes*[19] | (Paulsen) Balech | Grøntved and Seidenfaden (1938), Lovejoy et al. (2002) |
| *Protoperidinium brevipes*[20] | (Paulsen) Balech | Grøntved and Seidenfaden (1938), Lovejoy et al. (2002) |
| *Protoperidinium cerasus*[21] | - | Grøntved and Seidenfaden (1938) |
| *Protoperidinium conicoides*[21] | - | Grøntved and Seidenfaden (1938) |
| *Protoperidinium conicum*[21] | - | Grøntved and Seidenfaden (1938) |
| *Protoperidinium curvipes*[21] | - | Grøntved and Seidenfaden (1938) |
| *Protoperidinium depressum*[21] | - | Grøntved and Seidenfaden (1938) |
| *Protoperidinium granii* | (Ostenfeld) Balech | Lovejoy et al. (2002) |
| *Protoperidinium islandicum*[21] | - | Grøntved and Seidenfaden (1938) |
| *Protoperidinium laticeps*[21] | - | Grøntved and Seidenfaden (1938) |
| *Protoperidinium leonis* | - | Grøntved and Seidenfaden (1938) |
| *Protoperidinium monacanthum*[21] | - | Grøntved and Seidenfaden (1938) |
| *Protoperidinium ovatum*[21] | - | Grøntved and Seidenfaden (1938) |
| *Protoperidinium pallidum*[21] | - | Grøntved and Seidenfaden (1938) |
| *Protoperidinium pellucidum*[21] | - | Grøntved and Seidenfaden (1938) |
| *Protoperidinium pellucidum* Bergh | - | Lovejoy et al. (2002) |
| *Protoperidinium roseum*[21] | - | Grøntved and Seidenfaden (1938) |
| *Protoperidinium saltans*[21] | - | Grøntved and Seidenfaden (1938) |
| *Protoperidinium subinerme*[21] | - | Grøntved and Seidenfaden (1938) |

| **Taxonomic Nomenclature[1]** | **Authority[2]** | **Source(s)** |
|---|---|---|
| *Protoperidinium thorianum*[21] | (Paulsen) Balech | Grøntved and Seidenfaden (1938), Lovejoy et al. (2002) |
| *Pyrocystis* | Murray ex Haeckel sp. | Lovejoy et al. (2002) |
| *Torodinium robustum* | Kofoid and Swezy | Lovejoy et al. (2002) |
| *Torodinium teredo* | (Pouchet) Kofoid and Swezy | Lovejoy et al. (2002) |
| Parasitic dinoflagellates (associated with diatoms) cf. *Paulsenella chaetoceratis* | (Paulsen) Chatton | Lovejoy et al. (2002) |
| Duboscquellida | - | Joli et al. (2018) |
| Syndiniales[22] | - | Joli et al. (2018) |
| Ciliophora | | |
| *Acanthostomella* cf. *gracilis* | Brandt | Lovejoy et al. (2002) |
| *Acanthostomella norvegica* | (Daday) Jørgensen | Grøntved and Seidenfaden (1938) |
| *Askenasia* sp. | - | Joli et al. (2018) |
| *Askenasia* aff. *stellaris* | (Leegaard) Kahl | Lovejoy et al. (2002) |
| *Aspidisca* sp. | - | Lovejoy et al. (2002) |
| *Balanion comatum* | Wülff | Lovejoy et al. (2002) |
| Choreotrichida | - | Joli et al. (2018) |
| Ciliate cysts | - | Lovejoy et al. (2002) |
| *Codonella* sp. | - | Grøntved and Seidenfaden (1938) |
| *Coxliella ampla* | Jörgensen | Lovejoy et al. (2002) |
| *Didinium* sp. | Stein | Lovejoy et al. (2002) |
| *Euplotida* spp. | Small and Lynn | Lovejoy et al. (2002) |
| *Laboea strobila* | Lohmann | Lovejoy et al. (2002) |
| *Leegaardiella sol* | Lynn and Montagnes | Lovejoy et al. (2002) |
| *Leprotintinnus bottnicus* | (Nordqvist) Jørgensen | Grøntved and Seidenfaden (1938) |
| *Leprotintinnus pellucidus* | (Cleve) Jørgensen | Grøntved and Seidenfaden (1938) |
| Litostomatea | - | Joli et al. (2018) |
| *Lohmanniella oviformis* | Leegaard | Lovejoy et al. (2002) |
| *Mesodinium* spp. | Stein | Lovejoy et al. (2002) |
| *Mesodinium rubrum* | Leegaard | Lovejoy et al. (2002) |
| *Monodinium* sp. | - | Joli et al. (2018) |
| Oligotrichida | - | Joli et al. (2018) |

| **Taxonomic Nomenclature**[1] | **Authority**[2] | **Source(s)** |
|---|---|---|
| *Parafavella denticulata* | Ehrenberg | Grøntved and Seidenfaden (1938), Lovejoy et al. (2002) |
| *Parafavella edentata* | (Brandt) Kofoid and Campbell | Grøntved and Seidenfaden (1938) |
| *Parafavella elegans* | Ostenfeld | Lovejoy et al. (2002) |
| *Parafavella gigantea* | Brandt | Grøntved and Seidenfaden (1938), Lovejoy et al. (2002) |
| *Parafavella robusta* | (Jørgensen) Kofoid and Campbell | Grøntved and Seidenfaden (1938) |
| Peritrichous ciliates | - | Lovejoy et al. (2002) |
| *Ptychocylis* sp. | - | Acuña et al. (2002) |
| *Ptychocylis acuta* | Brandt | Lovejoy et al. (2002) |
| *Ptychocylis drygalskii* | Brandt | Grøntved and Seidenfaden (1938) |
| *Ptychocylis obtusa* | Brandt | Grøntved and Seidenfaden (1938), Lovejoy et al. (2002) |
| *Ptychocylis urnula* | (Claparéde and Lachmann) Brandt | Grøntved and Seidenfaden (1938) |
| *Salpingacantha undata* | (Jørgensen) Kofoid and Campbell | Grøntved and Seidenfaden (1938) |
| *Stenosemella steinii* | Jörgensen | Lovejoy et al. (2002) |
| *Strobilidium* sp. (with Chl) | Schewiakoff | Lovejoy et al. (2002) |
| *Strombidinopsis* sp. | Kent | Lovejoy et al. (2002) |
| *Strombidium* spp. | Claparédee and Lachmann | Lovejoy et al. (2002) |
| *Strombidium chlorophilum* | Montagnes et al. | Lovejoy et al. (2002) |
| *Strombidium conicum* | (Lohmann) Wülff | Lovejoy et al. (2002) |
| *Strombidium constrictum* | (Meunier) Wülff | Lovejoy et al. (2002) |
| *Strombidium* aff. *inclinatum* | Montagnes, Taylor and Lynn 1990 | Lovejoy et al. (2002) |
| *Strombidium lagenula* | Fauré-Fremiet | Lovejoy et al. (2002) |
| *Strombidium* aff. *striatum* | (Wülff) Kahl | Lovejoy et al. (2002) |
| *Tintinnopsis* sp. | - | Grøntved and Seidenfaden (1938) |
| *Tintinnopsis beroidea* | Stein | Lovejoy et al. (2002) |
| *Tintinnopsis lata* | Meunier | Grøntved and Seidenfaden (1938) |
| *Tintinnopsis sinuata* | Brandt | Grøntved and Seidenfaden (1938) |
| *Tontonia gracillima* | Fauré-Fremiet | Lovejoy et al. (2002) |
| *Urotricha* | - | Joli et al. (2018) |

