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BIOPHYSICAL AND ECOLOGICAL OVERVIEW OF THE TUVAIJUITTUQ AREA

by

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ABSTRACT

In August 2019, Tuvaijuittuq, the first Marine Protected Area (MPA) designated by ministerial order under Canada's *Oceans Act*, was created. This interim protection prohibits new or additional human activities within the MPA for up to five years in an effort to conserve, protect and understand the natural diversity, productivity and dynamism of the High Arctic sea ice ecosystem. Tuvaijuittuq comprises sounds and fiords, ice shelves, and the coastal and offshore region north of Ellesmere Island. Tuvaijuittuq is a complex region in terms of oceanography and sea ice conditions. It is influenced by both the Pacific and Atlantic waters, and its surface circulation is largely impacted by the Beaufort Gyre and the Transpolar Drift. Land-fast and pack-ice co-exist within the boundaries of the MPA. Multi-year ice prevails in the region, but first-year ice is also present. Tuvaijuittuq hosts the oldest and thickest multi-year ice in the Arctic, as complex atmospheric and oceanic forcings make it converge and accumulate along the northern boundary of the Canadian Archipelago. The region is also projected to become the last area of the Arctic Ocean where multi-year sea ice will remain present in the next decades. Yet, studies conducted within this unique area are extremely sparse, largely due to difficulty of access as a result of extreme remoteness and challenges associated with the presence of the thick multi-year ice cover. This report synthesizes current knowledge of the ecosystem of Tuvaijuittuq and adjacent areas, including baseline information on climate, oceanography and the different components of the marine food web, from microbes to marine mammals.

RÉSUMÉ

Charette, J., Melling, H., Duerksen, S., Johnson, M., Dawson, K., Brandt, C., Remnant, R. and Michel, C. 2020. Biophysical and Ecological Overview of the Tuvaijuittuq Area. Can. Tech. Rep. Fish. Aquat. Sci. 3408: xi + 110 p.

En août 2019, Tuvaijuittuq, la première zone de protection marine (ZPM) désignée par arrêté ministériel en vertu de la Loi sur les océans, fut créée. Cette protection provisoire interdit les activités humaines nouvelles ou additionnelles à l'intérieur de la ZPM pour une période maximale de 5 ans. Tuvaijuittuq inclut des détroits, des fjords, des plateaux de glace ainsi que les régions côtière et au large du nord de l'ile d'Ellesmere. Tuvaijuittuq est une région complexe en ce qui a trait à l'océanographie et aux conditions de glace de mer. Elle est influencée par les eaux pacifiques et atlantiques et sa circulation de surface est largement affectée par la gyre de Beaufort et la dérive transpolaire. La glace pluriannuelle domine dans la région, mais la glace annuelle est également présente. La banquise côtière et la banquise dérivante coexistent au sein de la ZMP. Tuvaijuittuq abrite la glace de mer pluriannuelle la plus vieille et la plus épaisse de l'océan Arctique, puisque la glace de mer transportée par les vents s'accumule à l'extrémité nord de l'archipel canadien. La région est également considérée comme la dernière zone de l'océan Arctique où la glace demeurera dans la prochaines décennies. À ce jour, les études réalisées dans cette région unique sont très éparses, principalement en raison de difficultés à accéder à cette région extrêmement isolée et de défis associés à la présence de glace pluriannuelle très épaisse. Ce rapport regroupe les connaissances actuelles de l'écosystème de Tuvaijuittuq et des régions adjacentes, incluant des informations sur le climat, l'océanographie et les différentes composantes du réseau trophique, des microbes aux mammifères marins.

INTRODUCTION

In August 2019, Tuvaijuittuq, an area of the Canadian High Arctic containing the oldest and thickest multi-year pack ice, became the first Marine Protected Area (MPA) designated for interim protection by ministerial order under Canada's *Oceans Act* (Figure 1; DFO 2019b). This designation was based on an urgent need to protect and conserve the area in light of continuing and significant negative impacts upon sea ice extent, thickness and duration in the Arctic as a whole (AMAP 2017) and potential for increased accessibility to the area. The ministerial order provides Tuvaijuittuq with interim protection (up to five years) which prohibits new or additional human activities while Canada and its partners determine the desirability of long-term protection and appropriate conservation tools through a feasibility assessment process.

Figure 1. Boundaries of the Tuvaijuittuq Marine Protected Area. Adapted from DFO 2019b.

The Tuvaijuittuq MPA spans a total of 319,411 km^2 of the Arctic Ocean and overlaps areas of importance identified by Fisheries and Oceans Canada (Ecologically and Biologically Significant Areas or EBSAs), Parks Canada Agency (candidate National Marine Conservation Areas or NMCAs) and environmental non-governmental organizations (ENGOs). Tuvaijuittuq overlaps the eastern portion of the Arctic Basin multi EBSA and the northern portion of the Nansen-Eureka-Greely Fiord EBSA. The Arctic Basin candidate NMCA and the Ellesmere Island ice shelves EBSA all fall within the

Tuvaijuittuq MPA boundaries, with the exception of a small number of fiords, inlets and islands along the coast of Ellesmere Island that are already protected within Quttinirpaaq National Park (Figure 2).
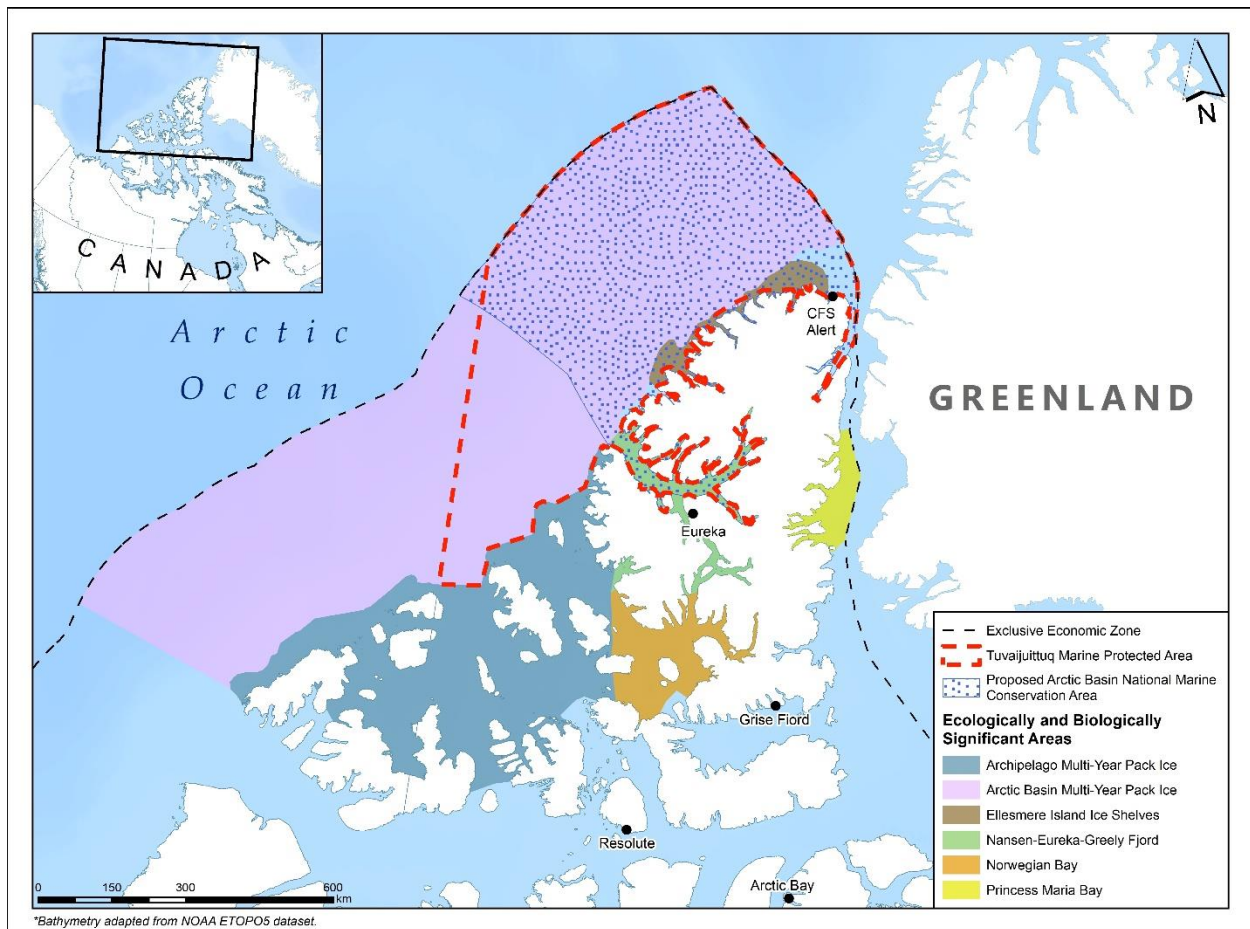
Figure 2. Ecologically and Biologically Significant Areas and the National Marine Conservation Area located within Tuvaijuittuq and adjacent areas.

Tuvaijuittuq falls within the Word Wildlife Fund's Last Ice Area (LIA) and overlaps the Remnant Arctic Multi-year Sea Ice and Northeast Water Polynya Ecoregion, proposed as World Heritage site of Outstanding Universal Value (OUV) (Speer et al. 2017; WWF 2020). The proposal is backed by a consortium that includes the Natural Resources Defense Council (NRDC), the United Nations Educational, Scientific and Cultural Organization's (UNESCO) World Heritage Marine Program, and the International Union for Conservation of Nature and Natural Resources' (IUCN) Global Marine and Polar Programme. Further international discussions focused on the LIA have encouraged the establishment of an "Ice refuge" special management area that prioritizes habitat conservation for ice-dependent species, reiterated by the recommendations by the Arctic Council to establish a conservation area in Northwest Greenland/Northeast Canadian Arctic Archipelago (Kovacs and Michel 2011; CAFF 2013). While this measure would not address greenhouse gas emissions and ensuing climate warming, it would provide protection of the sea ice habitat that is critical to Arctic marine food webs, as climate models predict a summer ice-free Arctic Ocean by mid-century.

Outposts of the Canadian government represent the only inhabited sites in the vicinity of Tuvaijuittuq. Canadian Forces Station (CFS) Alert, operated by the Department of National Defense, is located on the coastline of Tuvaijuittuq at the north-eastern tip of Ellesmere Island, approximately 25 km west of the entrance to Nares Strait (Figure 1). It is a military facility that also supports scientific research. Between 60 and 120 people live and work at CFS Alert on rotation basis at any given time. Environment and Climate Change Canada (ECCC) maintains the World Meteorological Organisation (WMO) Global Atmospheric Watch Observatory at CFS Alert. This is the northernmost site of the global observatory network supporting WMO's atmospheric monitoring program and one of the Arctic few climate observatories monitoring atmospheric CO_2 concentrations. The Alert observatory provides the global community with long-term monitoring of atmospheric measurements for climate, greenhouse gases, stratospheric ozone and air quality. The site also serves as an official site for greenhouse gas inter-comparison and provides long-term monitoring of essential climate variables including greenhouse gases, stratospheric ozone and air quality. In addition, ECCC maintains a weather observation and research support station in Eureka, at the southern boundary of Tuvaijuittuq, approximately 35 km from Greely Fiord.

Quttinirpaaq National Park, which includes portions of the northern shore of Ellesmere Island is adjacent to Tuvaijuittuq. It includes research stations at Ward Hunt Island, Lake Hazen and Tanquary Fiord, with the latter two being seasonally staffed (May to August) warden stations (Parks Canada 2009). There is also a coastal research station within Tuvaijuittuq at Cape Sudar, where d'Iberville Fiord meets Greely Fiord.

There are no communities located close to Tuvaijuittuq. Grise Fiord, which is situated more than 600 km southeast of Tuvaijuittuq, is the closest community to the MPA (DFO 2019b). However, there is evidence of historical human use of adjacent Ellesmere Island (Chambers and Brown 2019). The Arctic communities closest to Tuvaijuittuq (Grise Fiord, Resolute Bay, and Arctic Bay) have expressed concern that changes to the physical and ecological environments of Tuvaijuittuq could lead to broader scale impacts to the Canadian Arctic Archipelago. For example, industrial activities including oil and gas exploration, resource extraction and tourism are already associated with increased vessel traffic and potential risks to the environment and to traditional activities such as subsistence harvesting (Chambers and Brown 2019; Chambers, pers. comm.).

As global temperatures continue to rise, Tuvaijuittuq and northern Greenland are the only regions of the Arctic Ocean where sea ice is projected to persist in summer by mid-century (Pfirman 2009; DFO 2011b; WWF 2013). Tuvaijuittuq may then become the last area to provide summer sea-ice habitat, critical for many species, and as such, may become an increasingly important area for ice-dependent and ice-associated flora and fauna (Pfirman 2009; Speer and Laughlin 2011; AMAP 2017). Tuvaijuittuq also encompasses the ice shelves of northern Ellesmere Island, also threatened by the changing climate (Copland and Mueller 2017). Whereas their break-up and deterioration have been observed for a century, the rate of decrease has accelerated during recent exceptionally warm summers. Scientists believe that the few remaining shelves will disappear as warming of the Arctic continues (Copland et al. 2018). The loss of these shelves is anticipated to cause the extinction of the unique, biologically diverse microbial communities associated with cryo-

habitats that they provide (Jeffries 2017; Jungblut et al. 2017) while new ecosystems will be established in their place.

This document is intended as a summary of existing baseline scientific information and available Traditional Knowledge/Inuit Qaujimajatuqangit (TK/IQ) relevant to the Tuvaijuittuq MPA. It will be used as a basis for a Canadian Science Advisory Secretariat (CSAS) process seeking scientific guidance for the proposal. The resulting biophysical and ecological overview will represent an important component of the feasibility assessment for Tuvaijuittuq and will help inform long-term protection options for the area. With permission, select material presented herein was taken directly from a similar draft report prepared for DFO in 2018 (Johnson 2018) focusing on the broader LIA.

ENVIRONMENTAL AND ECOLOGICAL INFORMATION

REGIONAL CONTEXT

Tuvaijuittuq includes the marine waters off northern Ellesmere, Axel Heiberg, Meighen and Ellef Ringnes islands from the low water mark and to the outer boundary of Canada's Exclusive Economic Zone (Figure 3) (DFO 2019b). It extends from the western edge of Prince Gustav Adolf Sea at 110° W longitude to the Canada-Greenland marine boundary in the Lincoln Sea, southward along that boundary though Robeson Channel to Cape Baird. Archer Fiord, Nansen Sound, Greely Fiord and their adjoining fiords are within Tuvaijuittuq. Areas of the Ellesmere Island coastline that are part of Quttinirpaaq National Park are excluded.

Floating ice habitat within Tuvaijuittuq includes ice shelves found in fiords and parts of the continental shelf of north-western Ellesmere Island, fast-ice covering sheltered waters of the Canadian Arctic Archipelago and along its outer coast from November through July and pack ice beyond the fast-ice zone year-round. Most of Tuvaijuittuq area remains ice-covered even after fast-ice has weakened and broken free of coastal confinement in response to increasing summer temperaures between August and October after. However, there are some areas where fast-ice commonly persists year-round (DFO 2011b). Tuvaijuittuq is poorly studied, but other areas of MYI provide unique habitat for a number of ice-associated organisms such as ice-dependent amphipods, mat-forming centric diatoms and ice-adapted microbes.

Tuvaijuittuq lies within a larger area of multi-year pack ice in the Arctic Ocean. While Tuvaijuittuq is bounded by the 110° W meridian in the west and by approximately the 56° W meridian in the east, multi-year pack ice circulates widely in the Arctic Ocean, spreading: 1) north-east to Greenland, Fram Strait and eventually the Greenland Sea; 2) south across the Canadian Polar Shelf to Parry Channel, M'Clintock Channel, the mainland coast and Baffin Bay; 3) south-west to M'Clure Strait, Amundsen Gulf, the Beaufort Sea, the Alaskan Coast, Chukotka and sometimes as far south as Bering Strait. Eventually, the clockwise circulation of the Beaufort gyre brings some of the south-west drifting ice component back into Tuvaijuittuq from the north-west (Hibler III 1989; DFO 2011b; O'Brien 2019). The multi-year pack ice that lies within the Inuvialuit Settlement Region (ISR), can be considered contiguous habitat.

Figure 3. Location of important geographical features surrounding Tuvaijuittuq and adjacent areas. Bathymetry of the region is shown in blue. Adapted from NOAA (1988); Jakobsson et al. (2012).

Early in the winter, floes of MYI within drifting pack ice are fused within a matrix of new growing ice to form the immobile cover of land-fast ice that stays in place, in many areas, well into the month of August (Melling 2002; Münchow 2016; CIS 2020). Following breakup, this MYI may drift south-eastward into Baffin Bay, southward through M'Clintock Channel to Queen Maud Gulf or south-westward into Viscount Melville Sound and M'Clure Strait to the Beaufort Sea. Although the North Water is hundreds of kilometres south of Tuvaijuittuq, MYI drifting southward through Nares Strait after breakup does impact this contrasting light-ice-cover habitat from mid-August through October (Ingram et al. 2002; Barber et al. 2019).

CLIMATE

Most of Tuvaijuittuq area, extending 212 nautical miles (almost 400 km) from the north-west coasts of the High Arctic islands, does not have any climate stations. Thus, there are actually no consistent meteorological observations for most of Tuvaijuittuq. All the climate data reviewed below come from sheltered terrestrial locations distant from the outer coast – excepting those from Alert – with geography (topography, surface and sub-surface properties, vegetation, reflectivity, etc.) is very different from that of a ice-covered

ocean. The information reviewed below provides only an approximation to the actual climate of most of Tuvaijuittuq.

The climate of the Canadian High Arctic is generally described as arid and cold (Martec Ltd 1982). Sub-zero days typically begin in late August and continue to mid-June, with areas to the south-east experiencing fewer sub-zero days than those to the north-west. July is typically the warmest month, while the lowest temperatures occur during the second half of the polar night, in January, February and March.

Maxwell (1981) prepared a comprehensive description of the different climate regions of the Canadian Arctic islands, an area that border Tuvaijuittuq to the south-east. Tuvaijuittuq is adjacent to Maxwell's North-western and Northern climatic regions, within the closest (terrestrial) sub-regions being the North-western Island Fringe, the Nares Strait, and the Nansen Sound and Adjacent Lowland sub-regions.