| Taxonomic Nomenclature[1] | Authority[2] | Source(s) |
|---|---|---|
| Chlorophyta | | |
| *Brachiomonas submarina* | Bohlin | Lovejoy et al. (2002) |
| *Chlamydomonas* sp. | Ehrenberg | Lovejoy et al. (2002) |
| *Cymbomonas tetramitiformis* | Schiller | Lovejoy et al. (2002) |
| *Diplostauron pentagonium* | (Hazen) Pascher | Lovejoy et al. (2002) |
| *Dunaliella* spp. | Teodoresco | Lovejoy et al. (2002) |
| *Mamiella gilva* | (Parke and Rayns) Moestrup | Lovejoy et al. (2002) |
| *Mantoniella squamata* | (Manton and Parke) Desikachary | Lovejoy et al. (2002) |
| *Micromonas polaris* | Simon, foulon and Marin | Joli et al. (2018) |
| *Micromonas pusilla* | (Butcher) Manton and Parke | Lovejoy et al. (2002) |
| *Nephroselmis* sp. | Stein | Lovejoy et al. (2002) |
| *Nephroselmis pyriformis* | (N. Carter) Ettl | Lovejoy et al. (2002) |
| *Nephroselmis rotunda* | (N. Carter) Fott | Lovejoy et al. (2002) |
| *Pachysphaera* spp. | Ostenfeld | Lovejoy et al. (2002) |
| *Polytoma papillata* | Pascher | Lovejoy et al. (2002) |
| *Pseudoscourfieldia marina* | (Throndsen) Manton | Lovejoy et al. (2002) |
| *Pterosperma* spp. | Pouchet | Lovejoy et al. (2002) |
| *Pyramimonas* spp. | Schmarda | Lovejoy et al. (2002), Joli et al. (2018) |
| *Pyramimonas groenlandica* | Daugbjerg unpub | Lovejoy et al. (2002) |
| *Resultor mikron* | (Throndsen) Moestrup | Lovejoy et al. (2002) |
| Cryptophyceae | | |
| *Chroomonas* sp. | Hansgirg | Lovejoy et al. (2002) |
| *Falcomonas daucoides* | (Conradand Kufferath) Hill | Lovejoy et al. (2002) |
| *Goniomonas* spp. | Stein | Lovejoy et al. (2002) |
| *Hemiselmis* sp. | Parke | Lovejoy et al. (2002) |
| *Hillea* spp. | Schiller | Lovejoy et al. (2002) |
| *Plagioselmis nordica* | (Novarino, Lucas and Morrall) Novarino | Lovejoy et al. (2002) |
| *Rhinomonas* spp. | Hill and Wetherbee | Lovejoy et al. (2002) |
| *Rhodomonas* | Karsten (emended Hill and Wetherbee) | Lovejoy et al. (2002) |

| **Taxonomic Nomenclature[1]** | **Authority[2]** | **Source(s)** |
|---|---|---|
| *Teleaulax* sp. | Hill | Lovejoy et al. (2002) |
| *Teleaulax acuta* | (Butcher) Hill | Lovejoy et al. (2002) |
| *Baffinella fridgidis* | Norlin and Daugbjerg | Daugbjerg et al. (2018) |
| Kathablepharidacea | | |
| *Katablepharis sp.* | Skuja | Joli et al. 2018 |
| *Leucocryptos marina* | (Braarud) Butcher | Lovejoy et al. (2002) |
| *Leucocryptos remigera* | Vørs | Lovejoy et al. (2002) |
| Prymnesiophyceae | | |
| Coccolithophorida spp. | - | Lovejoy et al. (2002) |
| *Chrysochromulina* spp. | Lackey | Lovejoy et al. (2002), Joli et al. (2018) |
| *Chrysochromulina scutellum* | (Eikrem and Moestrup/C. ahrengotii Jensen and Moestrup | Lovejoy et al. (2002) |
| *Corymbellus aureus* Green | - | Lovejoy et al. (2002) |
| *Dicrateria*/*Imantonia* spp. | Parke/Reynolds | Lovejoy et al. (2002) |
| *Phaeocystis* spp. | Lagerheim | Lovejoy et al. (2002), Joli et al. (2018) |
| *Phaeocystis pouchetii* | (Hariot) Lagerheim | Grøntved and Seidenfaden (1938), Lovejoy et al. (2002) |
| Other Prymnesiophytes spp. | - | Lovejoy et al. (2002) |
| Raphidophyceae | | |
| *Heterosigma* sp. | Hada | Lovejoy et al. (2002) |
| *Heterosigma inlandica* | Hada | Lovejoy et al. (2002) |
| Straminopiles (incertae sedis heterotrophic taxa) | | |
| Commation cryoporinum | Thomsen and Larsen | Lovejoy et al. (2002) |
| Bicosoecida | | |
| Cafeteria spp. | Fenchel and Paterson | Lovejoy et al. (2002) |
| *Pseudobodo tremulans* | Griessmann | Lovejoy et al. (2002) |
| *Bicosoeca gracilipes* | James-Clark | Lovejoy et al. (2002) |
| *Bicosoeca planktonica* | Kisselew | Lovejoy et al. (2002) |
| *Bicosoeca mignotii* | Moestrup, Thomsen and Hibberd | Lovejoy et al. (2002) |
| Chrysophyceae | | |
| Parmales spp. | Booth and Marchant | Lovejoy et al. (2002) |

| **Taxonomic Nomenclature**[1] | **Authority**[2] | **Source(s)** |
|---|---|---|
| Chrysophyte (external epibionts of diatoms) | - | Lovejoy et al. (2002) |
| Chrysophyte (internal parasite of *Thalassiosira*) | - | Lovejoy et al. (2002) |
| Chrysophyte cysts spp. | - | Lovejoy et al. (2002) |
| *Dinobryon* sp. | - | Booth et al. (2002) |
| *Dinobryon balticum* | (Schütt) Lemmermann | Lovejoy et al. (2002) |
| *Dinobryon belgica* | Meunier | Lovejoy et al. (2002) |
| *Dinobryon faculiferum* | (Willén) Willén | Lovejoy et al. (2002) |
| *Ochromonas* spp. | - | Lovejoy et al. (2002) |
| *Ochromonas* cf. *bourrellyi* | Magne | Lovejoy et al. (2002) |
| *Ochromonas* cf. *cosmopoliticus* | Ruinen | Lovejoy et al. (2002) |
| *Sarcinochrysis* cf. *marina* | Geitler | Lovejoy et al. (2002) |
| *Ollicola vangoorii* | (Conrad) Vørs | Lovejoy et al. (2002) |
| Dictyochophyceae | | |
| *Actinomonas mirabilis* | Kent | Lovejoy et al. (2002) |
| *Apedinella spinifera* | (Throndsen) Throndsen | Lovejoy et al. (2002) |
| *Dictyocha speculum*[23] | Ehrenberg | Grøntved and Seidenfaden (1938), Mostajir et al. (2001), Booth et al. (2002), Lovejoy et al. (2002) |
| *Parapedinella reticulata* | Pedersen and Thomsen | Lovejoy et al. (2002) |
| Pedinellid spp. *(Pseudopedinella/Mesopedinella)* | N. Carter/Daugbjerg | Lovejoy et al. (2002) |
| *Pseudopedinella pyriforme* | N. Carter | Lovejoy et al. (2002) |
| *Pseudopedinella tricostata* | (Rouchijajnen) Thomsen | Lovejoy et al. (2002) |
| *Ciliophrys infusionum* | Cienkowski | Lovejoy et al. (2002) |
| Euglenophyceae | | |
| *Eutreptia* spp. | Perty | Lovejoy et al. (2002) |
| *Eutreptiella* spp. | de Cunha | Lovejoy et al. (2002) |
| *Anisonema* cf. *prosgeobium* Skuja sp. | - | Lovejoy et al. (2002) |
| Other heterotrophic protozists | | |
| Kinetoplastea | | |
| *Bodo* spp. | Ehrenberg | Lovejoy et al. (2002) |
| *Cryptaulax marina* | Throndsen | Lovejoy et al. (2002) |

| **Taxonomic Nomenclature[1]** | **Authority[2]** | **Source(s)** |
|---|---|---|
| *Bordnamonas tropicana* | Larsen and Patterson | Lovejoy et al. (2002) |
| *Rhynchomonas nasuta* | (Stokes) Klebs | Lovejoy et al. (2002) |
| Choanoflagellata | | |
| Choanoflagellates spp. colonial cf. *Parvicorbicula* spp. | - | Lovejoy et al. (2002) |
| *Salpingoeca* spp. | James-Clark | Lovejoy et al. (2002) |
| Fungi | | |
| Chytrid spp. (associated with diatoms) | - | Lovejoy et al. (2002) |
| Fungal (Hyphomycete reproductive bodies) | - | Lovejoy et al. (2002) |
| Discosea | | |
| *Thecamoeba orbis* | Schaeffer | Lovejoy et al. (2002) |
| Amoebozoa incertae sedis | | |
| *Vanella* spp. | Bovee | Lovejoy et al. (2002) |
| Thecofilosea | | |
| *Paulinella ovalis* | (Wülff) Johnson et al. | Lovejoy et al. (2002) |
| *Ebria tripartita* | (Shumann) Lemmermann | Lovejoy et al. (2002) |
| cf. *Hermesinum adriaticum* | Zacharias | Lovejoy et al. (2002) |
| *Metromonas simplex* | (Griessmann) Larsen and Patterson | Lovejoy et al. (2002) |
| Cryothecomonas spp. | Thomsen et al. | Lovejoy et al. (2002), Thaler and Lovejoy (2012) Thaler and Lovejoy (2015) |
| Cercozoa incertae sedis | | |
| *Allantion tachyploon* | Sandon | Lovejoy et al. (2002) |
| *Quadricilia rotundata* | (Skuja) Vørs | Lovejoy et al. (2002) |
| Heterolobosea | | |
| *Percolomonas cosmopolitus* | (Ruinen) Fenchel and Patterson | Lovejoy et al. (2002) |
| Heliozoa | | |
| *Meringosphaera mediterranea* | Lohmann | Lovejoy et al. (2002) |
| Picozoa | | |
| Picozoa spp. | Seenivasan et al | Freyria et al.( 2021), Joli et al. (2018). Thaler and Lovejoy (2015) |

| Taxonomic Nomenclature[1] | Authority[2] | Source(s) |
|---|---|---|
| Telonemia | | |
| *Telonemia spp.* | Shalchian-Tabrizi | Thaler and Lovejoy (2015) |
| *Telonema antarctica* | Thomsen | Lovejoy et al. (2002) |
| *Telonema subtile* | Griessmann | Lovejoy et al. (2002) |

1. An attempt was made to verify all synonyms using the taxonomic databases Algaebase and WoRMS. Where synonyms were found from multiple sources the most recently accepted name is reported. Where a species was not listed by more than one source the species name is generally included as provided in the source regardless of its current taxonomic standing.

2. Authorites are included only where provided by the source.

3. Originally reported as *Coscinodiscus curvatulus* v. *kariana* by Grøntved and Seidenfaden (1938).

4. Originally reported as *Chaetoceros septentrionalis* by Grøntved and Seidenfaden (1938).

5. Originally reported as *Bacteriosira fragilis* by Grøntved and Seidenfaden (1938).

6. Originally reported as *Nitzschia closterium* by Grøntved and Seidenfaden (1938).

7. The current standing of *Fragillaria* and *Fragillariopsis* is uncertain. Taxa are cited here as listed by the source.

8. Originally reported as *Nitzchia cylindrus* by Borstad and Gower (1984).

9. Originally reported as *Nitzchia grunowii* by Borstad and Gower (1984).

10. Reported as *N. implexa* by source.

11. Originally reported as *Achnanthes taeniata* by Grøntved and Seidenfaden (1938).

12. Originally reported as *Nitzschia seriata* by Grøntved and Seidenfaden (1938).

13. Originally reported as *Thalassiosira antarctica* var. *borealis* by Lovejoy et al. (2002).

14. Reported as *Scippsiella* by source.

15. Originally reported as *Glenodinium lenticula* by Grøntved and Seidenfaden (1938).

16. Reported as *Goniaulax* by source.

17. Reported as *L. polyedrun* by source.

18. Originally reported as *Peridinium ovatum* f. *arctica* by Grøntved and Seidenfaden (1938).

19. Originally reported as *Minuscula bipes* by Grøntved and Seidenfaden (1938).

10. Originally reported as *Peridinium brevipes* by Grøntved and Seidenfaden (1938).

21. Originally reported as *Peridinium* spp. by Grøntved and Seidenfaden (1938).

22. Reported as Syndinales by source.

23. Originally reported as both *Distephanus speculum* v. *regularis* and *D. speculum* v. *polyactis* by Grøntved and Seidenfaden (1938).

# APPENDIX 2: LIST OF ZOOPLANKTON AND ICE-ASSOCIATED INVERTEBRATE TAXA FROM MARINE WATERS OF THE NORTH WATER POLYNYA

*Table A.2. List of known zooplankton and ice-associated invertebrate taxa from marine waters of the North Water.*

| **Taxonomic Nomenclature** | **Source(s)** |
|---|---|
| Mollusca | |
| Gastropoda | |
| *Clione limacina* | Longhurst et al. 1984, Karnovsky et al. 2008 |
| *Limacina helicina* | Longhurst et al. 1984 |
| Arthropoda | |
| Amphipoda | |
| *Apherusa glacialis* | Karnovsky et al. 2008 |
| *Gammaracanthus loricatus* | Holst et al. 2001 |
| *Hyperia galba* | Holst et al. 2001 |
| *Themisto abyssorum* | Longhurst et al. 1984 |
| *Themisto libellula* | Longhurst et al. 1984, Holst et al. 2001, Karnovsky et al. 2008 |
| Copepoda | |
| *Acartia longiremis* | Tidmarsh 1973 |
| *Aetideopsis multiserrata* | Tidmarsh 1973 |
| *Aetideopsis rostrata* | Tidmarsh 1973 |
| *Atrophia glacialis* | Tidmarsh 1973 |
| *Augaptilus glacialis* | Tidmarsh 1973 |
| *Calanus finmarchicus* | Grainger 1961 |
| *Calanus glacialis* | Grainger 1961 |
| *Calanus hyperboreus* | Grainger 1961 |
| *Chiridius* sp. | Hobson et al. 2002a |
| *Chiridius obtusifrons* | Tidmarsh 1973 |
| *Drepanopus bungei* | Tidmarsh 1973 |
| *Farrania* sp. | Tidmarsh 1973 |
| *Gaetanus brevispinus* | Tidmarsh 1973 |
| *Gaetanus tenuispinus* | Tidmarsh 1973 |
| *Haloptilus acutifrons* | Tidmarsh 1973 |
| *Heterorhabdus norvegicus* | Tidmarsh 1973 |
| *Heterostylites major* | Tidmarsh 1973 |

| **Taxonomic Nomenclature** | **Source(s)** |
|---|---|
| *Metridia longa* | Tidmarsh 1973 |
| *Microcalanus pygmaeus* | Longhurst et al. 1984 |
| *Neomormonilla minor* | Tidmarsh 1973 |
| *Oithona similis* | Tidmarsh 1973 |
| *Oncaea* sp. | Tidmarsh 1973 |
| *Paraeuchaeta glacialis* | Tidmarsh 1973 |
| *Paraeuchaeta norvegica* | Tidmarsh 1973 |
| *Pseudaugaptilus polaris* | Tidmarsh 1973 |
| *Pseudoamallothrix ovata* | Tidmarsh 1973 |
| *Pseudocalanus minutus* | Longhurst et al. 1984 |
| *Scaphocalanus magnus* | Tidmarsh 1973 |
| *Scaphocalanus brevicornis* | Tidmarsh 1973 |
| *Scolecithricella minor* | Tidmarsh 1973 |
| *Spinocalanus abyssalis* | Tidmarsh 1973 |
| *Spinocalanus brevicaudatus* | Tidmarsh 1973 |
| *Spinocalanus magnus* | Tidmarsh 1973 |
| *Temorites brevis* | Tidmarsh 1973 |
| *Triconia borealis* | Tidmarsh 1973 |
| *Undinella oblonga* | Tidmarsh 1973 |
| *Xanthocalanus hirtipes* | Tidmarsh 1973 |
| Ostracoda | |
| Unidentified sp. | Longhurst et al. 1984 |
| Chaetognatha | |
| Unidentified sp. | Longhurst et al. 1984 |
| Tunicata | |
| Unidentified sp. | Longhurst et al. 1984 |
| *Oikopleura vanhoeffeni* | Acuña et al. 2002 |