The North-western Island Fringe is the narrow coastal zone adjacent to the Arctic Ocean (Maxwell 1981). It is distinguished by a greater persistence of stratus and stratocumulus cloud and fog during summer, conditions that result when moisture evaporating from melting pack ice remains trapped beneath the low-level temperature inversion in the polar atmosphere. This sub-region receives less than 100 mm of annual precipitation, 30–35% as rain; its mean daily temperature is -33 to -35 °C in January and 3 °C in July .

The Nansen Sound and Adjacent Lowland sub-region includes Nansen Sound, Greely Fiord and other smaller bays (Maxwell 1981). It is almost completely surrounded by mountains and has the lowest mean annual precipitation in Canada, less than 100 mm with 35–40% falling as rain. Mean daily temperature is -35 °C in January and 3 to 5 °C in July, with the higher value typical of the Eureka area.

The Nares Strait sub-region includes the eastern coast of Ellesmere Island (Maxwell 1981). It is differentiated from the region as a whole by the influential meteorological connection via Nares Strait through high mountains to Baffin Bay. Mean daily temperature ranges from -35 °C (in the north) to -28 °C (in the south) in January and 3 °C in July. The sub-region receives 150–175 mm of annual precipitation with 10–15% in the north and 40–50% in the south falling as rain.

Maxwell (1981) showed that annual mean daily temperature at Alert and Eureka cooled from the 1950s to the 1970s and subsequently warmed. This multi-decadal pattern is consistent with data from across the Arctic (Overland et al. 2017). Increased precipitation and a decrease in the number of days with snow cover have also been recorded since 1950 (Brown et al. 2018).

The observations compiled by Maxwell were recorded prior to 1980. Recent observations of weather on northern Ellesmere Island are available for Alert and Eureka; they form the basis of the present 30-year epoch's climate (1980-2010; ECCC 2018b). Alert is on the north coast of Ellesmere Island and Eureka is south of Greely Fiord; both are adjacent to the south-east boundary of Tuvaijuittuq. Although climate-grade weather data were measured until 1997 at a manned weather station, Mould Bay, on Prince Patrick Island, this station is 400 km from the south-west tip of Tuvaijuittuq and too distant to be of great use here. A manned station at Isachsen on Ellef Ringnes Island is closer, 160 km south-

east of Tuvaijuittuq, but the record of climate-grade data there ended more than 40 years ago when the station was closed in 1978.

Ignoring the shortcomings, all four stations have continued to experience similar long, cold winters and short cool summers, with Eureka being colder than the others during winter and warmer during summer (Figure 4). These differences are linked to its location within a fiord surrounded by high mountains, in contrast to less confinement by terrain at the other locations. From 1980-2010, average air temperature at Alert was -32 °C in January and 3 °C in July, while at Mould Bay and Isachsen, January averages were -33 °C and July averages were 4 °C. Precipitation in the region are very low (<250 mm annually); Alert received more annual precipitation than Eureka (158 mm compared to 79 mm), while Mould Bay received an intermediate amount (111 mm). Collection of precipitation data at Isachsen has been erratic.
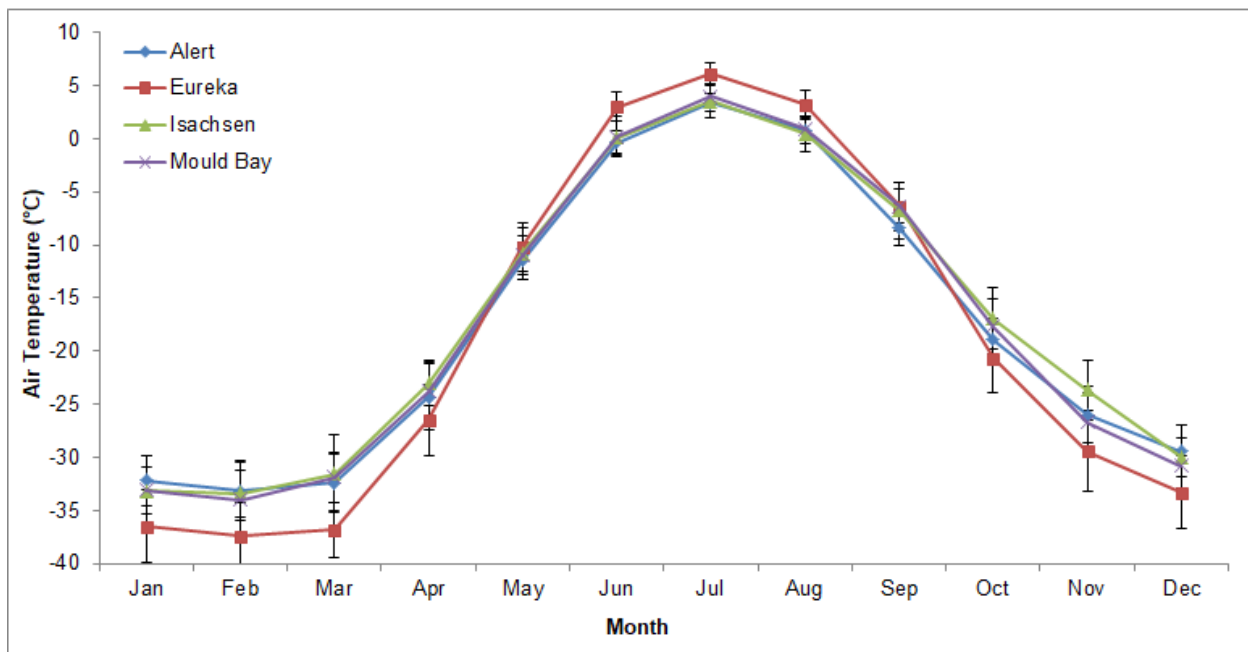
Figure 4. Average monthly air temperatures ± standard deviation recorded at the Environment Canada (EC) meteorological stations located at Alert and Eureka (1981–2010 data), Isachsen (1997–2010) and Mould Bay (1970–2000), NU. Source: ECCC (2018b).

It is problematic to lend credence to apparent changes over time at Mould Bay and Isachsen because automatic weather stations replaced standardized manual methods at these stations within 1980-2010 timeframe.

Data records are more reliable at Eureka and Alert. Lesins et al. (2010) have completed an analysis of climate trends at Eureka; for surface weather they have used a consistent 7-times daily record available for 54 years, from 1954 to 2007. They document a 2 °C drop in annual average surface temperature over the first 18 years and a 3.2 °C increase over the next 36 years (0.88 °C decade^{-1}). Trends by season over the same 36-year interval (1972-2007) were smallest for summer (JAS, 0.42 °C decade^{-1}), highest in autumn and spring (OND, 1.25 °C decade^{-1}; AMJ, 1.14 °C decade^{-1}) and intermediate in winter (JFM, 0.67 °C decade^{-1}). Trends at Alert have been smaller and not statistically

significant (Zhang et al. 2011). The temperature-change projection to 2050, barring reduction in CO_2 emissions, is a continuation of current trends.

There have also been modest changes in precipitation: a 12 mm per decade increase in the water equivalent of snowfall since 1950 at Alert, but little change in rainfall; a 7.6 mm per decade increase in the water equivalent of snowfall since 1950 at Eureka, and a 2.2 mm per decade increase in rainfall (Brown et al. 2018). There has been a decrease in the number of days with snow cover of 3–4 days per decade since 1950 at both locations. Future increase in the region's precipitation is generally anticipated but climate models give greatly different values of increase (AMAP 2017).
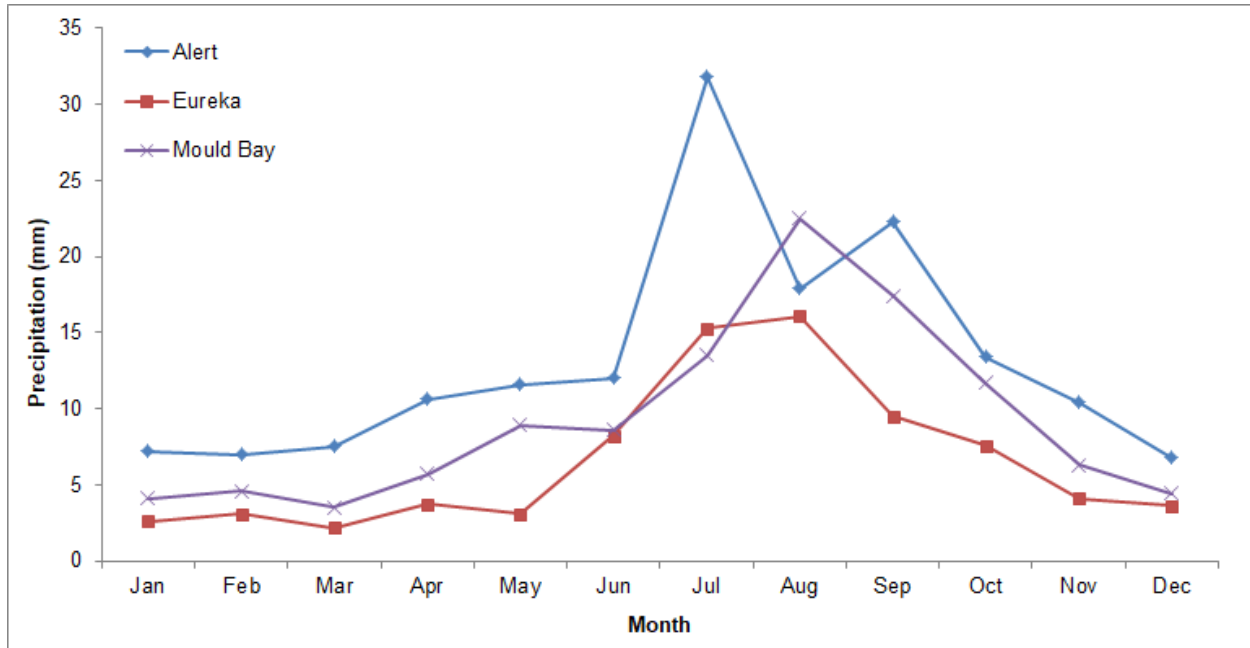
Figure 5. Average monthly precipitation collected at the Environment Canada (EC) meteorological stations located at Alert and Eureka (1981–2010 data), and Mould Bay (1970–2000), NU. Source: ECCC (2018b).

GEOLOGY AND BATHYMETRY

Tuvaijuittuq is located beyond the northern tip of the North American continent, with a south-eastern boundary that skirts the outer shorelines of the Queen Elizabeth Islands (QEI) (DFO 2019b). The area within its boundaries is Canada's northern-most marine habitat. Tuvaijuittuq includes a range of marine geographical features: deep (3000 m) offshore waters in the Canada Basin, much shallower undersea mountain ranges (Alpha and Lomonosov Ridges), channels extending to the shelf edge that connect the deep Canada Basin to shallower (500-800 m) basins in the interior of the Canadian Polar Shelf, shallower offshore and coastal areas on the Canadian Polar Shelf, and fiords extending far into the High Arctic islands themselves (Figure 3).

Only a few bathymetric soundings have been conducted within Tuvaijuittuq and adjacent areas (Figure 6). Nares Strait, south of Tuvaijuittuq, is one of the surrounding area where extensive soundings have been counducted. However, most fiords, including Archer and Disraeli fiords and large expenses of the coastal and offshore regions have not been surveyed at all.
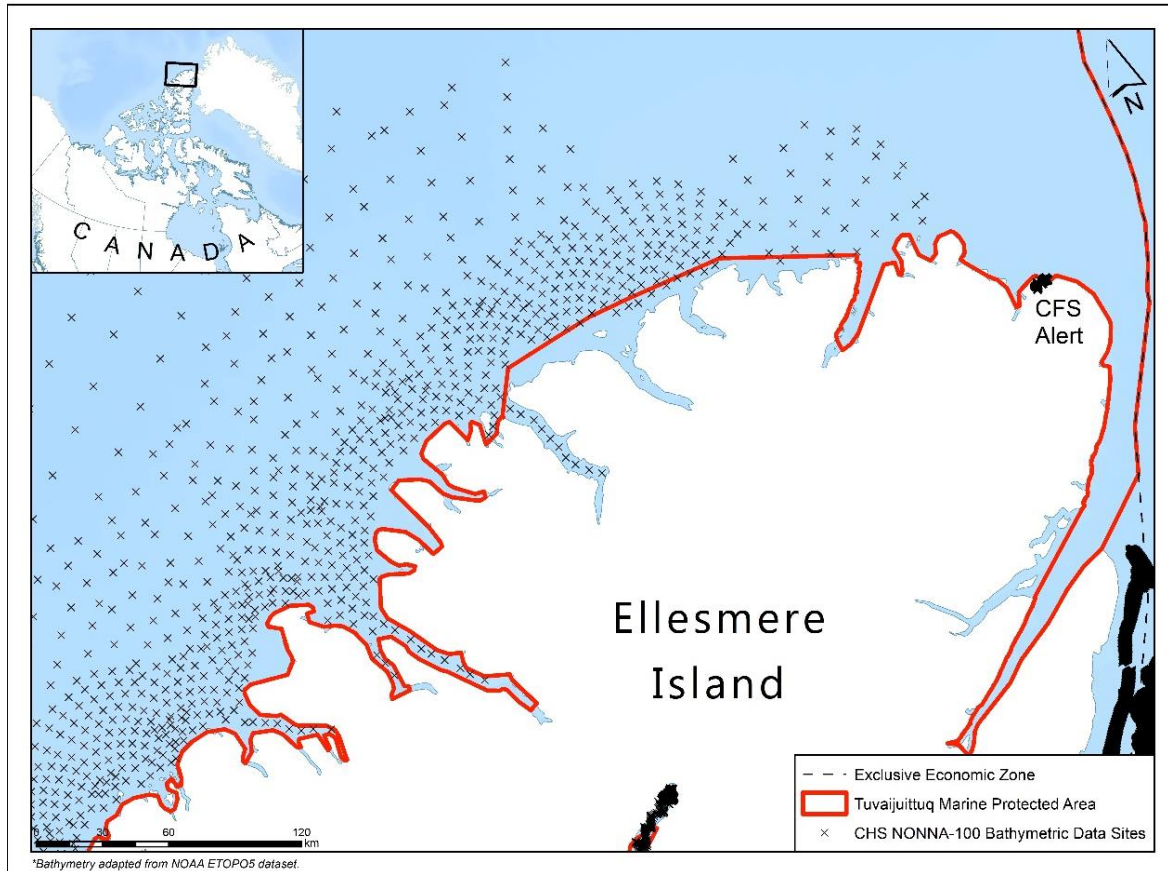
Figure 6. Location of the bathymetric soundings conducted within Tuvaijuittuq and adjacent areas. Adapted from the NONNA-100 Bathymetric Data product of the Canadian Hydrographic Service (2020)

The shorelines of Tuvaijuittuq span four different geological provinces (Martec Ltd 1982). The continental shelf and the northern coasts of the QEI to the west of Axel Heiberg Island belong to the Arctic Coastal Plain (ACP), while the northern shoreline of Axel Heiberg Island and the entire northern coast of Ellesmere Island are within the Franklinian Miogeosyncline (FM). Nansen Sound and Greely Fiord are within the Sverdrup Basin, while the eastern shoreline of Ellesmere Island, including Archer Fiord, is located in the Franklinian Eugeosyncline (FE). The compositions of these four provinces are quite different. The ACP, which extends all the way to Prince Patrick Island in the ISR, is comprised of Pliocene or Pleistocene sediments, while the FM was produced during the Ellesmerian Orogeny and is composed of carbonates, quartzose sandstones and shales. Most of the QEI are located in the Sverdrup Basin, which is composed primarily of sedimentary rock (sandstone and shale), up to 10 km thick. The western shoreline of Nares Strait, where Archer Fiord is located, is primarily volcanic rock with slate, chert and limestone.

The differences in geology shape distinct shoreline characteristics: the northern coasts of Ellesmere and Axel Heiberg islands are mountainous with numerous fiords; peaks poking through the ice sheets form rows of "nunataks" (Martec Ltd 1982). The terrain around Nansen Sound and Greely Fiord is described as "low dissected plateau and rolling uplands with altitudes generally less than 1000 m". The shorelines of Meighen and Ellef

Ringnes islands, in the western QEI just outside the south-eastern boundary of Tuvaijuittuq, are consistently low and flat. Lithified bedrock comprises the shorelines of Archer Fiord (Martec Ltd 1982; Bell and Brown 2018).

There are no sediment samples from the deep waters of the Canada Basin within Tuvaijuittuq, and very few samples exist to characterize the sediment on the continental slope and shelf (Pelletier 1962). Nearshore sediments over much of the Canadian Polar Shelf are mixtures of sand and gravel and to a lesser extent mud (Horn 1967; Martec Ltd 1982). Offshore areas are covered by muds and clays of uniform size. Granular sediments, rafted to the area by ice, sit upon these fines in the Prince Gustav Adolf Sea, Peary Channel, and Sverdrup Channel areas (Pelletier 1962). Ice scours are common throughout the basin (McLaren 1982).

The islands of the Canadian Arctic Archipelago are located on the Canadian Polar Shelf, a vast triangle of shallow seabed stretching 2,300 km north-eastward from the Beaufort Sea to the Lincoln Sea, 2,600 km south-eastward to Hudson Strait and 3,500 km westward back to the Beaufort Sea. The edge of the continental shelf, the shelf break, in the region of Tuvaijuittuq is at about 400 m depth. The distance from the shelf break to coastlines in the Tuvaijuittuq ranges between 75 km north-west of Ellesmere Island to 190 km north-west of Ellef Ringnes Island. Beyond the shelf break, a steeper slope descends into the Canada Basin, where water depth reaches about 3,500 m in places (Pelletier 1964; Martec Ltd 1982; Fissel et al. 1984a; 1984b). Along the continental shelf, Ballantyne and Wilkins straits in the south-west and Prince Gustav Adolf Sea and Sverdrup and Peary channels to their north-east connect the Canada Basin to the Sverdrup Basin (Martec Ltd 1982; Fissel et al. 1984a; 1984b). The former are shallower (100–140 m) than the latter (400–450 m) (Figure 3). Although sills at the outer edge of the continental shelf rise to a depth of 440 m, the trough in Peary Channel exceeds 700 m depth while those in Massey and Hassel Sounds (on either side of Amund Ringnes Island) exceed 500 m (Horn 1967). Shallow sills (100–200 m) are located within the smaller channels separating the south-eastern QEI (Byam Martin Channel, Hell Gate, Penny Strait/Queens Channel, Fitzwilliam Strait) (Greisman and Lake 1978; Martec Ltd 1982; Fissel et al. 1984a; 1984b).