# APPENDIX 3: LIST OF BENTHIC AND EPIBENTHIC TAXA FROM MARINE WATERS OF THE NORTH WATER

*Table A.3. List of known benthic and epibenthic taxa from marine waters of the North Water. For locations, North Water = North Water Polynya; NBB = northern Baffin Bay; SC = Stomach content of a marine mammal or bird that may feed in the North Water.*

| **Taxonomic Nomenclature** | **Location(s)** | **Source(s)** |
|---|---|---|
| Cnidaria | | |
| *Craspedacusta* sp. | North Water | Lalande 2003 |
| Annelida | | |
| Polychaeta | | |
| Alciopidae sp. | North Water | Lalande 2003 |
| *Ampharete* sp. | North Water | Lalande 2003 |
| *Ampharete arctica* | North Water | Lalande 2003 |
| *Aricidea nolani* | North Water | Lalande 2003 |
| *Bipalponephtys neotena* | North Water | Lalande 2003 |
| *Bylgides sarsi* | North Water | Lalande 2003 |
| *Chaetozone setosa* | North Water | Lalande 2003 |
| *Chirimia biceps biceps* | North Water | Lalande 2003 |
| Cirratulidae sp. | North Water | Lalande 2003 |
| *Cossura longocirrata* | North Water | Lalande 2003 |
| *Diplocirrus* sp. | North Water | Lalande 2003 |
| *Diplocirrus hirsutus* | North Water | Lalande 2003 |
| *Dipolydora caulleryi* | North Water | Lalande 2003 |
| Dorvilleidae sp. | North Water | Lalande 2003 |
| *Dorvillea* sp. | North Water | Lalande 2003 |
| *Eteone* sp. | North Water | Lalande 2003 |
| *Eteone longa* | North Water | Lalande 2003 |
| *Exogone* sp. | North Water | Lalande 2003 |
| Fabriciidae sp. 1 | North Water | Lalande 2003 |
| Fabriciidae sp. 2 | North Water | Lalande 2003 |
| Fabriciidae sp. 3 | North Water | Lalande 2003 |
| *Harmothoe extenuata* | North Water | Lalande 2003 |
| *Laonice cirrata* | North Water | Lalande 2003 |
| *Lumbrineris* sp. | North Water | Hobson et al. 2002a |
| *Macrochaeta polyonyx* | NBB | Lopez et al. 2016 |
| Maldanidae sp. | North Water | Lalande 2003 |
| *Maldane* sp. | North Water | Lalande 2003 |
| *Maldane sarsi* | North Water | Lalande 2003 |

| Taxonomic Nomenclature | Location(s) | Source(s) |
|---|---|---|
| *Mediomastus ambiseta* | North Water | Lalande 2003 |
| *Myriochele heeri* | North Water | Lalande 2003 |
| *Nereis zonata* | North Water | Lalande 2003 |
| *Nicomache quadrispinata* | North Water | Lalande 2003 |
| *Nicomache lumbricalis* | North Water | Lalande 2003 |
| *Nothria conchylega* | North Water | Lalande 2003 |
| *Ophelina cylindricaudata* | North Water | Lalande 2003 |
| *Owenia fusiformis* | North Water | Lalande 2003 |
| Paraonidae sp. | North Water | Lalande 2003 |
| *Pholoe minuta* | North Water | Lalande 2003 |
| *Phyllodoce mucosa* | North Water | Hobson et al. 2002a |
| *Pista maculata* | North Water | Lalande 2003 |
| *Praxillella gracilis* | North Water | Lalande 2003 |
| *Praxillura longissima* | North Water | Lalande 2003 |
| *Prionospio steenstrupi* | North Water | Lalande 2003 |
| Sabellinae sp. | North Water | Lalande 2003 |
| *Scalibregma inflatum* | North Water | Lalande 2003 |
| *Scoletoma fragilis* | North Water | Lalande 2003 |
| *Scoloplos acutus* | North Water | Lalande 2003 |
| *Sphaerodoropsis corrugata* | North Water | Lalande 2003 |
| Syllidae sp. | North Water | Lalande 2003 |
| *Syllis gracilis* | North Water | Lalande 2003 |
| Terebellidae sp. | North Water | Lalande 2003 |
| *Tharyx acutus* | North Water | Lalande 2003 |
| Trochochaetidae sp. | North Water | Lalande 2003 |
| Arthropoda | | |
| Acari | North Water | Lalande 2003 |
| Amphipoda | | |
| *Acanthostepheia* spp. | North Water | Hobson et al. 2002a |
| *Aceroides latipes* | North Water | Lalande 2003 |
| *Anonyx* sp. | North Water | Lalande 2003 |
| *Anonyx nugax* | SC, North Water | Holst et al. 2001, Fisk et al. 2001a, Hobson et al. 2002a |
| *Argissa hamatipes* | North Water | Lalande 2003 |
| *Arrhinopsis longicornis* | North Water | Lalande 2003 |
| *Atylus carinatus* | SC, North Water | Holst et al. 2001, Hobson et al. 2002a |
| *Byblis gaimardi* | North Water | Lalande 2003 |

| Taxonomic Nomenclature | Location(s) | Source(s) |
|---|---|---|
| *Ericthonius* sp. | North Water | Lalande 2003 |
| *Gammaropsis* sp. | North Water | Lalande 2003 |
| *Gammarus setosus* | SC | Holst et al. 2001 |
| *Haploops setosa* | North Water | Lalande 2003 |
| *Idunella aeqvicornis* | North Water | Lalande 2003 |
| Oedicerotidae sp. | North Water | Lalande 2003 |
| *Onisimus* sp. | North Water | Hobson et al. 2002a |
| *Onisimus edwardsii* | SC | Holst et al. 2001 |
| *Onisimus litoralis* | SC, North Water | Holst et al. 2001, Karnovsky et al. 2008 |
| *Paraphoxus oculatus* | North Water | Lalande 2003 |
| *Protomedeia stephenseni* | North Water | Lalande 2003 |
| *Unciola leucopis* | North Water | Lalande 2003 |
| Copepoda | North Water | Lalande 2003 |
| Cumacea | | |
| *Diastylis tumida* | North Water | Lalande 2003 |
| *Diastylis lepechini* | North Water | Lalande 2003 |
| *Diastylis spinulosa* | North Water | Lalande 2003 |
| *Eudorellopsis* sp. | North Water | Lalande 2003 |
| *Eudorella emarginata* | North Water | Lalande 2003 |
| *Eudorellopsis integra* | North Water | Lalande 2003 |
| *Leptostylis longimana* | North Water | Lalande 2003 |
| *Leucon* sp. | North Water | Lalande 2003 |
| *Leucon acutirostris* | North Water | Lalande 2003 |
| *Leucon pallidus* | North Water | Lalande 2003 |
| Pseudocumatidae sp. | North Water | Lalande 2003 |
| Decapoda | | |
| *Hymenodora glacialis* | SC | Holst et al. 2001 |
| *Lebbeus polaris* | SC | Holst et al. 2001 |
| *Pandalus* sp. | North Water | Hobson et al. 2002a |
| Euphausiacea | | |
| Euphausiid (unidentified) | North Water | Hobson et al. 2002a |
| Isopoda | | |
| *Eugerda tenuimana* | North Water | Lalande 2003 |
| *Disconectes furcatus* | North Water | Lalande 2003 |
| *Gnathia* sp. | North Water | Lalande 2003 |
| *Pleurogonium intermedium* | North Water | Lalande 2003 |

| **Taxonomic Nomenclature** | **Location(s)** | **Source(s)** |
|---|---|---|
| *Pleurogonium inerne* | North Water | Lalande 2003 |
| *Munna acanthifera* | North Water | Lalande 2003 |
| Leptostraca | | |
| *Nebalia bipes* | North Water | Lalande 2003 |
| Mysidacea | | |
| *Mysis oculata* | North Water | Hobson et al. 2002a |
| Ostracoda | North Water | Lalande 2003 |
| Pycnogonida | | |
| *Nymphon hirtum* | North Water | Lalande 2003 |
| Sessilia | | |
| *Balanus crenatus* | Rice Strait | Coulthard et al. 2010 |
| Tanaidacea | | |
| *Leptognathia* sp. 1 | North Water | Lalande 2003 |
| *Leptognathia* sp. 2 | North Water | Lalande 2003 |
| *Pseudosphyrapus anomalus* | North Water | Lalande 2003 |
| Echinodermata | | |
| Asteroidea | | |
| *Ctenodiscus crispatus* | North Water | Hobson et al. 2002a |
| Crinoidea | | |
| *Heliometra glacialis* | North Water | Hobson et al. 2002a |
| Echinoida | | |
| *Strongylocentrotus pallidus* | North Water | Hobson et al. 2002a |
| Ophiuroidea | | |
| *Amphiura* sp. | North Water | Lalande 2003 |
| *Gorgonocephalus arcticus* | North Water | Hobson et al. 2002a |
| *Ophiophthalmus* sp. | North Water | Hobson et al. 2002a |
| Ophiurida sp. | North Water | Lalande 2003 |
| *Ophiura robusta* | North Water | Lalande 2003 |
| *Ophiura sarsi* | North Water | Hobson et al. 2002a |
| Mollusca | | |
| Bivalvia | | |
| *Astarte* sp. | North Water | Hobson et al. 2002a, Lalande et al. 2003 |
| *Astarte borealis* | Rice Strait | Coulthard et al. 2010 |
| *Astarte elliptica* | North Water | Hobson et al. 2002a |
| *Astarte montagui* | North Water | Hobson et al. 2002a |
| *Cuspidaria arctica* | North Water | Lalande 2003 |

| **Taxonomic Nomenclature** | **Location(s)** | **Source(s)** |
|---|---|---|
| *Dacrydium vitreum* | North Water | Lalande 2003 |
| *Hiatella arctica* | North Water | Lalande 2003 |
| *Macoma* sp. | North Water | Hobson et al. 2002a |
| *Macoma calcerea* | North Water | Lalande 2003 |
| *Megayoldia thraciaeformis* | North Water | Hobson et al. 2002a |
| *Musculus niger* | North Water | Lalande 2003 |
| *Nucula* sp. | North Water | Lalande 2003 |
| *Thyasira* sp. | North Water | Lalande 2003 |
| *Yoldiella intermedia* | North Water | Lalande 2003 |
| Cephalopoda | | |
| *Bathypolypus arcticus* | SC, North Water | Holst et al. 2001, Treble 2007 in Gardiner 2015 |
| *Cirroteuthis muelleri* | North Water | Treble 2007 in Gardiner 2015 |
| *Gonatus fabricii* | NBB | cited in Gardiner 2015 |
| *Rossia moelleri* | SC, NBB | Holst et al. 2001, Treble 2007 in Gardiner 2015 |
| *Rossia palpebrosa* | NBB | Treble 2007 in Gardiner 2015 |
| Gastropoda | | |
| Acmeaidae sp. | North Water | Lalande 2003 |
| *Buccinum* sp. | North Water | Lalande 2003 |
| *Colus* sp. | SC, North Water | Holst et al. 2001, Hobson et al. 2002a |
| *Cylichna* sp. | North Water | Lalande 2003 |
| *Euspira* sp. | North Water | Lalande 2003 |
| *Lepeta caeca* | North Water | Hobson et al. 2002a |
| *Margarites* sp. | SC | Holst et al. 2001 |
| Nematoda | North Water | Lalande 2003 |
| Nemertea | | |
| Nemertea sp. 1 | North Water | Lalande 2003 |
| Nemertea sp. 2 | North Water | Lalande 2003 |
| Cephalorhyncha | North Water | Lalande 2003 |
| Sipuncula | North Water | Lalande 2003 |
| Phascolosomatidea | | |
| *Nephasoma eremita* | North Water | Hobson et al. 2002a |

# APPENDIX 4: LIST OF FISH TAXA FROM OR LIKELY TO OCCUR IN MARINE WATERS AND NEARSHORE HABITAT OF THE NORTH WATER

*Table A.4. List of fish taxa from or likely to occur in marine waters and nearshore habitat of the North Water.*

| Family | Common Name(s) | Species | Source(s) |
|---|---|---|---|
| Rajidae | Arctic Skate | *Amblyraja hyperborea* | Coad and Reist 2018 |
| Rajidae | Thorny Skate | *Amblyraja radiata* | Coad and Reist 2018 |
| Gadidae | Polar Cod | *Arctogadus glacialis* | Coad and Reist 2004, 2018 |
| Gadidae | Arctic Cod | *Boreogadus saida* | Bradstreet et al. 1986, Coad and Reist 2004, 2018 |
| Osmeridae | Capelin | *Mallotus villosus* | CAFF 2017, Coad and Reist 2018 |
| Salmonidae | Arctic Char | *Salvelinus alpinus* | Coad and Reist 2004, 2018 |
| Cottidae | Atlantic Hookear Sculpin | *Artediellus atlanticus* | Coad and Reist 2018 |
| Cottidae | Arctic Staghorn Sculpin | *Gymnocanthus tricuspis* | Coad and Reist 2018 |
| Cottidae | Twohorn Sculpin | *Icelus bicornis* | Coad and Reist 2018 |
| Cottidae | Arctic Sculpin | *Myoxocephalus scorpiodes* | Coad and Reist 2018 |
| Cottidae | Shorthorn Sculpin | *Myoxocephalus scorpius* | Coad and Reist 2018 |
| Cottidae | Bigeye Sculpin | *Triglops nybelini* | Coad and Reist 2018 |
| Cottidae | Ribbed Sculpin | *Triglops pingelii* | Coad and Reist 2018 |
| Agonidae | Atlantic Poacher | *Leptagonus decagonus* | Coad and Reist 2018 |
| Psychrolutidae | Polar Sculpin | *Cottunculus microps* | Coad and Reist 2018 |
| Liparidae | Sea Tadpole | *Careproctus reinhardti* | Coad and Reist 2018 |
| Liparidae | Gelatinous Seasnail | *Liparis fabricii* | Coad and Reist 2018 |
| Liparidae | Kelp Snailfish | *Liparis tunicatus* | DFO 2019a |
| Zoarcidae | Fish Doctor | *Gymnelus viridus* | Coad and Reist 2018 |
| Zoarcidae | Checkered Wolf Eel | *Lycenchelys kolthoffi* | DFO 2019a |

| Family | Common Name(s) | Species | Source(s) |
|---|---|---|---|
| Zoarcidae | Doubleline Eelpout | *Lycodes eudipleurosticus* | Coad and Reist 2018 |
| Zoarcidae | Arctic Eelpout | *Lycodes reticulatus* | Coad and Reist 2018 |
| Pleuronectidae | Greenland Halibut | *Reinhardtius hippoglossoides* | Coad and Reist 2018 |

# APPENDIX 5: LIST OF BIRD TAXA USING MARINE OR NEARSHORE HABITAT AND ADDITIONAL MAPS OF BIRD SPECIES OCCURANCE WITHIN THE NORTH WATER POLYNYA

*Table A.5. List of bird taxa using marine or nearshore habitat within the North Water Polynya.*

| Family | Common Name | Latin Name | Source |
|---|---|---|---|
| Anatidae | Brant | *Branta bernicla* | ONCS 2018 |
| Anatidae | Canada Goose | *Branta canadensis* | Vaughan 1988 |
| Anatidae | Common Eider | *Somateria mollissima* | Vaughan 1988, ONCS 2018 |
| Anatidae | King Eider | *Somateria spectabilis* | Vaughan 1988, ONCS 2018 |
| Anatidae | Long-tailed Duck | *Clangula hyemalis* | Vaughan 1988, ONCS 2018 |
| Anatidae | Snow Goose | *Chen caerulescens* | ONCS 2018 |
| Alcidae | Atlantic Puffin | *Fratercula arctica* | Vaughan 1988, Robards et al. 2000 |
| Alcidae | Black Guillemot | *Cepphus grylle* | Nettleship 1980, Vaughan 1988 |
| Alcidae | Dovekie (Little Auk) | *Alle alle* | Vaughan 1988, Brown et al. 1975 |
| Alcidae | Thick-billed Murre | *Uria lomvia* | Nettleship 1980, Vaughan 1988 |
| Charadriidae | Black-bellied Plover | *Pluvialis squatarola* | Vaughan 1988 |
| Charadriidae | Common Ringed Plover | *Charadrius hiaticula* | Vaughan 1988 |
| Charadriidae | Lesser Golden Plover | *Pluvialis dominica* | Vaughan 1988 |
| Gaviidae | Red-throated Loon | *Gavia stellata* | Vaughan 1988, ONCS 2018 |
| Laridae | Arctic Tern | *Sterna paradisaea* | Nettleship 1980, Vaughan 1988 |
| Laridae | Black-legged Kittiwake | *Rissa tridactyla* | Nettleship 1980, Vaughan 1988 |
| Laridae | Glaucous Gull | *Larus hyperboreus* | Nettleship 1980, Vaughan 1988 |
| Laridae | Ivory Gull | *Pagophila eburnea* | ONCS 2018 |
| Laridae | Sabine's Gull | *Xema sabini* | Vaughan 1988, Martec Ltd. 1982 |

| Family | Common Name | Latin Name | Source |
|---|---|---|---|
| Laridae | Thayer's Gull | *Larus thayeri* | Nettleship 1980, Vaughan 1988 |
| Procellariidae | Northern Fulmar | *Fulmarus glacialis* | Nettleship 1980, Vaughan 1988 |
| Scolopacidae | Baird`s Sandpiper | *Calidris bairdii* | Vaughan 1988 |
| Scolopacidae | Red Knot | *Calidris canutus* | Vaughan 1988, ONCS 2018 |
| Scolopacidae | Red Phalarope | *Phalaropus fulicarius* | Vaughan 1988, ONCS 2018 |
| Scolopacidae | Red-necked Phalarope | *Phalaropus lobatus* | Vaughan 1988 |
| Scolopacidae | Ruddy Turnstone | *Arenaria interpres* | Vaughan 1988, Robards et al. 2000 |
| Scolopacidae | Sanderling | *Calidris alba* | Vaughan 1988 |
| Stercorariidae | Parasitic Jaeger | *Stercorarius parasiticus* | Vaughan 1988, Martec Ltd. 1982 |