Nansen Sound, between Axel Heiberg and Ellesmere Islands, leads into Greely Fiord and its tributaries, forming the largest fiord within Tuvaijuittuq (Figure 3). There is a sill approximately 400 m deep beyond the western end of Nansen Sound, but depths along the axis of the sound are typically 700–750 m, with a maximum of 920 m (Hattersley-Smith 1969). Depths in Greely Fiord decrease from a maximum of 700 m at the western end. Its tributary fiords range in size, with Otto Fiord being the largest and deepest (500–600 m for its entire length), but most are shallower (200–400 m deep) and similar in extent to the other fiords on Ellesmere Island.

Nares Strait is 550 km long, connecting the Lincoln Sea, at the eastern boundary of Tuvaijuittuq, to Baffin Bay (Figure 3). At its narrowest point, across Robeson Channel, Nares Strait is 20 km wide. Water depths in the Lincoln Sea north of Nares Strait are shallow in the west toward Ellesmere Island and Alert (100–200 m), increasing from west to east to approximately 500 m off the coast of Greenland (Sadler 1976; Martec Ltd 1982). Water from the Lincoln Sea flows into Robeson Channel and Hall Basin, the deepest part of Nares Strait (Sadler 1976). Depths there reach almost 800 m (Jakobsson et al. 2012).

The entrance to Lady Franklin Bay (Archer Fiord) from Hall Basin is 500 m deep (Sadler 1976). Water depths decrease from north to south until reaching a 220 m sill at the northern end of Kane Basin (Jakobsson et al. 2012).

OCEANOGRAPHIC SYSTEMS

Water Masses

The Arctic Ocean, with its basins and surrounding shelf seas receives water from four sources: the North Atlantic Ocean, the North Pacific Ocean, rivers and precipitation. The North Atlantic provides the most saline and densest water while rivers and precipitation, being fresh, contribute water of the lowest density. The inflow from the North Pacific, already appreciably freshened by run-off from the North American Cordillera, has intermediate salinity and density. The Arctic Ocean loses water by evaporation and by out-flow of water and sea ice to the North Atlantic.

The annual inflows and outflows are small relative to the total volume of water in the Arctic, but the renewal time of water does vary from basin to basin and with depth. That in the upper 1500 m or so is the order of 1-3 decades (Schlosser et al. 1990; Smith et al. 2011). That near the seabed in the deepest water is measured in centuries, 250 years in the Eurasian Basin (Schlosser et al. 1997) and about twice that on the Amerasian side (Macdonald and Carmack 1993).

The relatively large dilution of near-surface seawater by fresh water has important implications in the Arctic Ocean. The dilution is not uniform; surface water is most heavily affected. Because dilution reduces the density of seawater, there is a relatively large increase in seawater density through the uppermost 300 m of the water column, particularly in the Canada Basin. This increase slows mixing of deeper water, which is typically warmer and more rich in nutrients, with colder less rich surface water. Slowed mixing weakens delivery of the ocean's stored heat to the surface, thereby protecting the Arctic's ice cover, an important factor for Tuvaijuittuq. Slowed mixing also weakens delivery of the ocean's stored nutrients to the photic zone, thereby primary production at the base of the food web.

Continental runoff and precipitation are the principal contributors of fresh water to the Arctic Ocean (Aksenov et al. 2010); the supply of freshwater via dilution of the Pacific inflow ranks third (Serreze et al. 2006). Canadian Arctic through-flow carries two-thirds of the total freshwater exported from the Arctic (Aksenov et al. 2010); sea ice is not a big contributor via this pathway. Outflow via Fram Strait carries the remainder. Fresh water held within the Beaufort Gyre is linked to the accumulated imbalance between Arctic fresh-water inflows and outflows. It has increased by more than 11% since 2003 compared to the 1980–2000 average (AMAP 2017). Spin-up of the gyre, increased river runoff and net precipitation and reduced ice cover have all contributed to this change

There are several distinct layers or water masses prevalent throughout the Arctic, with only modest regional variation (Figure 7; CAFF 2013). From top to bottom these are the Arctic Surface Water, the Pacific Water, the Atlantic Water and the Deep Water. The Pacific Water is confined to the western hemisphere of the Arctic (the Amerasian Basin) and has minimal presence on the far side of the Lomonosov Ridge.

Most of Tuvaijuittuq lies within the Canada Basin. Here the Arctic Surface Layer extends to approximately 50 m depth. In winter it is coincident with the polar mixed layer, wherein water has uniform properties resulting from convective mixing by dense brine that is rejected during ice formation. In summer, the Arctic Surface Layer splits into two layers, a deep relict of the previous winter's polar mixed layer and a shallow (5-15 m) overlying layer freshened by melting snow and sea ice. The halocline – an unmixed interfacial layer wherein salinity increases from Arctic to Atlantic values – lies beneath the Arctic Surface Layer and extends to about 250 m depth. It is dominated by water of Pacific origin throughout the western Arctic (i.e., in the Canada and Makarov Basins and adjacent shelf seas), including most of Tuvaijuittuq. There are three variants of Pacific water stacked above one another (Steele et al. 2004). The uppermost and least saline is fed by a relatively warm, brackish current following the Alaskan coast northward from Bering Strait in summer (Alaskan Coastal Water). Below this is the cooler, more saline summer Bering Sea Water that entered the Chukchi Sea from the eastern Bering Sea in summer and followed broad shallow valleys across the Chukchi seabed to enter the Arctic Ocean north-west of Barrow Alaska. The lowest layer (Chukchi Sea Water, or winter Bering Sea Water) has the same origin but reaches the Chukchi Sea in winter; it is chilled to freezing and enriched with salt via ice growth over the Chukchi shelf; beyond the Chukchi Sea, it feeds a thick cold (-1.5 °C) temperature minimum layer that spreads halfway across the Arctic Ocean. All Pacific-derived waters, and especially the Chukchi Sea Water are rich in dissolved nutrients that are critical to the Arctic marine food web (Rudels et al. 2004; Woodgate 2013). Most of the water beneath the halocline, deeper than about 250 m depth, originates in the North Atlantic. The relatively steep increase in salinity (density) over depth between the Arctic surface layer and the Atlantic layer impedes mixing between the layers.
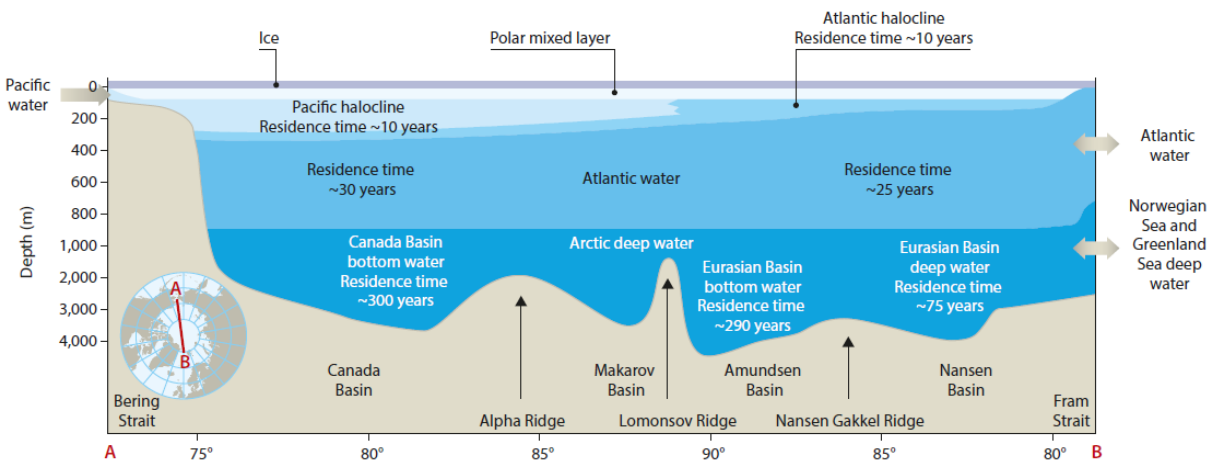
Figure 7. Schematic representation of water masses in the Arctic Ocean. From CAFF (2013).

Tuvaijuittuq's straddles the Trans-Polar Drift, a broad current that flows across the Arctic Ocean from the Russian side towards Ellesmere Island. Because the QEI block the Trans-Polar Drift, it splits within Tuvaijuittuq so that conditions in its north-eastern part are more influenced by waters from the Atlantic side of the Trans-Polar Drift than by Pacific-derived waters. This is evident in observations at stations in the Arctic Basin north of Ellesmere Island in 2000 and 2003 (Alkire 2010). Here near-surface waters were 86–

100% Pacific water and 0–14% Atlantic water, whereas at relatively shallow depths (125–130 m) and in the south-western part of Tuvaijuittuq Atlantic water (60–75%) made a greater contribution than Pacific water (25–40%). Tuvaijuittuq therefore spans both the Pacific-dominated and Atlantic-dominated sectors of the Arctic ocean; it has marine connections to both major oceans of the northern hemisphere.

Circulation

The Trans-Polar Drift is the feature of the Arctic Ocean's circulation that defines Tuvaijuittuq. It is a broad stream driven by prevailing winds that carries ice and upper-ocean waters from the Siberian shelf to Ellesmere Island. It has been well delineated by the tracking of sea ice from satellite since the late 1970s (Untersteiner and Thorndike 1982). Figure 8 displays the observed pattern and speed of ice drift during contrasting patterns of wind (Rigor et al. 2002). The dashed lines mark the dividing line between ice circulating in the Beaufort Gyre (to the lower left) and that moving towards an exit via Fram Strait (at the lower right). Under wind conditions associated with the upper frame, more than half the Arctic Ocean is occupied by the Beaufort Gyre; because the dividing line points to the Lincoln Sea, almost all Tuvaijuittuq is within the influence of the Beaufort Gyre. Under wind conditions associated with the lower frame, the Beaufort Gyre is much smaller; because the dividing line points to Ellef Ringnes, more than half of Tuvaijuittuq is within the influence of the Trans-Polar Drift exit stream.

Direct knowledge of ocean circulation beneath the surface within Tuvaijuittuq is very limited. In water deeper than about 1000 m, current is likely driven by geostrophic adjustment to the prevailing wind and a progressively weaker image of that at the surface down to 300-400 m depth. So, deeper flow likely approaches Tuvaijuittuq from the north-west and splits into north-east and south-west-flowing branches on reaching the continental slope. The former continues towards the Lincoln Sea and Fram Strait the latter flows towards the Beaufort Sea. The average speeds of these two branches in Tuvaijuittuq are likely low because of the retarding effect of heavy ice cover, perhaps 2 km day^{-1} in summer and 1 km day^{-1} in winter (Martec Ltd 1982).

In the Lincoln Sea, over the upper continental slope and outer shelf, there is evidence from direct measurements spanning two years of an undercurrent (that is, in the opposite direction at depth than at the surface) flowing towards the north-east (Newton and Sotirin 1997); where water was 600 m deep, the reversal occurred at about 100 m depth. This observation is consistent with indirect evidence provided by Steele et al. (2004) using the signature of water from the Alaskan Coastal Current, which suggested that this water flows at depth counter-clockwise around the Canada Basin from Barrow Alaska to the Lincoln Sea. The differing basin and slope circulations allow Tuvaijuittuq to receive Pacific-derived water both from the south-west (Arctic Coastal Water) and from the north-west (summer and winter variants of Bering Sea Water).

Smaller streams apparently branch from both surface current and undercurrent to move southward down channels across the Canadian Polar Shelf (Martec Ltd 1982; Wekerle et al. 2013). In fact, most of the Canadian Arctic through-flow of seawater and sea ice appears to pass either through between the QEI or down Nares Strait between Greenland and Ellesmere Island (de Lange Boom et al. 1988; Fissel et al. 1988; Kwok 2006). It is the opinion of many scientists that a decrease in sea level of 10-15 cm between the Arctic

Ocean and the north Atlantic Ocean, linked to the former's lower salinity, is the primary driver of the Canadian Arctic through-flow (Stigebrandt 1984; Melling 2000; McLaughlin et al. 2004; Münchow and Melling 2008; McGeehan and Maslowski 2012). A quasi-periodic store-release cycle governing fresh water in the Beaufort Gyre appears to impose a corresponding variation in the through-flow (Peterson et al. 2012)
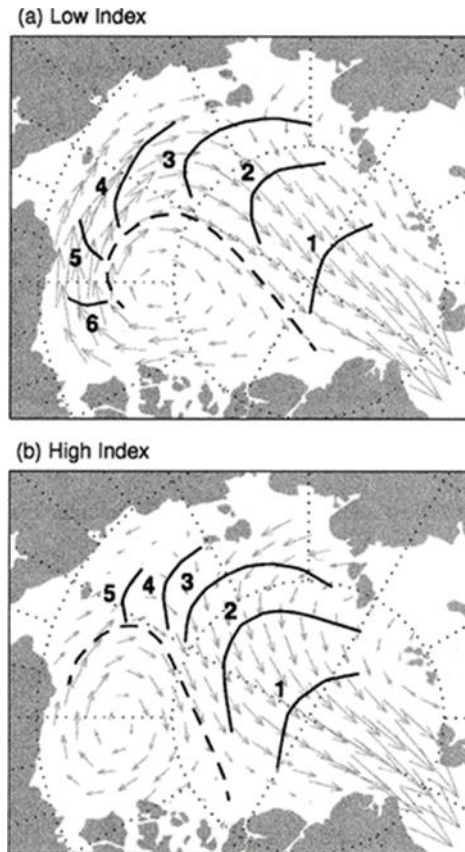
Figure 8. Mean pattern of ice drift over the Arctic Ocean at times of anomalously (a) high and (b) low sea-level air pressure. Arrows represent ice drift. Numbered curves show the position of ice at intervals in years prior to the ice' exit through Fram Strait. The dashed the position of ice at intervals in years prior to the ice' exit through Fram Strait. The dashed line the boundary between the clockwise and counter-clockwise components of the pattern of the stream. From Rigor et al. (2002).

In addition to Arctic Surface Water, the branching streams carry waters of Pacific and Atlantic origin across the Canadian Polar Shelf. The sills to the north of Prince Gustav Adolf Sea and Peary and Sverdrup channels are as much as 440 m deep. Atlantic water therefore readily floods the deep basins of the northern and western parts of the Canadian Polar Shelf, but it is too dense to pass unmodified across the shallow sills (80-180 m, depending on the pathway) that partially obstruct channels near the centre of the polar shelf (Melling 2000). Much appears to remain in these basins for decades (Melling et al. 1984) and most eventually leaks back into the Canada Basin. Some may be sufficiently diluted by mixing with overlying Pacific waters, driven by strong tidal currents in the central area, to eventually pass eastward over the central sills.

The Pacific and Arctic waters are little impeded by the sills (Figure 9). Indeed the sluggish flows across the basins of the polar shelf accelerate appreciably as they pass over the

sill to reach Parry Channel (Byam Martin Channel, Penny Strait) and Baffin Bay (Cardigan Strait, Hell Gate, Nares Strait; Fissel et al. 1988; Melling 2000). The magnitude of the Canadian Arctic through-flow ranges between 0.7–2 Sv (1 Sv is 1 million m^3 s^{-1}; Fissel et al. 1988; Melling 2000; Melling 2004; Melling et al. 2008; Beszczynska-Moeller et al. 2011), summed over Nares Strait, Jones Sound and Lancaster Sound (Kliem and Greenberg 2003). Prinsenberg and Hamilton (2005) have suggested that between 90 and 110 mSv of this flow is freshwater flux.
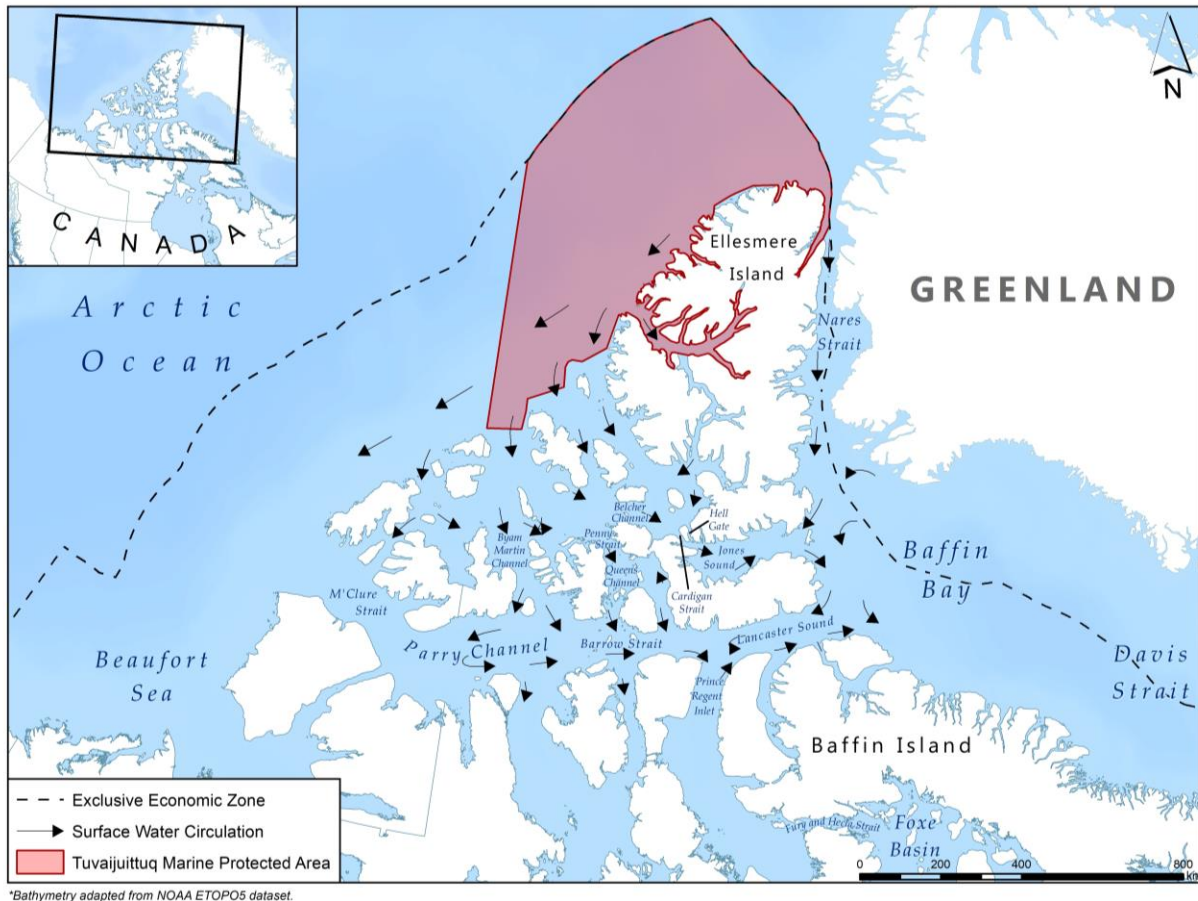
Figure 9. Surface water (< 50 m water depth) circulation in the QEI and surrounding waterbodies. Adapted from Martec Ltd (1982).