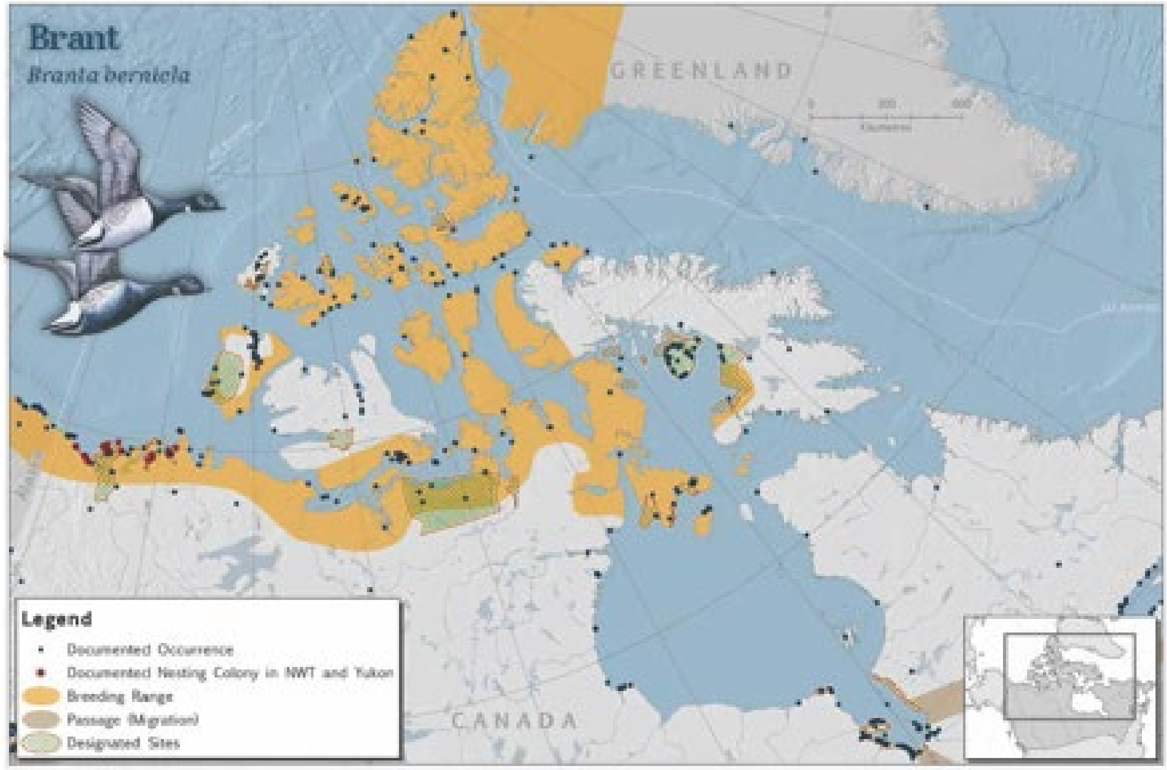

*Figure A1. Brant documented occurrences, known Canadian colonies, general range, and designated sites. Source: Oceans North Conservation Society et al. (2018).*

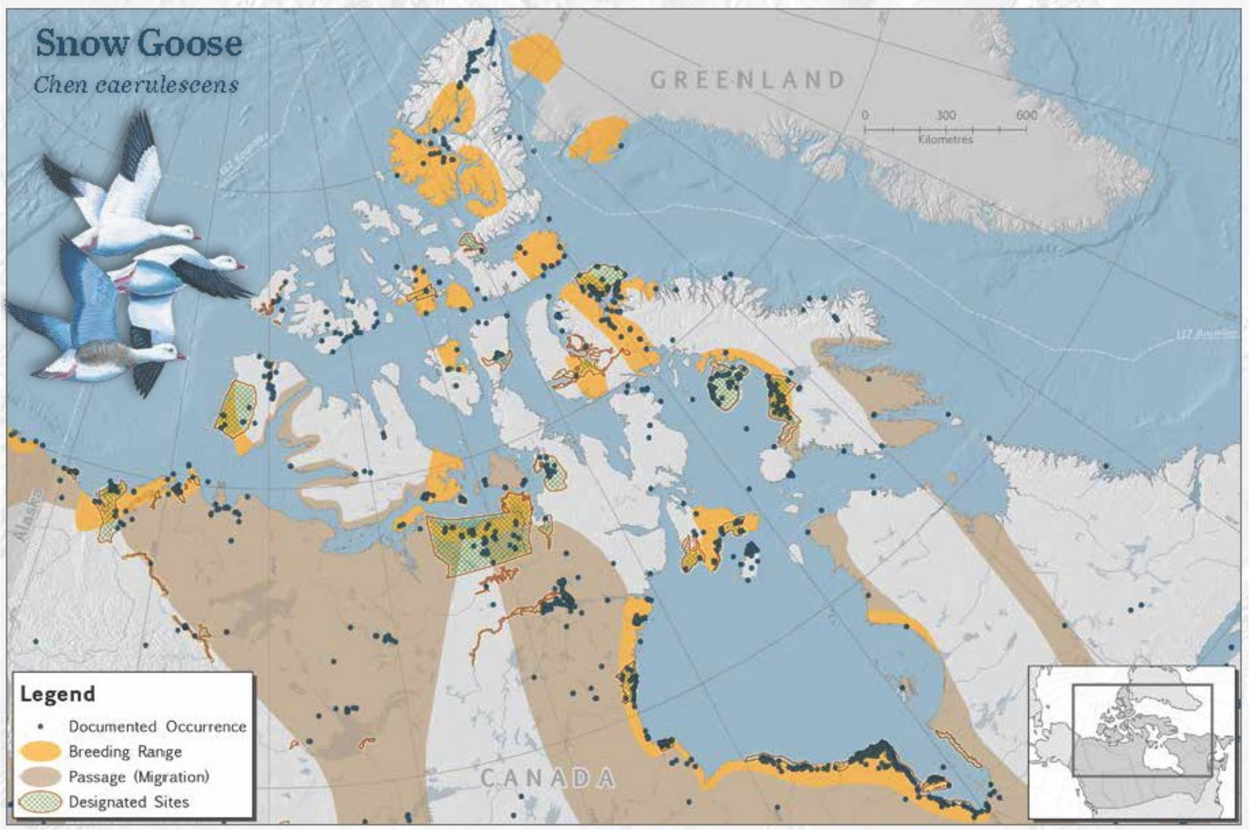

*Figure A2. Snow Goose documented occurrences, known Canadian colonies, general range, and designated sites. Source: Oceans North Conservation Society et al. (2018).*

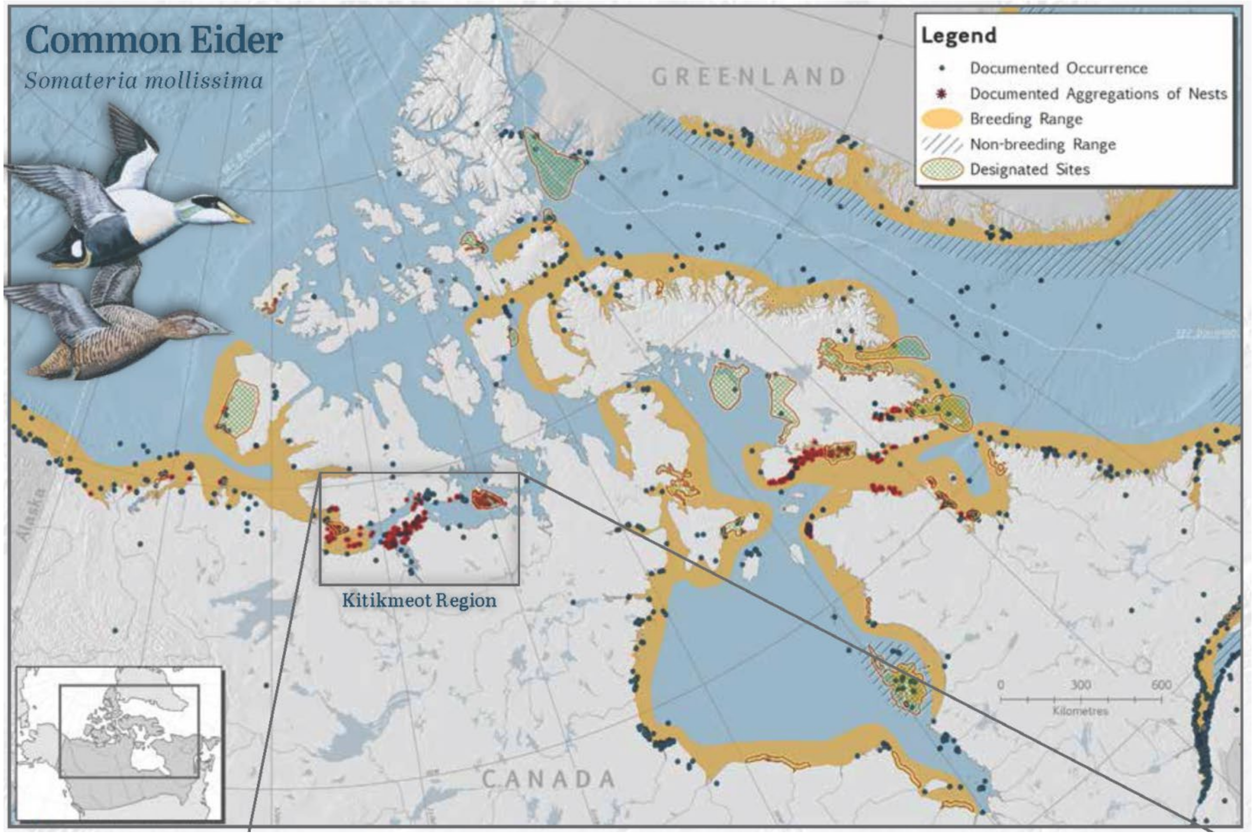

*Figure A3. Common Eider documented occurrences, known Canadian colonies, general range, and designated sites. Source: Oceans North Conservation Society et al. (2018).*

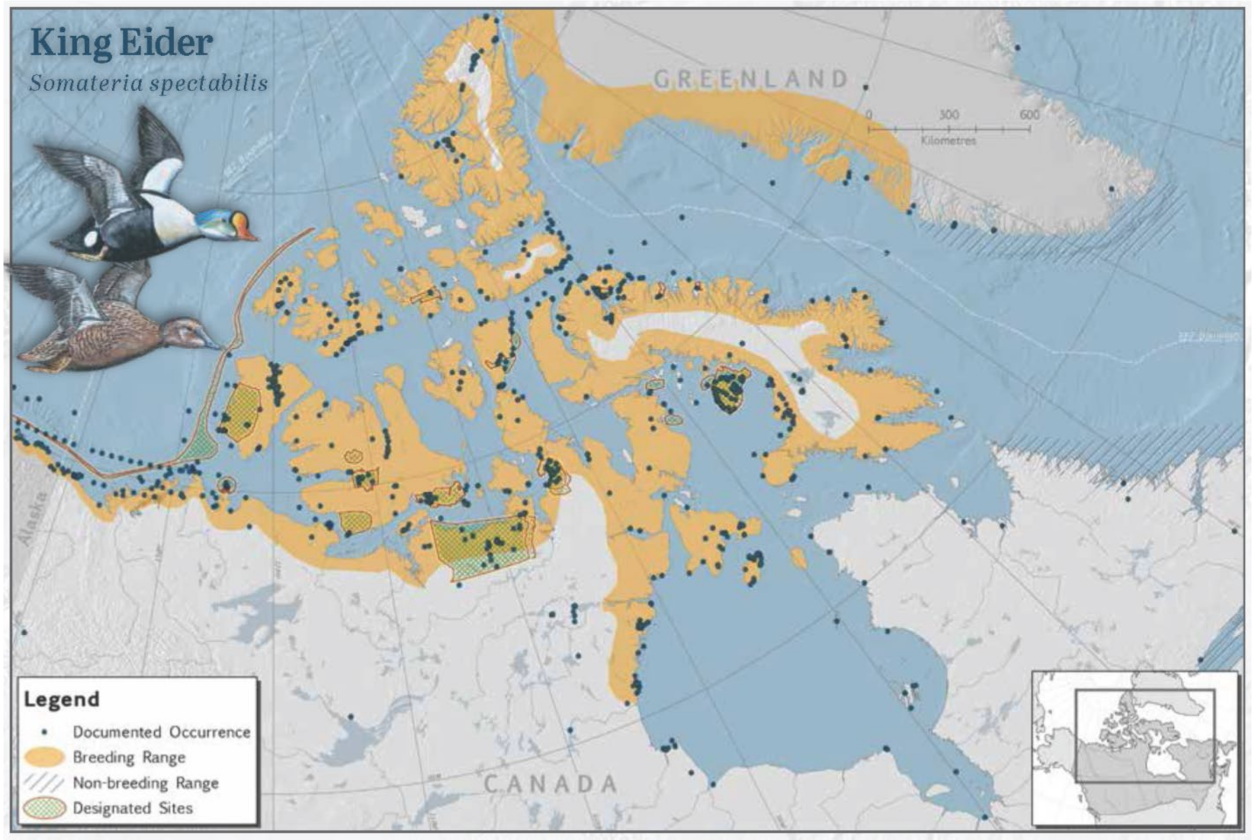

Figure A4. King Eider documented occurrences, known Canadian colonies, general range, and designated sites. Source: Oceans North Conservation Society et al. (2018).

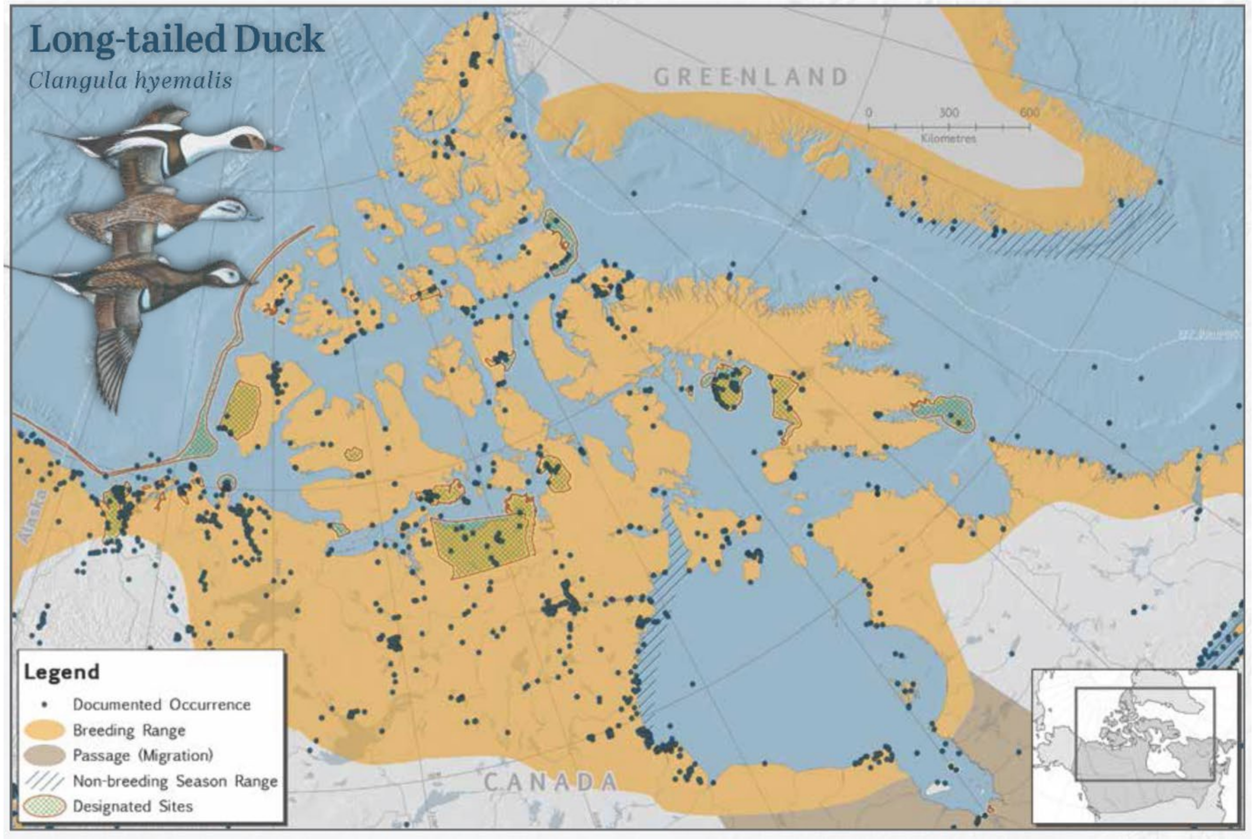

*Figure A5. Long-tailed Duck documented occurrences, known Canadian colonies, general range, and designated sites. Source: Oceans North Conservation Society et al. (2018).*