Nares Strait transports water from the Arctic Ocean into Baffin Bay (Muench 1970; Sadler 1976). A sill at 300 m depth along the shelf edge in the Lincoln Sea prevents water from the core of the Arctic's Atlantic layer from entering Robeson Channel. Therefore, only Arctic Surface Water, Pacific Water and a warmer Atlantic Water fraction diluted with Pacific Water can flows into Nares Strait (Münchow et al. 2007; Melling et al. 2008).

Within Tuvaijuittuq in Robeson Channel, southward current was fastest (40 cm s^{-1}) at 100–200 m depth, 3 km from Ellesmere Island (Münchow et al. 2007). In the centre of the channel, at a depth of 50 m, there was a 20 cm s^{-1} southward current, while at the bottom of the water column there was a 10 cm s^{-1} current to the north. Data collected further south in Kennedy Channel by Münchow and Melling (2008) confirmed that there is a weak

northward current within 5 km of Greenland that moves water northward from Baffin Bay; its flow is only about 5% of the southerly current.

Off the shore of Ellesmere Island in Robeson Channel in 2003, Pacific Water made up 75% of the total flow down to a depth of 100 m, but this layer on the Greenland side was thinner (50 m) and Pacific water comprised only 25% of the flow at a depth of 100 m. To reach Baffin Bay, the flow must pass over a 220 m sill at Kane Basin that blocks the more saline water near the seabed (Melling et al. 2008). However the upward slope of isohalines towards Greenland, linked to geostrophic adjustment of the flow, does allow some of the salty Atlantic layer mixed with less dense Pacific water to flow across this sill and onward to Baffin Bay.

The amount of water that enters Baffin Bay through Nares Strait is 1.0 ± 0.2 Sv. The net southward volume flux increased from north to south in Nares Strait, from 0.77 Sv in Robeson Channel to 1.03 Sv in Smith Sound. This increase reflects the entrainment of north-flowing water from the West Greenland Current on the eastern side of the strait into the south-flowing Arctic outflow current on its western side (Münchow et al. 2007). The rate at which nutrient-rich Pacific Water leaves the Arctic affects the amount of dissolved nutrients that is stored in the Arctic, principally in the Canada Basin, and therefore may affect marine productivity in Tuvaijuittuq. Long-term changes in outflows of nutrient-rich Pacific Water and freshwater across the Canadian Polar Shelf and through Nares Strait could affect productivity of Tuvaijuittuq's marine ecosystem.

River Discharge and Glacier Melt

River discharge is an important source of freshwater input to the Arctic Ocean and the Canadian Arctic Archipelago (e.g., Aagaard and Carmack 1989; McLaughlin et al. 2004). There are no major rivers in Tuvaijuittuq, therefore any impact of river plumes will be local and short-lived during freshet in early summer. To the west, the Mackenzie river carries high suspended matter load and freshwater discharge into the Beaufort Sea, outside of Tuvaijuittuq.

The QEI islands have only small- to moderately-sized rivers that drain numerous tundra lakes or nivel (meltwater) streams that are frozen solid for most of the year (McLaren 1981; Woo et al. 2000; McLaughlin et al. 2004; Carmack and Wassmann 2006). These small rivers flow for only a short period of time, with extreme seasonal runoff during the spring freshet, no input during the winter, and high interannual variability (McLaughlin et al. 2004).

Glacier lakes and associated rivers can be unique features of Tuvaijuittuq, and are also subjected to rapid changes due to Arctic warming. In northeastern Ellesmere Island, the Ruggles River is the outflow of Lake Hazen, High Arctic's largest lake by volume, and drains into Lady Franklin Bay at the entrance of Archer Fiord via Chandler and Coneybeare fiords (St. Pierre et al. 2019). Climate warming has resulted in ca. 10-fold increase in glacier meltwater input into Lake Hazen for the period of 2007–2012 (Lehnherr et al. 2018). This input increased the mean annual discharge into the Ruggles River by almost 4-fold (from 0.49 to 1.8 km^3 y^{-1}) compared to 1996–2006, also decreasing the residence time of lake water from ca. 89 to 25 years. In 2015 and 2016, the increased glacier melt delivered high nutrient loads to Lake Hazen, which acted as a sink for all

nutrients but not for dissolved organic carbon (DIC), such that large amounts of DIC were released into the Ruggles River (St. Pierre et al. 2019). This example shows how changing glacial melt is expected to have significant impacts on the quantity and quality of freshwater input to the Arctic ocean and to Tuvaijiuttuq, where increases in glacial meltwater input from Ellesmere Island is already observed.

Sea Ice

The formation of sea ice as the poles cooled over two million years ago during the Pliocene epoch led to a major speciation event, including the evolution of the many ice-associated or ice-dependent flora and fauna (Arrigo 2014). Polar sea ice supports a diverse range of organisms from microbes and ice algae to large amphipods, fish, seabirds, marine mammals and humans. Sea ice is strongly linked to the marine habitat (pelagic and benthic) through the exchange of dissolved and particulate constituents including nutrients and organisms that can be incorporated in or released from the ice, and through trophic interactions.

Polar sea ice (Arctic plus Antarctic) represents a large area of distinct habitat that has varied in extent seasonally from 15 to 22 million km^2 (4.1–6.1% of the global ocean) since all-weather satellite reconnaissance began in 1979. In the northern hemisphere over the last four decades, notional minimum sea ice extent in September is 6.3 million km^2, almost all within the Arctic Circle, and the notional maximum extent in March is 15.5 million km^2, with lobes extending into temperate latitudes (NSIDC 2020b).

Ice cover on the oceans reduces the exchange of mechanical and thermal energy between the ocean and atmosphere compared to open water (Barber et al. 2015). Ice cover increases friction on currents and thereby modifies the amplitude and phase of tides (Prinsenberg and Ingram 1991). Sea ice participates in biogeochemical cycling by impeding the transfer of gases and solid matter between ocean and atmosphere and by carrying fresh water, biota, dissolved chemicals and sediment around the Arctic and beyond it. Sea ice facilitates Inuit's travel and access to food resources and supports many nutritionally and culturally important marine species, particularly in locations where ice meets open water (Aporta 2011).

Tuvaijuittuq is located within an area of persistent sea ice cover that spans approximately 500,000 km^2 in the Canadian High Arctic. This area is approximately one tenth of the Last Ice Area in its present state (Pfirman 2009). This ice is delivered by the Transpolar Drift and packed against the obstacle of the Canadian Arctic Archipelago with its ice-choked channels by wind and current. The MYI within Tuvaijuittuq extends hundreds of kilometres offshore, an equal distance across the Canadian Polar Shelf and farther yet to the north-east and south-west along the continental margin. It is characterized by heavy ridging, accumulated during many years at sea and augmented locally through the action of high compressive and shearing forces generated where the moving pack contacts fast ice and shorelines (Hibler III 1989; Melling 2002; Perovich et al. 2015; 2017). MYI is persistent at high latitude because of the very cold climate there, and can persist in the more southerly places to which it drifts if it is thick enough to survive summer's melt. It therefore provides summertime habitat in these areas which in Canadian waters include the southern Canada Basin and the Beaufort Sea, the part of the Canadian Polar shelf south of the QEI (Melling 2002), Nares Strait, Baffin Bay and the Labrador Sea.

Sea ice can also be found in ice shelves, even though it is less common. A more detailed description of Ellesmere Island ice shelves and their composition can be found in the Ice Shelves section.

<u>Physical Structure</u>

Ice fields are composed of two main ice types: FYI and MYI (Figure 10). FYI forms when crystals of frazil ice, that are the first result of freezing seawater, aggregate and bond together to form pancakes or nilas (NSIDC 2018). FYI is the dominant ice type in winter, all or most which clears or melts in summer. It is not so common within most of Tuvaijuittuq where much of the sea surface is already occupied by ice at the end of the thaw season. However, FYI does form during the freezing season in the leads that continually open in pack ice, and in fiords and embayments. MYI is FYI that has lost thickness over the summer, and has begun to accumulate new ice on its under-surface (Barber et al. 2010; NSIDC 2018). First- and multi-year ice have distinct physical and morphological properties that distinguish them from one another (Johnston 2017). Moreover, there are important differences between MYI formed largely via thermodynamic processes and hummocked MYI which is derived from pressure ridges. MYI is the dominant ice form within Tuvaijuittuq (CIS 2010). Indeed, this dominant ice type is precisely the reason for creating this MPA.

The crystals comprising FYI in most areas of the Arctic form vertical columns below a 10-20 cm thick top layer of granular ice. MYI, because it has experienced a number of freeze-thaw cycles and incorporates weathered and consolidated ridges and rafts, has a less organized crystal structure. It incorporates ice formed in previously water-filled voids and blocks of columnar and granular ice originally associated with first-year pressure ridges wherein they were piled with random orientations (e.g., Lange et al. 2015).

Pockets and tubes of highly saline brine are embedded within the crystal of sea ice. When the ice warms in summer, these brine-filled cavities expand, coalesce and eventually form drainage systems that allow the dense brine to escape to the ocean. At the same time, snow-melt water from the ice surface flushes the submarine part of these systems (air fills the sub-aerial parts). When this fresh water freezes, without brine inclusion, it freezes solid, thereby greatly enhancing the strength of MYI relative to FYI of the same thickness (ECCC 2016; NSIDC 2018).

All ice types decrease in strength during the melt season, but the decrease is smallest in MYI, especially the hummocked types that are abundant in Tuvaijuittuq (Johnston 2017). Ridging is a very important factor in the ice regime of Tuvaijuittuq because of high ice pressure. It dramatically and rapidly increases ice thickness all along the outer coast from Fram Strait to M'Clure Strait (Bourke and Garrett 1987).
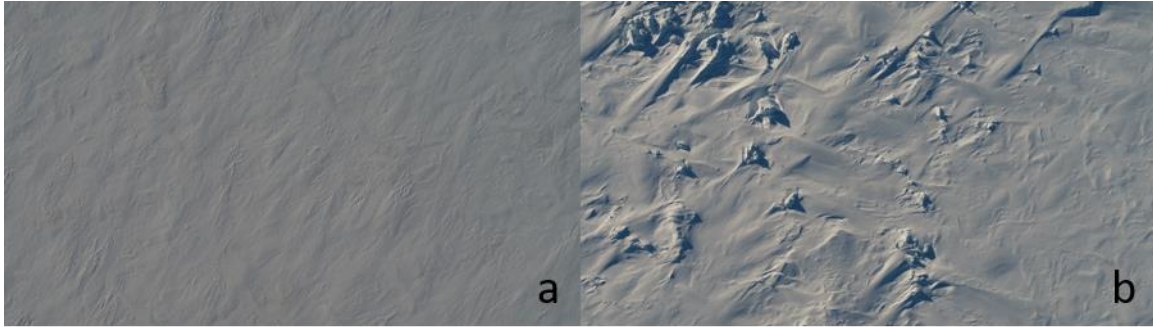
Figure 10. FYI (a) and MYI (b) aerial photos from an unmanned aerial vehicle operated during the Multidisciplinary Arctic Program –Last Ice Program in spring 2019. Photo credits: Pascal Tremblay, DFO

<u>Sea Ice Thickness</u>

Our knowledge of the thickness of sea ice in the central and high Arctic during past times is completely based on measurements by sonar on patrolling submarines (Bourke and Garrett 1987). Although the maps of measured ice draft (the submerged fraction of ice thickness, approximately 90% of thickness) in their paper suggest thorough surveying in the area of Tuvaijuittuq, the information there is based on only a few traverses (Lyon 1984). Nonetheless, the general pattern of thickness variation that submarines documented is consistent with present understanding: spatially averaged ice draft is greatest at the outer coast of the Canadian Arctic islands and northern Greenland; highest values (6-7 m) were measured between the northern capes of Ellef Ringnes Island and Greenland, in the south-eastern part of Tuvaijuittuq. Values decreased in both directions along the coast to 3 m in the Beaufort and Greenland Seas. Values decreased with distance from the coast to 5 m at the North Pole and 3 m on the Russian side of the Arctic Basin. This spatial pattern of ice thickness is also replicated by numerical simulation on a regional scale, as demonstrated for Tuvaijuittuq by Moore et al. (2019).

Maykut and Untersteiner (1971), using of a numerical model of the physics of sea ice growth and decay, showed that level floes of MYI could develop over a succession of annual freeze-thaw cycles under the climatic conditions found at high latitudes in the Arctic Ocean. Studies with more advanced models since that time have not changed this general conclusion. However, these studies have shown that thermodynamic MYI development is possibly only in the harshest Arctic climatic zone, which includes Tuvaijuittuq (e.g., Steele and Flato 2000). Here a floe of FYI can grow to as much as 2.5 m thickness during its first winter. During the following summer, which is short at high latitude, the FYI floe may not completely melt. During its second winter, more ice accumulates on it lower surface to yield a thickness by summer greater than attained during the first winter. The floe thins somewhat during the second summer, but its thickness at summer's end is greater than that a year earlier. More ice is added during the next winter, and so on. The model revealed that floes could reach a maximum thickness of about 3 m after a decade of present climate. This result has been confirmed by airborne measurements of sea ice thickness in the Transpolar Drift near the North Pole, (Haas et al. 2008).

With this knowledge, it became clear that the 3.5 million square kilometres of ice in the Arctic, thicker than 3 m in the 1970s, must have owed their greater thickness to ice ridging.

From that perspective, the very thick ice in Tuvaijuittuq is a reflection not only of the cold climate of the central Arctic and the age of ice reaching the region but also of the prevailing wind on the ice, continually driving it towards northern Canada and Greenland. If pack ice is strong enough to counteract the wind stress, it stops moving. When it doesn't stop, the forces cause floes to buckle, shear and fracture and pile the floe fragments into massive sinuous heaps that can be 30-40 m thick and stretch for hundreds of kilometers parallel to the coast. Such features contain 100% of the ice mass near the boundary between the moving pack and fast ice and 50-75% of ice mass for a few hundred kilometres further out to sea (Williams et al. 1975; Tucker III et al. 1979; Hibler III 1989; Melling and Riedel 1995). Beyond several hundred kilometres from shore, pressure ridges are relatively widely spaced, accounting for only 2–20% of pack-ice mass (Koerner 1973; Hibler III 1989).

During the past two decades, the older (> 4 years) Arctic MYI decreased significantly, covering only 0.9 million km² in 2019 (Perovich et al. 2019; NSIDC 2020a). Tuvaijuittuq now harbours most of the oldest and thickest ice in the Arctic and a sizeable fraction of the remaining MYI (Tilling et al. 2018; Perovich et al. 2019), chiefly because the wind contains to push the Arctic's oldest ice into Tuvaijuittuq (Hibler III 1989; Melling 2002; Michel et al. 2015; Perovich et al. 2015; 2017). This thick, hummocky ice possibly provides habitat to a unique ice-associated algal and faunal communities (Hop et al. 2000; Lange et al. 2015; AMAP 2017; Lange et al. 2017).

Recent estimates of ice thickness across the Arctic have been derived from satellites using scatterometers in the optical and microwave bands to measure the snow-top elevation above the geoid. Ice thickness is calculated as roughly ten times the elevation of the ice top above the sea surface, which requires prior estimation of the height of the sea surface above the geoid and the average depth of snow at each target point. Both prior estimates are particularly challenging in Tuvaijuittuq because heavy ice provides few check-points at sea level and notoriously variable snow depth must be estimated year-round from past measurements, which are also rare. All steps are challenging and errors are magnified roughly ten times by the scaling factor.

Nonetheless, during 2011–2016 it was determined from Earth satellites that average sea ice thickness along the northern edge of the QEI in April was 5 m, with ice thickness decreasing to between 3 m and 4 m in the Canada Basin (Perovich et al. 2019), values that are smaller than those reported by Bourke and Garrett (1987).

Most up-to-date data on ice thickness pertinent to Tuvaijuittuq has been acquired either at its extreme north-eastern corner, or outside Tuvaijuittuq, in Nares Strait. Typical ice thicknesses in both these locales, beyond the influence of high ice pressure, may under-represent the thickness of ice characteristic of the outer coast.

Thickness of nearshore fast ice at Alert and Eureka measured by weekly drilling, 1957-2014, shows that maximum thickness in this corner of Tuvaijuittuq occurs in May each year. The means of yearly maxima over this period have been 1.98 and 2.27 m (Howell et al. 2015). FYI of this thickness readily melts before summer's end at these high latitude locations within 100 m of shore, showing that micro-climate is important to sea ice. As everywhere in polar seas, the depth of snow cover is a critical factor impacting ice

thickness and its variation in the region with location and time (Brown and Cote 1992; Dumas et al. 2005; Lange et al. 2015; 2017).

Coastal surveys of ice thickness have also been made via electromagnetic induction in accessible parts of the Lincoln Sea in spring and summer. In the springs of 2004 and 2005, they revealed modal ice-plus-snow thickness values of 3.9 m and 4.2 m, respectively (Haas et al. 2006). Ice-plus-snow thicknesses of selected floes in the Lincoln Sea were again measured in the spring of 2009, revealing modes in the 3.9-4.7 m range. The floes were tracked and re-measured in Nares Strait in August of the same year, when the modes (ice only, snow melted) had decreased to 2.2-3.0 m (Lange et al. 2019a), confirming that MYI floes can thin rapidly over summer in this area.

During August 2007 and 2009, Johnston (2019) collected ice thickness measurements from between 10 and 50 holes drilled through floes of MYI in Nares Strait selected on the basis of their ruggedness and freeboard as likely to be very thick. The mean thicknesses of floes ranged from 4.6 to 8.3 m (3 in Hall Basin), 5.1 m (1 in Kennedy Channel) and from 4.2–9.4 m (5 in Kane Basin). The greatest mean floe thickness measured in Nares Strait was 16.6 m. In Kane Basin in August of a different year (2013), sampled floes were appreciably thinner (2.95 m; Prinsenberg 2014). The extreme thickness of some floes measured in the past decade should not be overlooked. The data illustrate that a warmer Arctic remains capable of creating very thick sea ice, even though its persistence appears to have decreased. The wide variation in the thickness of MYI floes is commonplace; it reflects the diversity of a population with differences in age, place of origin, mechanical deformation and regions of prior travel.

Continuous year-round ice-draft measurements were acquired using submerged up-looking sonar (Melling et al. 1995) over a nine-year period in Kennedy Channel. At this location the sonar measured ice-free conditions, FYI formed within the strait or in the Arctic Ocean and MYI departing from Tuvaijuittuq. The sonar operated during land-fast periods, when the ice target was the same for prolonged periods and during periods when the pack was in motion. The daily median draft (including open areas as zero draft) ranged from zero to almost 10 m, with annual averages between 0.95–1.98 m. Ice draft exceeded 2 m during more than 38% of the nine-year record, and exceeded 5 m during between 9 and 16% of each year-long interval. Median ice draft varied from year to year with no trend detectable between 2003 and 2012. Ryan and Münchow (2017) also observed that sea ice on the Ellesmere Island side had average draft higher by almost 1 m than that observed near Greenland. This difference reflects the effect of north-east wind, which not only drives ice southward from the Lincoln Sea, but pushes it over to the Ellesmere side, leaving Greenland waters less ice-congested.

Ice forming between the islands of the High Arctic is less ridged than that drifting in from Tuvaijuittuq because waters within the archipelago are less exposed to high stresses from wind and current that causes ridging (Melling 2002). Most deep ridges in the QEI are likely imported from Tuvaijuittuq (Martec Ltd 1982; Hudson 1987; Melling 2002). Average thickness of MYI in the QEI ranged 3-5 m during the 1970s, which is the only time for which data are available. Ice patches in some areas reached a mean thickness of 5.5 m over a 10-30 km scale (Melling 2002). Ice was thicker in the north-west – Prince Gustav Adolf Sea – and thinnest ice in the south-east – Byam Martin Channel and Penny Strait (Martec Ltd 1982; Fissel et al. 1984a; Fissel et al. 1984b; Melling 2002).

Sea Ice Formation and Concentration

Tuvaijuittuq means "the place where the ice never melts" in Inuktut, as MYI is present there at concentrations of 9 to 10 tenths year-round (CIS 2020). In winter, its mobile component (pack ice) can be at varying distances offshore, but it is separated from the outer coastlines of the High Arctic islands by a zone of land-fast (10/10) ice, containing a dense aggregation of MYI floes within a matrix of FYI (Melling 2002). Episodic wind-driven movements of the pack ice away from the edge of fast ice repeatedly open a flaw lead (part of the circumpolar flaw lead system) along this edge (Figure 11). The lead sometimes extends 2000 km from Amundsen Gulf to the northern tip of Ellesmere Island (Figure 12; Stirling and Cleator 1981; Fissel et al. 1984a; Fissel et al. 1984b; Smith Jr and Barber 2007; Hannah et al. 2009; Currie 2014). Under frigid winter conditions, the opening flaw lead becomes quickly covered by thin FYI. In summer, the same events expose the sea surface that remains ice-free. Although such open-water events are more common and long-lived further south in the Beaufort Sea, they are nonetheless likely areas of enhanced marine productivity at multiple trophic levels in spring and summer (Barber et al. 2010). However, their importance to the marine ecosystem of Tuvaijuittuq remains unknown.
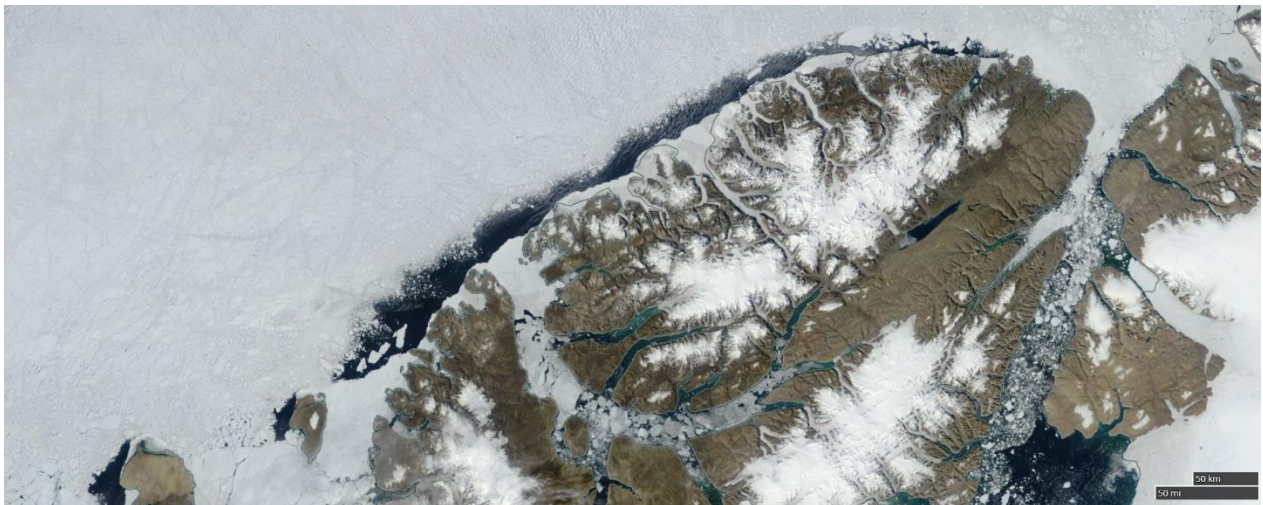
Figure 11. Flaw lead along the coast of Ellesmere Island on August 5th 2007. From: NASA Worldview 2020.

Based on the analysis of Canadian Ice Service (CIS) digital charts from 1983 to 2009, Galley et al. (2012) determined that ice between the northern QEI remained land-fast through the summer in 20–40% of years (depending on the exact location), while in other years it broke up in late August. For decades prior to 1998, land-fast ice plugged the northern openings to Peary and Sverdrup Channels and to Nansen Sound year-round (Jeffers et al. 2001). Fast-ice plugs have been described by Jeffries et al. (1992) as an "agglomeration of ice of different ages and thicknesses", protected from melting in summer by a cold high-latitude climate and close-crowding pack ice. Historically, they persisted year-round, preventing the flow of MYI from the Arctic Basin into the QEI and Nansen Sound, but since 1998 they have frequently broken-up during summer (Maxwell 1981; Alt et al. 2006). A similar plug has never formed in the wider Prince Gustaf Adolf Sea between Ellef Ringnes and Borden Islands (at the western edge of Tuvaijuittuq),

making it one of two channels within Tuvaijuittuq through which MYI was historically transported southward out of the Arctic Ocean during summer (Melling 2002).

1	Cape Bathurst	9	Franklin Strait	17	Hell Gate – Cardigan Strait
2	Lambert Channel	10	Bellot Strait	18	Lady Ann Strait
3	Roes Welcome Sound	11	Prince Regent Inlet	19	Bylot Island
4	Committee Bay	12	Lancaster Sound	20	Coburg Island
5	Foxe Basin	13	Viscount Melville Sound	21	North Water (NOW)
6	Frobisher Bay	14	Karluk Brooman	22	Flagler Bay
7	Cumberland Sound	15	Queens Channel and Penny Strait	23	Lincoln Sea
8	Fury and Hecla Strait	16	Dundas Island		

Figure 12. The continental flaw lead and Lincoln Sea polynya: zones of intermittent open water and thin ice in parts of Tuvaijuittuq that are otherwise ice-covered during winter. From Hannah et al. (2009).

However, these plugs disintegrated during the unusual summer of 1998. The structures have not yet been re-established and now generally fracture in late summer (Melling 2002; Pope et al. 2017). Regardless, the channels opening onto the Arctic Ocean are still filled with MYI at high concentration, driven south-eastward by prevailing wind. Typically, less than 20% of old and 50% of new ice between the QEI melts each summer (Melling 2002). Thus, although ice concentration decreases to the south-east for this reason in summer, it increases again at the bottlenecks for outflow to Parry Channel, namely Byam Martin Channel, Penny Strait and Cardigan Strait. Only when wind reverses to the south-east in summer does ice get pushed backward towards the Arctic Ocean, creating open

areas along the north-western shores of the islands (Bathurst, Melville, Ellef Ringnes and Axel Heiberg) (Figure 12; CIS 2020). Concentrated MYI (9–10/10) is also found along the northern shoreline of Ellesmere Island and within the fiords in late summer (CIS 2020). Although MYI is still densely packed (9–10/10) in the offshore Beaufort Sea in summer, areas of low ice concentration may form, if wind is favourable, along the outer shores of Prince Patrick and Borden Islands (CIS 2020). Freeze-up in late September or early October sees the return of the land-fast ice, initially only along the shorelines of the northern QEI (including the north shore of Ellesmere Island), but by the end of November/beginning of December it is ubiquitous throughout the QEI (Bilello 1960; Barber et al. 2010; Galley et al. 2012; CIS 2020).

In winter, the land-fast ice along the northern shore of Ellesmere Island extends into Nansen Sound and Greely Fiord (CIS 2010). Similar to the fast ice in the channels of the northern QEI, it forms in November and the last of it melts in late August; that in Greely Fiord melts in late July under influence of a benign micro-climate in this sheltered mountain valley. In past decades, Nansen Sound rarely had less than 9/10 ice coverage during summer, while open conditions have always been frequent in Greely Fiord (Maxwell 1981). The ice regime in Nansen Sound has changed since the ice plug broke in 1998. There has been no enduring plug across Nansen Sound in 10 of the 12 summers between 2005 and 2016 (Pope et al. 2017) and Nansen Sound has been generally ice-free by late August (CIS 2020). For this reason, the wintertime ice cover is now largely FYI.

In Nares Strait, the land-fast ice usually breaks up by early August (CIS 2018, 2020). However, because break-up opens the strait to MYI, the period of lighter ice conditions between loss of winter's ice and the arrival of heavy drift ice is usually only 2-3 weeks. The re-establishment of fast ice is extremely variable; it can occur as early as November, or not at all (Markham 1981; Barber et al. 2001; Kwok 2005; Dumont 2019). Between 2003–2012, the duration of land-fast ice ranged from 47 days (winter of 2007-08) to 190 days (winter of 2011-12) (Galley et al. 2012).

In years with no fast ice in Nares Strait, an ice bridge may form at the northern end of Robeson Channel or, less frequently, across the Lincoln Sea (Moore and McNeil 2018). By stabilizing fast ice to their north, such bridges enable the opening of a polynya in Robeson Channel or in the southern Lincoln Sea (Ryan and Münchow 2017). The ecological consequences of such dramatically different wintertime ice conditions in this corner of Tuvaijuittuq have yet to be studied.

Sea Ice Transport

The two main ice streams within the Arctic Basin are the clockwise Beaufort Gyre in the western Arctic, and the Transpolar Drift which stretches across the central Arctic from the Siberian shelf Seas to northern Ellesmere Island (Bourke and Garrett 1987; Mysak 2001; Krumpen et al. 2019; Spall 2019). The two streams merge when crossing the central Arctic and divide on approach to Ellesmere Island. Both streams are driven by the pattern of the wind, which is generally clockwise in the Canada Basin and counter-clockwise in the Eurasian Basin. These patterns are modulated in intensity and extent on periods of 5-10 by the northern annular mode (Arctic Oscillation), dipolar anomaly and other recurrent patterns of atmospheric circulation (Wang et al. 2009; Darby et al. 2012). An

example of their impact on ice drift is shown in Figure 8. Most sea ice within the Canada Basin circulates within the Beaufort Gyre, traveling south-east into Tuvaijuittuq, then turning south-west along the outer coastline of the QEI (Hibler III 1989; Michel et al. 2015). The Beaufort Gyre can trap ice within the Canada Basin for several circuits, enabling it to become thicker than the ice on the Eurasian side, that drifts out through Fram Strait at about three years' age (Nummelin et al. 2016). Sea ice also leaves the Arctic Basin via the channels between the Canadian Arctic islands (Hibler III 1989; Gerland et al. 2007; O'Brien 2019). Ice from both the Beaufort Gyre and the Transpolar Drift currents may follow this pathway through Canadian waters (Gerland et al. 2007; Michel et al. 2015).

Ice export from Tuvaijuittuq occurs via Prince Gustav Adolf Sea, Peary Channel, Sverdrup Channel and Nares Strait (Melling 2002; Howell et al. 2013). Ice is also transported out of the Canada Basin to the south-west of Tuvaijuittuq via Ballantyne and Wilkins straits. Despite favourable prevailing wind, transport along these pathways is smaller than that via Nares Strait (Kwok 2006) due to the narrow inter-island channels and land-fast ice during more than half the year (Melling 2002; Agnew et al. 2008; Howell et al. 2013). Perennial ice plugs in some channels have contributed to the relatively small movement of ice across the Canadian Polar shelf prior to 1998. Kwok (2006) and Howell et al. (2013) both noted a mean annual ice influx of 8 x 10^3 km^2 from the Arctic Ocean to the QEI, most of which entered via Prince Gustav Adolf Sea, Wilkins Strait, and Ballantyne Strait and the remainder to the north through Peary and Sverdrup channels. Ice movement from the QEI to the Canada Basin was rare (Kwok 2006; Howell et al. 2013). Ice drifts through the QEI to Parry Channel and from there spreads to populate the southern part of the shelf to the west, to the east and to the south (Fissel et al. 1984a; Fissel et al. 1984b; Alt et al. 2006; Howell et al. 2008; Michel et al. 2015).

Kwok (2005) estimated the area and volume of sea ice moving annually from Tuvaijuittuq into Nares Strait, assuming that ice averaged 4 m in thickness: 33 x 10^3 km^2 year^{-1} and 130 km^3 year^{-1} of sea ice from the Lincoln Sea. Annual volumes ranged from 64 km^3 in 1999-2000 to 193 km^3 in 1998-1999. Other studies using automated floe identification and tracking in satellite images have obtained comparable results (Kwok et al. 2010; Rasmussen et al. 2010). Combined measurements of ice drift and ice draft by sonar (Melling et al. 1995) can provide direct estimates without assuming thickness, albeit for a different period of years; Ryan (2018) used this method to determine a value of 291 ± 88 km^3 year^{-1} using data from 2003–2006 and 2007–2009. O'Brien (2019) has summarized data from satellite-tracking buoys on ice passing though Nares Strait in 2009, 2010, 2011 and 2014. Reviews of the forcing and controls on the movement of ice and seawater through Nares Strait have been published by Melling (2002) and Melling et al. (2008).

In addition to MYI and FYI, ice islands that calve from the glaciers in north-west Greenland (Petermann, Steensby, Ryder and C.H. Ostenfeld glaciers) add an intermittent stream of fragments to the southward flow of ice through Nares Strait (Crawford et al. 2018). For example, in 2010, a total of 1,493 ice islands greater than 0.25 km in diameter were recorded through Nares Strait, as far north as Hall Basin. Additional information regarding Ellesmere Island ice shelves and ice islands can be found in sections below.

Ice Shelves

Ice shelves are thick (≥20 m) and large ice masses that float on the ocean's surface but remain attached to land (Dowdeswell and Jeffries 2017; Copland et al. 2018). These features are more common in Antarctica than in Arctic, where northern Ellesmere Island hosts the most extensive ice shelves of the Arctic and the only ones in Canada (Dowdeswell and Jeffries 2017; Jeffries 2017). As such, ice shelves are one of the unique and important features of Tuvaijuittuq.

A total of 13 ice shelves remain from a larger, more contiguous shelf (8,900 km²) that fringed the entire northern coast of Ellesmere Island ca. 5,500 years ago (Vincent et al. 2001; England et al. 2008; Mueller et al. 2017). The largest one of these ice shelves, containing the oldest sea ice in the entire Arctic, is the Ward Hunt Ice Shelf, with an areal extent of 224 km² (Figure 13; Dowdeswell and Jeffries 2017; Jeffries 2017). The Milne (106 km²), Ward Hunt East (73.2 km²) and Petersen (17 km²) ice shelves are the three other major ice shelves (>10 km²) remaining north of Ellesmere Island (Mueller et al. 2017; Copland et al. 2018; WIRL 2020). The Milne Ice Shelf, which is considered the thickest, with a mean thickness of 55 m (Mortimer et al. 2012), lost 81 km² after a major calving event at the end of July 2020 (WIRL 2020). The Serson Ice Shelf was one of the last major ice shelf of Ellesmere Island, with an extent comparable to the Milne Ice Shelf, until an important calving event in 2008 occurred, when the ice shelf lost 80 % of its extent (Mueller et al. 2017). The Serson Ice Shelf is now one of the 9 minor Ellesmere ice shelves (<10 km²), along with Ward Hunt Northwest, Ward Hunt North, M'Clintock, Ayles East, Petersen North, Wooton, Wooton East, and Serson East ice shelves (Mueller et al. 2017). The Ward Hunt, Ward Hunt East, Ward Hunt Nothwest, Ward Hunt North and M'Clintock ice shelves are part of the Quttinirpaaq National Park (Parks Canada 2009). As of 2015, the Ellesmere Island ice shelves extent was 535 km², compared to 2168 km² in 1959 (Mueller et al. 2017).

Classical ice shelves are extensions of glaciers that do not calve icebergs when they reach the ocean because of protection by the topography of fiords and persistent sea ice (Copland et al. 2018). When glacial ice is narrow and comes from a single glacier, the floating section is called an ice tongue (Mueller et al. 2017). If an ice tongue is connected and provides ice to an ice shelf, it is considered as a section of the ice shelf. Ice shelves can also be composed of sea ice (sea-ice ice shelf), or both sea ice and glacial ice (composite ice shelf) (Dowdeswell and Jeffries 2017). These three ice shelf types are found along the northwest coast of Ellesmere Island. The Milne Ice Shelf is a classical one while Ward Hunt and Serson Ice Shelves are sea-ice and composite ice shelves, respectively (Dowdeswell and Jeffries 2017).