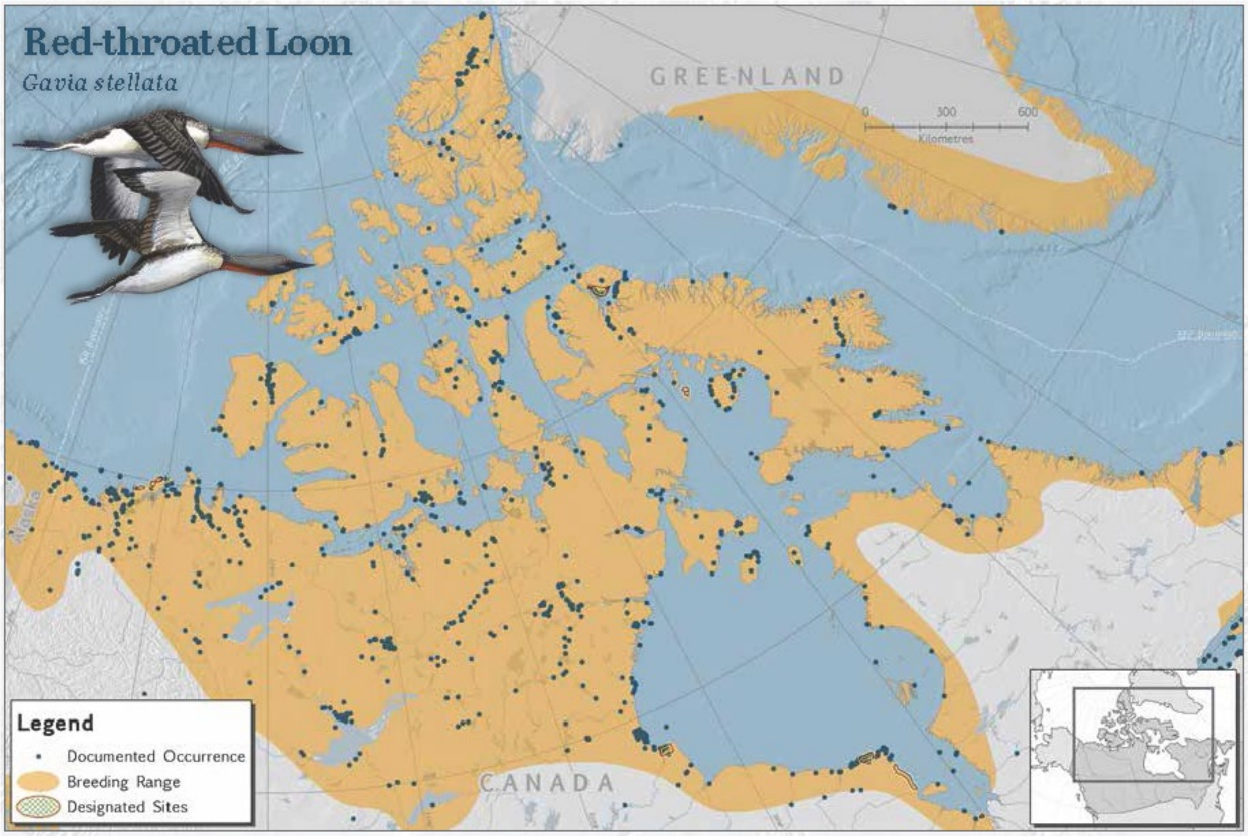

*Figure A6. Red-throated Loon documented occurrences, known Canadian colonies, general range, and designated sites. Source: Oceans North Conservation Society et al. (2018).*

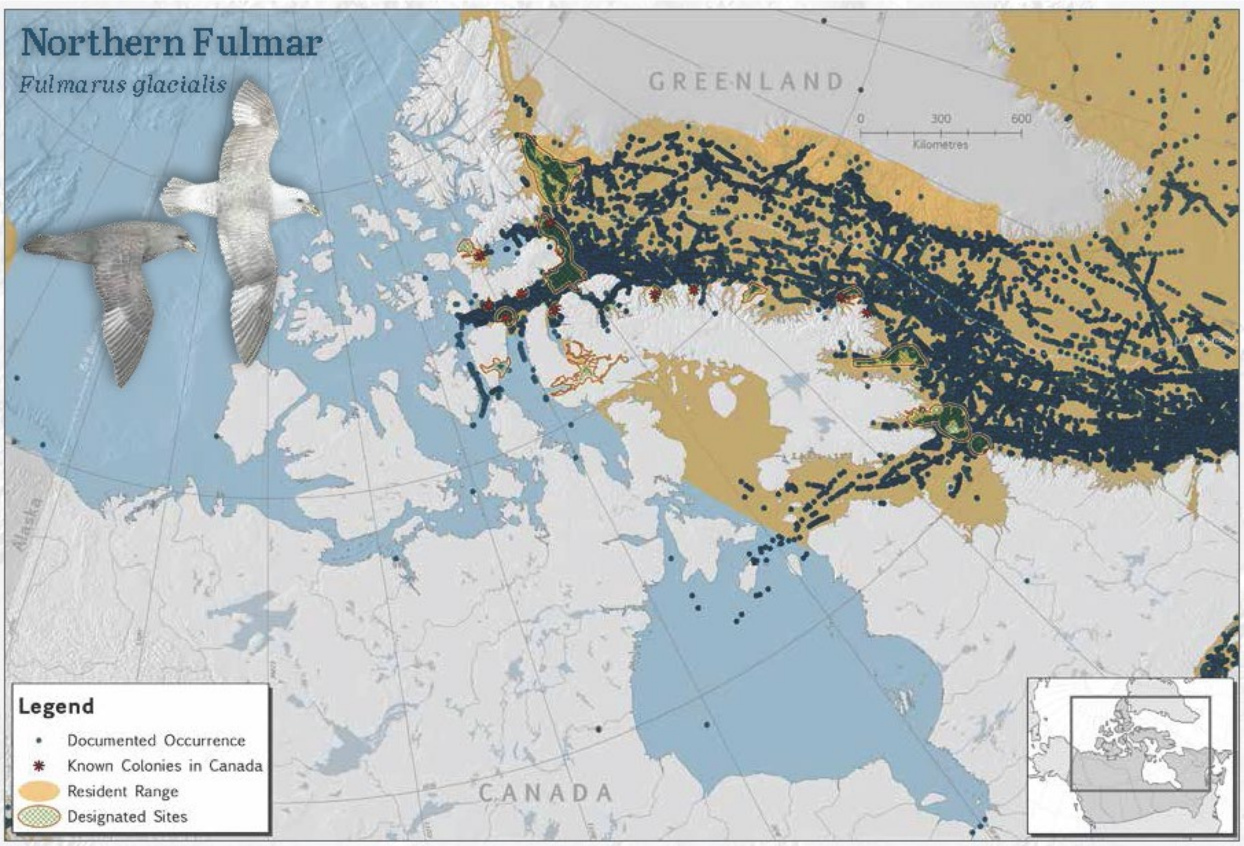

*Figure A7. Northern Fulmar documented occurrences, known Canadian colonies, general range, and designated sites. Source: Oceans North Conservation Society et al. (2018).*