Ice shelves can gain mass by advection of ice from a glacier, accumulation of snow on its surface or freezeing of marine or fresh water at its bottom (Dowdeswell and Jeffries 2017). Ice shelves can loose mass by calving of icebergs or ice islands and surface or basal melting (Dowdeswell and Jeffries 2017). The Ellesmere Ice shelves mainly gain their mass from *in situ* snow accumulation and sea ice thickening while glacial input only occurs on the Milne and Petersen Ice shelves (Dowdeswell and Jeffries 2017; Copland et al. 2018). Bottom freezing followed by surface melting has, over time, lifted benthic sediments and fossil marine organisms (e.g., siliceous sponges, molluscs, echinoids, fish remains, annelids) to the surfaces of some shelves (e.g., Crary 1960; Smith 1964; Lyons

and Mielke 1973; Jeffries 2017). Remains of terrestrial plants and mammals have also been found on the surface of shelves and ice islands (Crary et al. 1952; Polunin 1955, 1958; Jeffries 2017). The mass balance of the three main ice shelves north of Ellesmere Island is currently negative, which means that they all are losing mass (Copland et al. 2018).
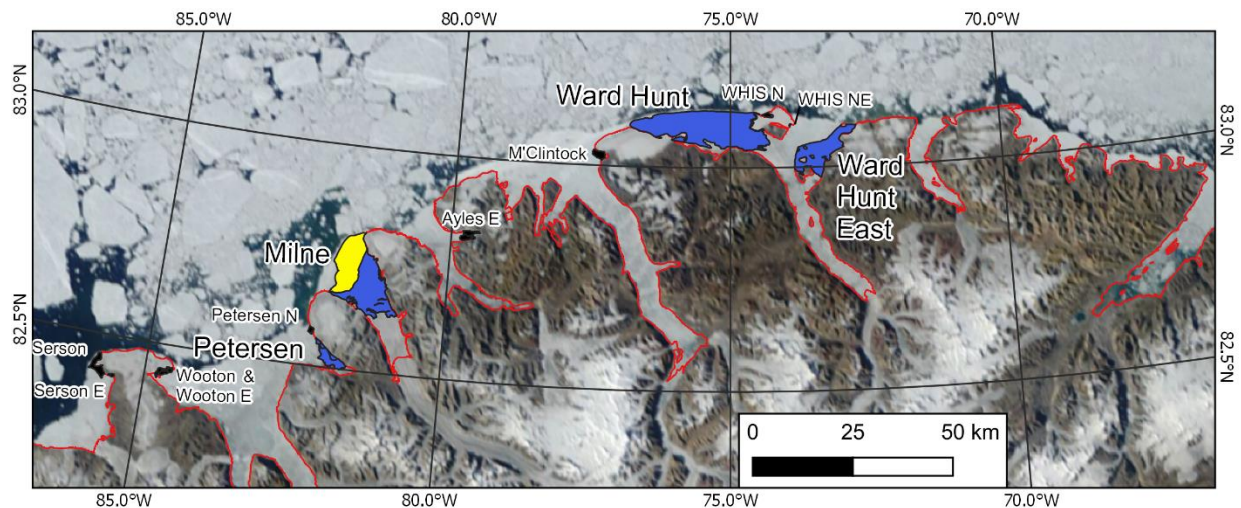
Figure 13. Location of the four major (>10 km²; in blue) and 9 minor (in black) Ellesmere Island ice shelves as of 2015 (Mueller et al. 2017). The area that calved from the Milne Ice Shelf at the end of July 2020 is shown in yellow. Some of the minor ice shelves are too small to be clearly seen at this scale and therefore are not labelled on the figure. The July 26, 2020 MODIS image in the background is courtesy of NASA. WHIS: Ward Hunt Ice Shelf.

The upper surface of the Ellesmere ice shelves has a rolling or undulating topography with the valleys filled by meltwater during the brief summers (Jeffries 2017). Recent surveys with ground-penetrating radar have shown similar undulations at the bottom of the Milne Ice Shelf (Mortimer et al. 2012; Jeffries 2017). The origin of the undulations is thought to be either genetic (i.e., created during the formation of the shelves) or superimposed (i.e., added after shelf formation) (Jeffries 2017). Thermal stress, pack ice pressure, pressure ridge stacking, glacier compression and/or tidal action are examples of factors contributing to a genetic origin while snow dune formation, orientation of meltwater lakes and/or wind may create undulations from superimposed origin undulations (Holdsworth 1987; Jeffries 2017).

There is renewed efforts and urgency in the study of the Ellesmere Island ice shelves as they are experiencing rapid mass loss due to climate change (Dowdeswell and Jeffries 2017; Jeffries 2017; Copland et al. 2018). The Ellesmere Island ice shelves have been losing mass for over a century, with an estimated loss of 94% of their area between 1906–2015 (Jeffries 2017; Copland et al. 2018). Records from 1999 to 2015 show that the Ellesmere Island ice shelves losses are proportionally greater than losses from nearby ice caps and glaciers (White and Copland 2018; White 2019).

Ice shelf losses are largely due to major calving events (e.g., Hattersley-Smith 1963; Jeffries and Serson 1983; Jeffries 1986; Mueller et al. 2017). Recent important calving events include the complete disappearance of the Ayles and Markham Ice Shelves in 2005 and 2008, respectively (Copland et al. 2007; Mueller et al. 2008; White et al. 2015a)

and large losses from the Ward Hunt, Petersen and Serson shelves (White et al. 2015a; Copland et al. 2018). Most of the periods of extensive calving and break-up of ice shelves have coincided with warmer than usual summers in northern Ellesmere Island (White et al. 2015a; Braun 2017). The potential future loss of MYI and presence of open water along the northwest coast of Ellesmere Island can also favour ice shelf break-up by decreasing the protection offered by MYI at the ice shelf margin (White et al. 2015a). Pre-existing fractures, ice shelf thinning and offshore to along-shore winds can also facilitate ice shelf calving (Copland et al. 2007; White et al. 2015a).

Decreases or elimination of glacial inputs can also affect ice shelf mass balance (Copland and Mueller 2017). For example, the loss of glacial input to the Ayles Ice Shelf in the 1960s is thought to have contributed to its demise along with the concurrent loss of large quantities of land-fast MYI in the surrounding ocean (Copland et al. 2007; Copland and Mueller 2017).

Thinning of ice shelves favors calving, and is also considered as ice shelf loss. For example, the Ward Hunt Ice Shelf is continuing to lose mass and has become thinner with basal melting and negative surface mass balance identified as the main causes of its reduced stability (Braun 2017). These basal losses are outpacing accumulation via snow at the surface or land-fast MYI at the bottom of the ice shelf. In certain areas, the Ward Hunt Ice Shelf thinned from 50–60 m in 1951 to < 25 m in 2002 (Braun 2017). Other remaining ice shelves on Ellesmere Island appear to be experiencing similar effects.

The Milne Ice Shelf was considered relatively stable since 1988, losing about 13 km^2 of surface area since 1988, prior to the major calving event of 2020 (Mueller et al. 2017; WIRL 2020). The relative stability of the Milne Ice Shelf was attributed to the long, steep-walled, protected fiord in which it is located and the absence of contact between the ice shelf and the relatively warm Atlantic water (Hamilton 2016). However, measurements of ice thickness show a loss of 13%, or an average of 8.1 m, for the Milne Ice Shelf from 1981–2009 (Mortimer et al. 2012). Recent calving events at landward margins (White 2019) and the 2020 calving event show that the climate-mass balance equilibrium of the Milne Ice Shelf no longer exists.

The loss of the Ellesemere ice shelves could result in potentially large increases in newly exposed shoreline damage and erosion, especially with longer ice-free periods, as observed in other areas of the Canadian Arctic (Forbes et al. 2018). Loss of ice shelves and associated MYI can also result in the recession of glacier tongues. This was the case in Yelverton Bay, north of Ellesmere Island, where eight ice tongues shrunk by more than 49 km^2 since 1959, with unusually large losses after 2005 due to exposure to open water (White 2019; White and Copland 2019). The MYI in the bay has since all been replaced with FYI (Pope et al. 2012), which will further exacerbate future losses.

The combination of all the factors that negatively affect the mass balance of ice shelves and future projections of climate change suggest that the long-term survival of these unique habitat features is threatened (Copland et al. 2018; Van Wychen et al. 2020).

Epishelf Lakes

Epishelf lakes consist of an oligotrophic freshwater layer formed at the rear of an ice shelf, typically in a fiord, and floating on the higher density sea water below (Thaler et al. 2017;

Copland et al. 2018). Meltwater supplies the epishelf lake during the brief summer (Copland et al. 2018). The last remaining deep epishelf lake on Ellesmere Island is located behind the Milne Ice Shelf and consists of a 16 m thick freshwater layer atop seawater. It is still unclear if the epishelf lake survived the calving event of July 2020 (WIRL 2020). Salinity and temperature of an epishelf lake range from 0.6–3.0 and 0–3.6 °C, respectively for the freshwater layer, compared to salinity of > 30 and temperatures between -1.5 and 0.3 °C for the seawater layer underneath (Veillette et al. 2008; Jungblut et al. 2017). Other small, shallow epishelf lakes are scattered throughout Tuvaijuittuq, but most have disappeared as their associated ice shelves calved and broke apart (White et al. 2015b; Thaler et al. 2017; Copland et al. 2018). For example, the epishelf lake behind the Ward Hunt Ice Shelf, once the largest in the Northern Hemisphere, drained through a fissure in the ice shelf in 1999–2002 (Mueller et al. 2003). There is evidence that a similar process is occurring on the Milne Ice Shelf. Rajewicz (2017) used ice-penetrating radar to investigate a depression running across the outer Milne Ice Shelf that was thought to indicate a basal channel of outflow from the epishelf lake. The channel was confirmed as a drainage outlet 39–45 m in height and 57–87 m in width. Conductivity-temperature-depth profiles and current measurements revealed a fast flowing (>60 cm s^{-1}) stream of water draining from the epishelf lake, likely indicating a substantial structural weakness where the ice shelf is anticipated to break in the future (Rajewicz 2017).

Ice Islands

The widespread calving events of the Ellesmere Island ice shelves have produced long-lived, tabular ice islands of up to 700×10^6 tonnes (Sackinger et al. 1989), 50 m thick (Copland et al. 2007; Jeffries 2017) or 750 km^2 in area (Jeffries 1992). These ice islands drift throughout the Arctic for years to decades, gradually disintegrating as they drift. The drift of ice islands calved from Ellesmere Island ice shelves occurs along three main routes: west into the Arctic Ocean where they persist for decades, west and then into the QEI as far south as Byam Martin Channel, Penny Strait and Hell Gate, where warmer temperatures contribute to more rapid disintegrations, and, rarely, east into Nares Strait where they can drift as far south as the Labrador Sea (Van Wychen and Copland 2017). Bessonov (2018) mapped the trajectory of the largest ice island produced from the collapse of the Markham Ice Shelf. During the first two years following calving, the ice island drifted approximately 1,000 km to the Beaufort Sea.

Ice islands can be hazardous to maritime navigation along shipping lanes and for Arctic resource extraction and scientific exploration (Copland et al. 2018). They have also been used by the military during the cold war (Althoff 2017) and as Russian/Soviet, American and Canadian research platforms (Belkin and Kessel 2017; Bessonov 2018).

LOWER TROPHIC LEVELS

Lower trophic level investigations for Tuvaijuittuq and adjacent MYI areas are extremely limited. As a result of unique sea ice and oceanographic conditions in Tuvaijuittuq, compared to other Arctic or Canadian Arctic regions, comparisons do not necessarily apply. Therefore, extreme caution should be used when drawing comparisons with, or

inferences from, other Arctic regions, despite the potential relevance of general ecological processes.

Microbial community

In the Arctic, as in other oceans, microbial communities comprise the vast majority of the biodiversity. Yet they still receive little attention relative to other biota (Galand et al. 2009a; Archambault et al. 2010). This is exacerbated in the data-poor region of Tuvaijuittuq and adjacent areas covered by MYI. Microbial communities are comprised of viruses as well as Archaea, bacteria, and protists (single-cell autotrophic, heterotrophic or mixotrophic eukaryotes) and play important roles in the cycling of carbon, nitrogen and other key elements in marine ecosystems (Lovejoy 2013). Photosynthetic eukaryotes, i.e., phytoplankton and ice algae, will be described in the next section.

Based on DNA sequencing, up to 54,500 microbe OTUs (Operational Taxonomic Unit) could be present in the Arctic, most of which are represented by bacteria (Archambault et al. 2010; Lovejoy et al. 2011). Arctic marine microbes are considered to be well-adapted to conditions unique to this high-latitude ecosystem, in particular the low temperatures and irradiance that prevail for most of the year (e.g., Galand et al. 2006; Galand et al. 2009a). Diverse microbial communities are also found in sea ice, where they are adapted to extreme low temperatures and high salinity in brine channels (e.g., D'Amico et al. 2006; Deming and Collins 2017). Microbial communities play important roles in Arctic biogeochemical cycles (e.g., Comeau et al. 2011; Galindo et al. 2015) and marine food webs where they can be herbivorous, mixotrophs, phagotrophs or parasites (e.g., Laurion et al. 1995; Riedel et al. 2007b; Piwosz et al. 2013).

In the Arctic marine ecosystem, the bacterial community is dominated by Gram-negative bacteria (Bluhm et al. 2017). In sea ice, common genera include *Pseudoalteromonas*, *Colwellia*, *Shewanella*, *Flavobacterium* and *Polaribacter*, but there can be large spatial variability (Deming and Collins 2017; Yergeau et al. 2017). In the Beaufort Sea and the Canadian Arctic Archipelago, the surface water bacterial community was found to be dominated by Alphaproteobacteria, Bacteroidetes and Gammaproteobacteria (e.g., Garneau et al. 2006; Galand et al. 2008a; Comeau et al. 2011; Garneau et al. 2016). In the Arctic Ocean, the bacterial community in deep waters is different than the surface community (Galand et al. 2010). The same is true for archaeal communities (Galand et al. 2009b). Marine Group I (MGI) Crenarchaeota is the most abundant group of Archaea in the Arctic Ocean and is found in abundance in the surface layer and in oligotrophic offshore waters (Bano et al. 2004; Galand et al. 2008a; 2008b; Galand et al. 2009b).

Bacterial production and abundance is typically correlated with chlorophyll *a* (chl *a*) in sea ice and in the water column (Garneau et al. 2008; Deming and Collins 2017). In the Beaufort sea, bacterial production and biomass reach their maximum during summer, controlled by environmental parameters (Garneau et al. 2008). Bacterial production and abundance is generally higher in surface waters than at depth (Garneau et al. 2008; Kalenitchenko et al. 2019). Bacteria, autotrophic and heterotrophic protists are incorporated into the sea ice at the time of its formation (Riedel et al. 2007a). Heterotrophs can dominate the sea ice microbial community prior the ice-algal bloom, but heterotrophic activity persists during this period (Riedel et al. 2008; Campbell et al. 2018). Bacterial production typically represents a small fraction of the sea ice primary production;

however, bacterial abundance in sea ice is higher than that of ice algae (Smith and Clement 1990; Campbell et al. 2018). Archaea have been detected in sea ice during winter (Collins et al. 2010). However, they were not detected in sea ice during spring and summer, likely due to higher bacterial abundance during the ice algal bloom, as it would mask a potentially small proportion of archaea (Brinkmeyer et al. 2003; Deming and Collins 2017).

Hatam et al. (2016) compared bacterial communities in surface waters, FYI, and MYI north of Ellesmere Island, within Tuvaijuittuq. These authors report similar class-level phylogenetic groups in the two ice types, but differences between surface water and ice communities. The diversity and richness of OTUs were found to be higher in FYI compared to MYI and surface waters, whereas the latter had similar OTU richness. The MYI OTU richness and diversity observed in Tuvaijuittuq by Hatam et al. (2016) are comparable to those found in other MYI studies in the Arctic Ocean (Bowman et al. 2012; Hatam et al. 2014). The MYI bacterial community was considered to be mature, because of the OTUs constant relative abundance in time and space (Hatam et al. 2016). These results suggest that MYI can act as a stable environment for microbial communities, as suggested earlier by Collins (2015).

The current knowledge on viruses in the Arctic is limited. Arctic viruses found in sea ice and marine waters, are considered to be mainly bacteriophages (Maranger et al. 1994; Hodges et al. 2005) and can reach higher abundance than their hosts (Maranger et al. 1994; Middelboe et al. 2002). Viruses were found to be responsible for a significant proportion of bacterial mortality in different regions of the Arctic (Steward et al. 1996; Middelboe et al. 2002). Little if any details are available regarding Arctic virus phylogenetic diversity (Deming and Collins 2017; Yau and Seth-Pasricha 2019). During spring 2018, bacterial and viral abundances were investigated in FYI and MYI in Tuvaijuittuq, as part of the Multidisciplinary Arctic Program (MAP)-Last Ice program. Results show significant positive correlations between viral and bacterial abundances in both ice types, supporting that viruses are mostly bacteriophages (Duffaud 2020).

Phytoplankton and Ice Algae

In the Arctic Ocean, as in other oceans, the bulk of primary production is accounted for by microscopic algae. In the Arctic, these include ice algae and phytoplankton. Using nutrient distribution, Codispoti et al. (2013) estimated that total primary production in the Arctic is c.a. 1000 Tg C y^{-1}. Tuvaijuittuq is partially located in the Canadian Archipelago and in the Amerasian Basin sub-regions described in Codispoti et al. (2013), where they estimated total production to be respectively high (30 - 40 g C $m^{-2} y^{-1}$) and very low (1 - 5 g C $m^{-2} y^{-1}$). Relatively important contributions of ice and sub-ice primary production is documented across the Arctic (e.g., Gosselin et al. 1997; Matrai et al. 2013; Jin et al. 2016). Matrai et al. (2013) estimated that together, ice and sub-ice algae production can represent up to 50 % and 90 % of total production on the Canadian Arctic shelf and in the Canada Basin, respectively. In a following assessment, Michel et al. (2015) suggested that ice algal production was underestimated in the Canadian Archipelago, a hypothesis of particular relevance to Tuvaijuittuq.

Ice and sub-ice primary production was estimated at ca. 15 g C $m^{-2} y^{-1}$ at a site located within Tuvaijuittuq, west of Ellesmere Island (Matrai et al. 2013). Phytoplankton

production in Dumbell Bay, north of Ellesmere Island, was estimated at 9 g C m^{-2} y^{-1} (Apollonio 1980). To our knowledge, there is no other estimate of primary production in the Tuvaijuittuq region. This important data gap, together with the divergent estimates for the two sub-regions represented in the Tuvaijuiittuq area and the variable contribution of ice algae and phytoplankton to total primary production, emphasize the importance of obtaining primary production measurements in Tuvaijuittuq.

The only published study on phytoplankton in Tuviaijuittuq was carried out in Dumbell Bay and reports the occurrence of a phytoplankton bloom in late August , with maximum chl *a* concentrations reaching 8.2 mg m^{-3} (Apollonio 1980). Other studies on ice algae within the area report ice algal chl *a* biomass of ca 4.5 mg m^{-2} in Robeson Channel (Dunbar and Acreman 1980), and ranging from 0.23 to 2.56 mg m^{-2} in the Lincoln Sea during May (Lange et al. 2017; Lange et al. 2019b). Biomarker results reflecting little biological activity were associated with sea ice west of Ellesmere Island, likely due to the prevalence of thick MYI (Belt et al. 2007). Thick MYI hummocks were found to have significantly higher bottom ice chl *a* biomass than thinner MYI or FYI (Lange et al. 2017). However, preliminary results from the MAP-Last Ice showed higher bottom ice algal biomass in FYI than in MYI (Lange et al. 2019b), emphasizing the high variability of ice-associated production under the variety of sea ice conditions in Tuvaijuittuq.

Phytoplankton blooms develop in open water, at the ice edge, or under the ice during spring, summer and fall (Wassmann and Reigstad 2011; Ardyna et al. 2014). Because primary producers require light for photosynthesis, the photoperiod sets the limit of the potential growth season for ice algae and phytoplankton in the Arctic. Light is therefore the limiting factor for the onset of ice algal development in the spring, and it can also limit ice algal or phytoplankton growth under thick snow/ice cover such as under thick MYI in Tuvaijuittuq (Tremblay et al. 2012). As the growth season progresses, nutrient supply, largely controlled by environmental forcing such as advection or vertical mixing induced by winds or convection, regulates primary production (Tremblay and Gagnon 2009).

The abundance of ice algae is low during winter and increases during the spring to reach high abundances during the bloom, with particularly intense blooms in the Canadian Arctic Archipelago (Michel et al. 1996; Niemi et al. 2011; Leu et al. 2015). Ice algae can be found at the surface, interior and bottom of the ice (Arrigo 2017). Surface assemblages generally occur when the ice surface has been flooded with seawater, allowing for colonization by phytoplanktonic algae. Interior assemblages can occur at the interfaces between annual layers of MYI and in the brine channels of FYI and MYI. The bottom community is located in the few last centimeters of the ice close to the ice-water interface, and is responsible for a high proportion of ice-associated primary production in the Canadian Arctic. The accumulation of high biomass in this layer is responsible for the brownish color at the bottom of the ice. Sub-ice assemblages are also found at the bottom of the ice and include frazil, strand, and unattached free-floating communities (Cota et al. 1991; Fernández-Méndez et al. 2014). The horizontal distribution of ice algae is known to be patchy, largely linked to snow distribution for bottom ice algae in the Canadian Arctic Archipelago (Mundy et al. 2005; 2007). Low to moderate snow covers generally produce peak algal blooms (Mundy et al. 2005; Pogson et al. 2011), although responses can be variable among taxa (Rózańska et al. 2009).

In the Canadian Arctic Archipelago, irradiance regulates the onset of the ice algal bloom, while nutrients are generally considered the limiting factor for its termination (Lavoie et al. 2005), with mixing (e.g., tidal mixing) having an important influence on nutrient fluxes to the bottom ice layer and therefore, on sustaining ice algal growth (Cota et al. 1987; Mundy et al. 2009). Sea ice melt constrains the ice algal growth season during spring/early summer, possibly impacting the maximum biomass attained, such that a slower melt may allow for a longer bloom and higher maximum biomass (Lavoie et al. 2005). Earlier or faster melt can result in a shorter ice-algal bloom period and rapid export to the benthos. The latter has been observed in the Canadian Archipelago, with years of rapid melt showing increased export of ice algae to the benthos compared to slow melt years (Fortier et al. 2002).

Within the Tuvaijuittuq region, Lange et al. (2019b) found a negative correlation between the biomass of bottom-ice algae and snow depth in MYI, but not in FYI. Little topographic variation of FYI increased variability in snow depth and solar transmittance while the regular undulations of MYI resulted in more constant snow depth (consistently thin on top of the hummocks and thick in the troughs). Lange et al. (2017) hypothesized that hummocks on MYI can constitute a reliable habitat for ice algal growth due to consistently low snow cover that allows for increased light transmittance. Since Tuvaijuittuq is predicted to be the last area to retain MYI in the Arctic Ocean, it may become an important location for unique sea ice habitats such as hummocks.

Recent estimates of marine unicellular eukaryote diversity identified 1,350 taxa throughout the Canadian Arctic (Poulin et al. 2011) which is actually higher than estimates from the Pacific or Atlantic coasts (Archambault et al. 2010; Darnis et al. 2012). A higher diversity is present in the water column, compared to sea ice, with respectively 1,229 and 540 taxa recorded across the Canadian Arctic (Poulin et al. 2011). Diatoms dominate phytoplankton and ice algal communities in the Arctic during the bloom period (Figure 14; Poulin et al. 2011). Ice algae can be found in the water column for a brief period during ice melt, or can possibly seed the phytoplankton bloom (Michel et al. 1993; Galindo et al. 2014), which can temporarily increase the number of taxa found in this habitat (Archambault et al. 2010). As an example, a recent survey of the central Arctic Ocean found protist diversity and abundance in MYI to be higher than in the neighboring water column (Hardge et al. 2017). During winter, ice algal diversity can be comparable to that in spring although the abundance during the dark season is lower (Niemi et al. 2011). A few taxonomic surveys were conducted within Tuvaijuittuq and adjacent areas in the 1970s and 1980s (Table 1). Recent results in Tuvaijuittuq offshore of CFS Alert show that the structure and diversity of ice algal communities in MYI varies between different sea ice layers, highlighting the complexity of sea ice communities in Tuvaijuittuq (Charette, pers. comm.).
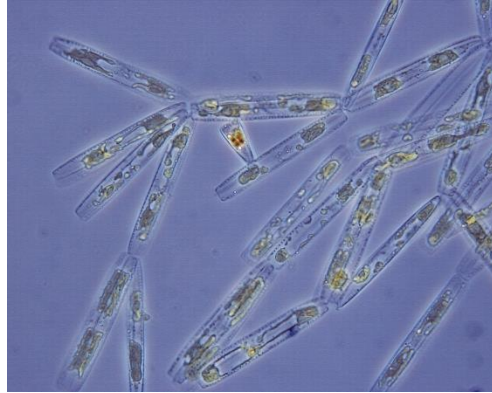
Figure 14. Chain-forming diatoms *Nitzschia frigida*, a dominant diatom in sea ice. The photo is from a bottom ice sample collected near Barrow Strait during DFO's Biological Impacts of Trends in the Arctic (BIOTA) Program. Photo credit: M. Poulin, Canadian Museum of Nature.

Table 1. List of phytoplankton and ice algae taxa reported from marine waters within Tuvaijuittuq and adjacent areas of MYI.

Taxonomic Nomenclature	Within Tuvaijuittuq? (Y/N)	Location(s)[1]	Source(s)
Chromista			
Bacillariophyceae			
Achnanthes arctica	Y	North of EI, KB	Hsiao 1983
Achnanthes brevipes var. *intermedia*	Y	North of EI	Hsiao 1983
Achnanthes coarctata	Y	North of EI	Hsiao 1983
Achnanthes groenlandica	Y	RC	Hsiao 1983
Amphipleura paludosa	N	AC	Thomson et al. 1975
Amphiprora glacialis	N	AC	Thomson et al. 1975
Amphora eunotia	Y	North of EI, KB	Hsiao 1983
Amphora proteus	Y	North of EI	Hsiao 1983
Amphora terroris	Y	North of EI	Hsiao 1983
Caloneis aemula	Y	North of EI	Hsiao 1983
Caloneis amphisbaena var. *subsalina*	Y	AF, NSt	Hsiao 1983
Caloneis latefasciata	Y	North of EI	Hsiao 1983
Catacombas camtschatica	N	AC	Thomson et al. 1975
Chaetoceros ceratosporus	N	QEI	Hsiao 1983
Cocconeis arctica	N	KB	Hsiao 1983
Cocconeis costata	Y	AF, North of EI	Hsiao 1983
Cocconeis distans	Y	North of EI	Hsiao 1983
Cocconeis scutellum	Y	AF, North of EI, KB, RC	Hsiao 1983
Cosmioneis pusilla	Y	North of EI	Hsiao 1983
Craticula ambigua	Y	AF, KB	Hsiao 1983
Ctenophora pulchella	N	KB	Hsiao 1983
*Cylindrotheca closterium****	Y	AC, CB, North of EI, KB, QEI	Thomson et al. 1975; Hsiao 1983
Cymbella botellus	N	KB	Hsiao 1983
Cymbella cistula	Y	AF, KB	Hsiao 1983
Cymbopleura rupicola	N	KB	Hsiao 1983
Denticula tenuis var. *frigida*	Y	AF, KB	Hsiao 1983
Diatoma elongata	N	KB	Hsiao 1983
Diploneis bomboides var. *media*	Y	North of EI	Hsiao 1983
Diploneis didyma	Y	AF, North of EI, KB	Hsiao 1983
Diploneis interrupta	Y	North of EI	Hsiao 1983

Taxonomic Nomenclature	Within Tuvaijuittuq? (Y/N)	Location(s)[1]	Source(s)
Diploneis littoralis*	Y	North of EI, RC	Hsiao 1983
Diploneis smithii	Y	North of EI, KB, NSt	Hsiao 1983
Encyonopsis falaisensis	N	KB	Hsiao 1983
Entomoneis paludosa var. *duplex*	Y	AF	Hsiao 1983
Eucocconeis flexella	N	KB	Hsiao 1983
Eunotia arcus	N	KB	Hsiao 1983
Eunotia diodon	N	KB	Hsiao 1983
Fragilaria recapitellata	N	KB	Hsiao 1983
Fragilaria striatula	Y	North of EI, KB, NSt	Hsiao 1983
Fragilariopsis cylindrus*	N	AC	Thomson et al. 1975
Fragilariopsis oceanica*	Y	AC, KB, NSt, QEI, RC	Thomson et al. 1975; Hsiao 1983
Gomphonema angustatum	N	KB	Hsiao 1983
Gomphonema exiguum	N	AC	Thomson et al. 1975
Gomphonema kamtschaticum var. *sibiricum*	Y	North of EI	Hsiao 1983
Grammatophora angulosa var. *islandica*	Y	AF	Hsiao 1983
Grammatophora arctica	N	KB	Hsiao 1983
Hannaea arcus	Y	AF, KB	Hsiao 1983
Haslea crucigeroides*	N	AC	Thomson et al. 1975
Haslea kjellmanii	Y	RC	Hsiao 1983
Haslea spicula*	Y	AF	Hsiao 1983
Humidophila perpusilla	N	KB	Hsiao 1983
Lyrella david-mannii	Y	North of EI	Hsiao 1983
Meridion circulare	Y	AC, AF, KB	Thomson et al. 1975; Hsiao 1983
Navicula algida	N	AC	Thomson et al. 1975
Navicula cryptocephala	Y	AF, KB	Hsiao 1983
Navicula digitoradiata var. *cyprinus*	Y	North of EI	Hsiao 1983
Navicula directa*	Y	AC, AF, North of EI, QEI	Thomson et al. 1975; Hsiao 1983
Navicula fortis	Y	AF, NSt	Hsiao 1983
Navicula glacialis	Y	North of EI	Hsiao 1983
Navicula peregrina	Y	North of EI, RC	Hsiao 1983
Navicula rhynchocephala	N	KB	Hsiao 1983
Navicula viridula	N	KB	Hsiao 1983
Navicula vulpina	Y	North of EI	Hsiao 1983
Neidium iridis	N	KB	Hsiao 1983
Nitzschia amphiprora	Y	North of EI, KB	Hsiao 1983
Nitzschia angularis*	Y	North of EI, KB	Hsiao 1983
Nitzschia frigida*	Y	AC, RC	Thomson et al. 1975; Hsiao 1983
Nitzschia frustulum	Y	AF	Hsiao 1983
Nitzschia laevissima*	Y	AF	Hsiao 1983
Nitzschia longissima*	N	AC	Thomson et al. 1975
Nitzschia sigma	N	KB, NSt	Hsiao 1983
Nitzschia vitrea	Y	AF	Hsiao 1983
Pauliella taeniata	N	AC	Thomson et al. 1975
Pinnularia borealis	Y	AF, KB	Hsiao 1983
Pinnularia globiceps	Y	AF, KB	Hsiao 1983
Pinnularia mesolepta	Y	AF, KB	Hsiao 1983
Pinnularia quadratarea*	Y	AC, North of EI	Thomson et al. 1975; Hsiao 1983
Planothidium quarnerense	Y	North of EI, KB	Hsiao 1983
Pleurosigma angulatum	N	AC	Thomson et al. 1975
Pleurosigma kjellmanii	N	AC	Thomson et al. 1975
Pleurosigma longum	Y	AF, NSt, RC	Hsiao 1983
Pleurosigma stuxbergii*	N	AC	Thomson et al. 1975

Taxonomic Nomenclature	Within Tuvaijuittuq? (Y/N)	Location(s)[1]	Source(s)
Pseudoamphiprora stauroptera	Y	North of EI	Hsiao 1983
*Pseudo-nitzschia delicatissima**	N	AC	Thomson et al. 1975
Pseudo-nitzschia lineola	N	QEI	Hsiao 1983
Pseudo-nitzschia pungens	N	QEI	Hsiao 1983
*Pseudo-nitzschia seriata**	N	AC, QEI	Thomson et al. 1975; Hsiao 1983
Rhabdonema arcuatum	Y	RC	Hsiao 1983
Rhabdonema torellii	Y	AF, RC	Hsiao 1983
Rhoicosphenia abbreviata	Y	AF, North of EI	Hsiao 1983
Stauroneis anceps	N	KB	Hsiao 1983
Stauroneis quadripedis	N	AC	Thomson et al. 1975
Surirella minuta	Y	KB, RC	Hsiao 1983
Surirella smithii	N	KB	Hsiao 1983
Surirella subsalsa	N	KB	Hsiao 1983
Synedra kamtschatica	Y	North of EI	Hsiao 1983
Synedra fulgens	Y	AF, KB	Hsiao 1983
Synedra superba	N	KB, NSt	Hsiao 1983
Tabularia parva	Y	North of EI	Hsiao 1983
Tabularia tabulata	Y	North of EI, KB, NSt	Hsiao 1983
Thalassionema nitzschioides	Y	North of EI	Hsiao 1983
Trachyneis aspera	Y	North of EI, KB	Hsiao 1983
Tryblionella marginulata	Y	North of EI	Hsiao 1983
Tryblionella navicularis	Y	AF	Hsiao 1983
Coscinodiscophyceae			
Coscinodiscus centralis	Y	North of EI	Hsiao 1983
Coscinodiscus radiates	Y	AF, KB, NSt, RC	Hsiao 1983
Coscinodiscus subtilis	N	KB, NSt	Hsiao 1983
Hyalodiscus scoticus	Y	North of EI	Hsiao 1983
*Melosira arctica**	Y	AC, AF, QEI	Thomson et al. 1975; Hsiao 1983
Melosira discigera	Y	AF, NSt	Hsiao 1983
Melosira lineata	N	AC	Thomson et al. 1975
Paralia sulcata	Y	AF, North of EI, RC	Hsiao 1983
Podosira hormoides	Y	North of EI	Hsiao 1983
Trigonium arcticum	Y	AF, KB, NSt, RC	Hsiao 1983
Mediophyceae			
Lindavia antiqua	N	KB	Hsiao 1983
Odontella aurita	Y	AF, North of EI, RC	Hsiao 1983
Skeletonema mediterraneum	Y	North of EI	Hsiao 1983
Thalassiosira eccentrica	Y	AF, KB, NSt	Hsiao 1983
Thalassiosira gravida	N	KB	Hsiao 1983
Thalassiosira hyalina	Y	AF	Hsiao 1983
Thalassiosira nordenskioeldii	Y	AC, AF, North of EI, KB, NSt, QEI, RC	Thomson et al. 1975; Hsiao 1983
Tropidoneis longa	Y	AF, North of EI, KB	Hsiao 1983
Dinophyceae			
Ceratium arcticum	N	AC	Thomson et al. 1975

[1] AC = Austin Channel, AF = Archer Fiord, EI = Ellesmere Island, KB = Kane Basin, NSt = Nares Strait, QEI = Queen Elizabeth Islands, RC = Robeson Channel

* – Present in sea ice samples collected during MAP-Last Ice, off CFS Alert in spring 2018

<u>Current and Future Trends</u>

The pan-arctic net annual phytoplankton production increased by 5.75 ± 1.51 g C m^{-2} per decade between 2003 and 2019 (Frey et al. 2019). Other studies report an increase of more than 20% of phytoplankton production since the end of the 1990's (Arrigo and van Dijken 2011; Bélanger et al. 2013). Thinning of the sea ice cover and replacement of MYI by FYI is anticipated to increase light transmission through the snow/ice cover before and throughout the melt season (Nicolaus et al. 2012; Lange et al. 2019b), but sea ice melt also increases surface stratification (Tremblay and Gagnon 2009). These changes have opposing effects on primary producers, and therefore the resulting impact is difficult to predict. In addition, sea ice decline also affects the nutrient regime in coastal regions where mixing events are favoured by ice-free conditions (Wassmann and Reigstad 2011; Tremblay et al. 2012). Therefore, different trends can be observed in offshore and coastal regions (Tremblay et al. 2012).

For phytoplankton, impacts of these changes are already observed, such as the development of fall blooms during the longer open water production season (Ardyna et al. 2014), with changes in phytoplankton community structure, favoring smaller over larger phytoplankton offshore (Li et al. 2009; Tremblay et al. 2012), and more frequent occurrence of under-ice phytoplankton blooms (Meier et al. 2014). Such blooms have been documented within the Canadian Arctic Archipelago (Fortier et al. 2002; Mundy et al. 2009; 2014) and in the Chukchi Sea (Arrigo et al. 2012).

Besides being influenced by changes in light and nutrient regimes, as phytoplankton, ice algae can also be affected by the a variety of factors, including precipitation, projected to increase in the Arctic as a result of the changing climate (Lique et al. 2016). The type and timing of precipitation is important for ecosystem impacts. Increased snow precipitation would decrease light transmission through the ice while rain would increase it and, depending on its timing, can cause early termination of the ice algal bloom (Fortier et al. 2002; Campbell et al. 2014; Galindo et al. 2014).

In Tuvaijuittuq, both local and far-field influences combine to impact productivity patterns. Therefore, the multiple and cumulative effects of the changing Arctic Ocean sea ice cover, including its effect on the prevalence of ridges where snow accumulates, the timing of ice formation and melt, and sea ice transport pathways will influence the diversity and productivity of sea ice communities. The nutrient regime in Tuvaijuittuq is also largely determined by far-field transport of nutrient-depleted waters from upstream phytoplankton blooms in the Beaufort Sea and Canada Basin (Tremblay et al. 2015), showing again the importance of the connection to the broader Arctic region and its implications on the marine food web (see Ice-Pelagic-Benthic Coupling section).

Ice shelves biota

Three ecosystems are associated with ice shelves, the supraglacial ecosystem (melt water ponds), the englacial ecosystem (microhabitats within ice and snow) and the epishelf lake (Jungblut et al. 2017). In the Arctic, the microbial community of the englacial ecosystem has not yet been studied, but the supraglacial ecosystem and the Milne Fiord epishelf lake had been studied (Jungblut et al. 2017). Ice islands and retreating glaciers also contain unique microbial communities (Tsuji et al. 2018, 2019a, b).

In the Milne Fiord epishelf lake, bacterial and viral abundances are higher than in the marine layer bellow (respectively 6.4×10^8 and 4.1×10^8 bacteria L^{-1} and 2.2×10^9 and 1.4×10^9 virus-like particles L^{-1}, Veillette et al. 2011). Betaproteobacteria, mainly *Rhodoferax saidenbachensis* and the genus *Polaromonas*, as well as Bacteroidetes are ubiquitous in the epishelf lake ecostsem but the contribution of the former is lower in the marine layer (Veillette et al. 2011; Thaler et al. 2017). At the halocline depth, the alphaproteobacterial *Roseobacter*-group account for an important proportion of the bacterial community while non-proteobacteria, as acidobacteria and planctomycetes, are present in the marine layer (Veillette et al. 2011; Thaler et al. 2017). The richness of the viral assemblage, mainly composed of T4-like bacteriophage, is higher in the marine layer than in the lake (Veillette et al. 2011). Group I.1a Thaumarchaeota, the dominant Archaea present in the epishelf lake ecosystem, is widespread in the three different layers, while the archaeal clade Pendant-33 and Halobacteriales are restricted to the lake and marine layer respectively (Thaler et al. 2017).

The chl *a* biomass in the epishelf lake was found to reach a maximum of 2.53 mg m^{-3} at 6 m during summer 2012 (Thaler et al. 2017). A maximum in chl *a* biomass can also be found at the halocline depth (1.26 mg m^{-3} in 2009; Veillette et al. 2011). Either cyanobacteria or picoeukaryotic algae dominate the lake community and they are both also present in the marine layer (Thaler et al. 2017). In July 2009, Veillette et al. (2011) identified three distinct phytoplanktonic communities in three distinct layers, i.e., the freshwater layer was dominated by chlorophytes, the halocline was dominated by prasinophytes, and the marine layer was dominated by fucoxanthin-containing algae, diatoms, chrysophytes or prymnesiophytes. In July 2011, chlorophytes from the Radicarteria clade dominated the algal community at all depths (Thaler et al. 2017). The lake community was also composed of the cryptophyte *Teleaulax gracilis* and the pigment composition suggests the presence of diatoms or prymnesiophytes in the marine layer (Thaler et al. 2017). Uncertainties remain regarding the Milne epishelf lake after the calving of July 2020 emphasizing the importance of monitoring ecosystem changes after this event as complete ecosystem changes are anticipated.

The supraglacial ecosystem biota is dominated by benthic microbial mat assemblages, the planktonic community of supraglacial ecosystem is negligible (Mueller et al. 2006; Jungblut et al. 2017). Over time, the long lakes located between the rolling topographic features of the ice shelves, the melt ponds and the melt holes, also named cryoconite holes, accumulate sediment that can be colonized by microbial organisms (Jungblut et al. 2017). These microbial organisms form a matrix known as the microbial mats. In 2001 and 2002, 8 % of the six major ice shelves of Ellesmere Island (before Markham and Ayles calving) provided a sediment cryohabitat for these microbial mats (Mueller et al. 2006).

Three mat types were identified on the Ellesmere Island ice shelves, the mallet, the orange, and the sediment mats (Mueller et al. 2006). The orange mats are only found on marine ice. Moreover, marine ice has higher sediment content than meteoric ice and therefore hosts a higher proportion of the microbial mats found on the Ellesmere Island ice shelves (Mueller et al. 2006). The majority of the supraglacial biota is located on the Ward Hunt Ice Shelf, the sea-ice ice shelf of the region (Mueller et al. 2006).

On Ward Hunt Ice Shelf, the bacterial and viral abundances of the microbial mats vary between 0.7-7.5 × 10^7 cells cm^{-2} and 2.3-16.5 × 10^7 cells cm^{-2}, respectively (Vincent et al. 2000). Bacterial recycling efficiency within the mats was ca. 30 % and the bacterial production was three orders of magnitude lower than primary production (Mueller et al. 2005).

The standing stock of the four major remaining ice shelves north of Ellesmere Island was estimated at 34 Gg of organic material in 2001-2002 (Mueller et al. 2006). The Ward Hunt Ice Shelf mats, can reach up to 15.3 µg chl *a* cm^{-2} (Vincent et al. 2000). The orange mats color come from the high concentration of carotenoid pigments present in the algae, with an average of 2.1 µg of carotenoids per µg of chl *a* (Vincent et al. 2000). The Ward Hunt Ice Shelf mats annual primary production was determine to be 108 g C m^{-2} y^{-1} (Mueller et al. 2005). As of 2001, 10% and 44% of the surface of the two best-studied ice shelves, respectively Ward Hunt and the now extinct Markham, was estimated to be suitable for microbial mat communities (Mueller et al. 2006). Calving over the 2008-2012 period resulted in the loss of the vast majority of this prime ice shelf habitat (Mueller et al. 2008; Vincent et al. 2011; Mueller et al. 2017).

Microbial mats of Ellesmere Island ice shelves are dominated by cyanobacteria from the Oscillatoriales order (Vincent et al. 2000; Mueller et al. 2006). Eukaryotic algae, such as diatoms, mainly *Chamaepinnularia begeri*, and chlorophytes are also present in these mats (Table 2). Chrysophyte cysts were also found associated with the Ward Hunt Ice Shelf microbial mats, alike other organisms, such as ciliates, rotifers, nematodes, Platyhelminthes and tardigrades (Vincent et al. 2000).

Table 2. List of microbe taxa reported from ice shelf ecosystems within Tuvaijuittuq and adjacent areas.

Taxonomic Nomenclature	Within Tuvaijuittuq? (Y/N)	Location(s)[1]	Source(s)
Chromista			
Bacillariophyceae			
Achnanthes petersenii	N	WHIS	Vincent et al. 2000
Chamaepinnularia begeri	Y	MLSI, SIS, WHIS	Vincent et al. 2000; Mueller et al. 2006
Chamaepinnularia gandrupii	N	WHIS	Vincent et al. 2000
Chamaepinnularia krookii	N	WHIS	Vincent et al. 2000
Luticola palaearctica	N	WHIS	Vincent et al. 2000
Navicula cf. phyllepta	Y	SIS, WHIS	Mueller et al. 2006
Navicula phylleptosoma	N	WHIS	Vincent et al. 2000
Nitzschia homburgiensis	N	WHIS	Vincent et al. 2000; Mueller et al. 2006
Nitzschia cf. pusilla	N	WHIS	Vincent et al. 2000
Nitzschia palea	N	WHIS	Vincent et al. 2000
Pinnularia borealis	N	WHIS	Vincent et al. 2000
Myzozoa			
Dinophyceae			

Taxonomic Nomenclature	Within Tuvaijuittuq? (Y/N)	Location(s)[1]	Source(s)
Gymnodinium sp.	Y	MFEL	Veillette et al. 2011
Peridium sp.	Y	MFEL	Veillette et al. 2011
Plantae			
Chlorococcaceae			
Bracteacoccus sp.	Y	MIS, MLSI, SIS, WHIS	Vincent et al. 2000; Mueller et al. 2006
Chlorophyceae			
Chlamydomonas sp.	Y	MFEL, WHIS	Vincent et al. 2000; Veillette et al. 2011
Chlamydoscapsa sp.	N	WHIS	Vincent et al. 2000
Clorococcum sp.	N	WHIS	Vincent et al. 2000
Chlorosarcinopsis sp.	N	WHIS	Vincent et al. 2000
Chlorella sp.	N	WHIS	Vincent et al. 2000
Klebsormidium sp.	N	WHIS	Vincent et al. 2000
Palmellopsis sp.	N	WHIS	Vincent et al. 2000
Pleuratrum sp.	N	WHIS	Vincent et al. 2000
Radicarteria sp.	Y	MFEL	Thaler et al. 2017
Cryptophyceae			
Rhodomonas sp.	Y	MFEL	Veillette et al. 2011
Teleaulax gracilis	Y	MFEL	Thaler et al. 2017
Choanoflagellates			
Monosiga sp.	Y	MFEL	Veillette et al. 2011
Zygnematophyceae			
Ancyclonema nordenskioldii	N	WHIS	Mueller et al. 2006
Cylindrocystis cf. brebissonii	Y	MIS, WHIS	Mueller et al. 2006
Eubacteria			
Cyanophyceae			
cf. Aphanocapsa sp.	N	WHIS	Mueller et al. 2006
cf. Aulosira sp.	Y	MIS, MLSI, WHIS	Mueller et al. 2006
Gloeocapsa sp.	Y	MIS, WHIS	Mueller et al. 2006
Nostoc sp.	Y	MIS, WHIS	Mueller et al. 2006
Oscillatoria sp.	Y	MIS, MLSI, SIS, WHIS	Mueller et al. 2006
Phormidium sp.	Y	MIS, MLSI, SIS, WHIS	Mueller et al. 2006
cf. Pseudanabaena sp.	Y	MIS, SIS, WHIS	Mueller et al. 2006

[1] MFEL = Milne Fiord Epishelf Lake, MIS = Milne Ice Shelf, MLSI = Multi-year land-fast sea ice adjacent to Ellesmere Island ice shelves, SIS = Serson Ice Shelf, WHIS = Ward Hunt Ice Shelf

Macrophytes

Macrophytes are found along the coasts, mainly in the intertidal and sublittoral zones. A total of 210 macrophyte taxa are documented for the Canadian Arctic (Archambault et al. 2010). Most species would have originated in the Pacific Ocean, colonizing the Arctic during interglacial period (Lindstrom 2001). Historical records of macrophyte species in the Canadian Arctic Archipelago are presented in Table 3. More recently, Mathieson et al. (2010) summarized historical collection records across Arctic and subarctic regions, and reported 131 seaweed taxa in the region of Ellesmere and Baffin Islands, consisting of Chlorophyta (n = 36), Phaeophyceae (n = 51), Phaeothamniophyceae (n = 1), and Rhodophyta (n = 43). This region had the highest total and unique richness of the four arctic and sub-arctic regions studied (Figure 15).

Information specific to macrophytes in the Tuvaijuittuq region is not available. Since ice cover, ice scouring, substrata, light availability and salinity are considered the main factors influencing macrophyte growth and distribution in the Arctic (Mathieson et al. 2010; Michel 2013), it is likely that these factors, in particular the perennial ice cover, will play an important role in structuring macrophyte communities in Tuvaijuittuq.

Table 3. List of macroalgae taxa reported in coastal waters of Tuvaijuittuq and adjacent areas of MYI.

Taxonomic Nomenclature	Within Tuvaijuittuq? (Y/N)	Location(s)[1]	Source(s)
Chromista			
Phaeophyceae			
Alaria esculenta	N	BC	Lee 1980
Battersia arctica	N	HGB, WS	Lee 1973, 1980
Chaetopteris plumosa	N	KS	Lee 1980
Desmarestia aculeata	N	BC, KS	Lee 1980
Desmarestia viridis	N	BC, BMC, WS	Lee 1973, 1980
Elachista fucicola	N	HGB	Lee 1980
Hincksia ovata	N	WS	Lee 1973, 1980
Laminaria solidungula	N	BC, BMC, WS	Lee 1973, 1980
Omphalophyllum ulvaceum	N	KS, WS	Lee 1973, 1980
Phaeostroma parasiticum	N	BMC	Lee 1980
Phaeostroma pustulosum	N	KS, WS	Lee 1980
Pseudolithoderma extensum	N	WS	Lee 1980
Pseudolithoderma subextensum	N	WS	Lee 1980
Pylaiella littoralis	N	HGB, WS	Lee 1980
Ralfsia ovata	N	WS	Lee 1980
Saccharina latissima	N	BC, BMC, KS	Lee 1980
Stictyosiphon tortilis	N	HGB, KS	Lee 1980
Plantae			
Chlorophyceae			
Arthrochaete penetrans	N	WS	Lee 1980
Chlorochytrium inclusum	N	WS	Lee 1980

Blidingia minima var. ramifera	Y	North of EI	Lee 1980
Compsopogonophyceae		WS	
Erythropeltis discigera var. flustrae	N		Lee 1980
Florideophyceae			
Coccotylus truncatus	N	KS	Lee 1980
Leptophytum foecundum	N	SC, WS	Lee 1980
Leptophytum laeve	N	BMC, SC, WS	Lee 1980
Lithothamnion glaciale	N	WS	Lee 1980
Petrocelis sp.	N	BMC	Lee 1980
Peyssonnelia rosenvingei	N	BMC	Lee 1980
Phycodrys rubens	N	WS	Lee 1973, 1980
Polyostea arctica	N	BC, BMC, HGB	Lee 1980; McLaren 1982
Rhodomela lycopodioides	N	HGB, KS	Lee 1980
Rhodophysema elegans	N	BMC	Lee 1980
Rubrointrusa membranacea	N	WS	Lee 1980
Turnerella pennyi	N	WS	Lee 1973
Ulvophyceae			
Chaetomorpha melagonium	N	BMC, HGB, KS	Lee 1980, McLaren 1982
Gomontia polyrhiza	N	HGB	Lee 1980
Pseudendoclonium submarinum	N	WS	Lee 1980
Spongomorpha sp.	N	WS	Lee 1973
Ulothrix flacca	Y	North of EI, WS	Lee 1980
Ulva lactuca	Y	North of EI	Lee 1980
Ulvella viridis	N	KS, WS	Lee 1980

[1] BC = Belcher Channel, BMC = Byam Martin Channel, EI = Ellesmere Island, HGB = Hecla and Griper Bay, KS = Kellett Strait, SC = Sverdrup Channel, WS = Wilkins Strait
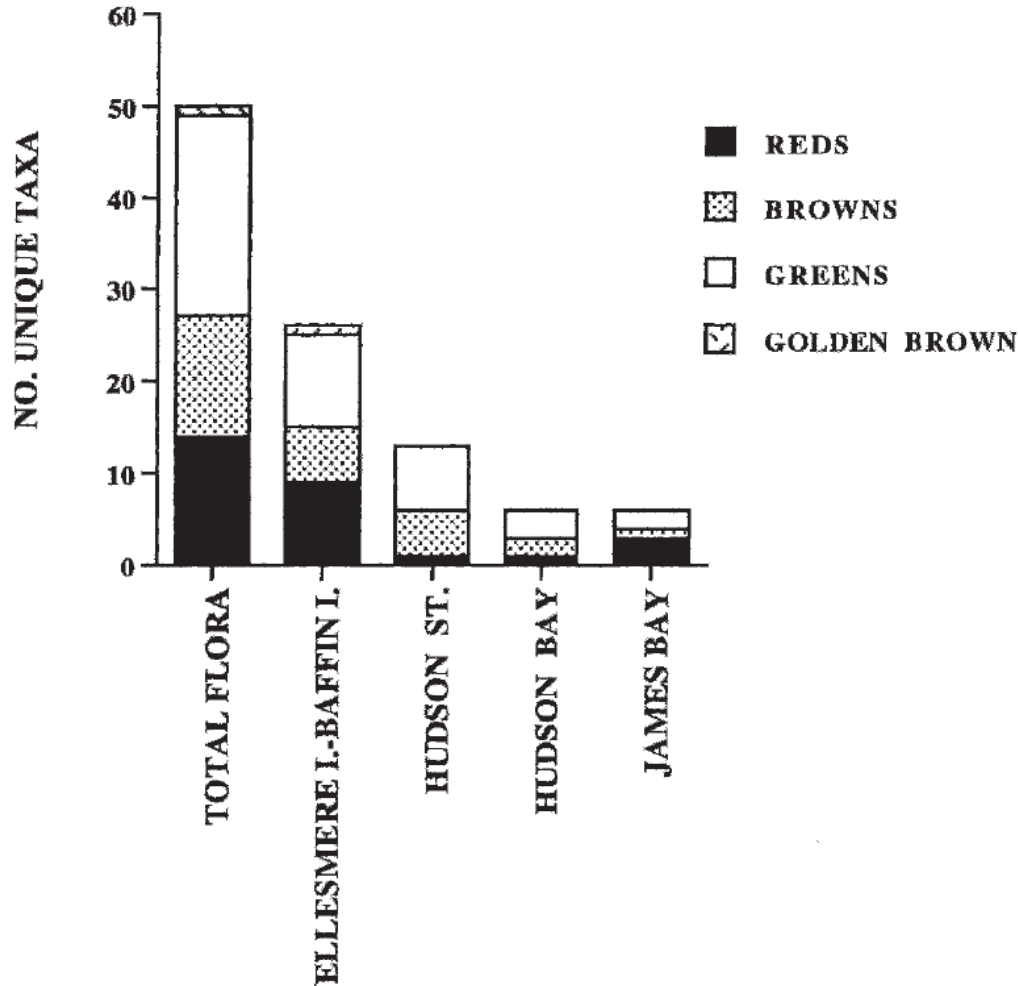
Figure 15. Number of taxa recorded in only one location (unique richness) for the entire studied region and for each of the region presented. From Mathieson et al. (2010).

Ice-Associated Invertebrates and Zooplankton

Invertebrates act as the link in Arctic marine food webs, making the energy from primary producers available to higher trophic levels such as fish (Crawford and Jorgenson 1996; Michaud et al. 1996), whales (Lowry and Frost 1984; Lowry 1993; Lowry et al. 2004; Pomerleau et al. 2011), seals (Smith and Harwood 2001; Harwood et al. 2015), and birds (Bradstreet 1980; Jakubas et al. 2017).

Ice associated invertebrates can be divided into two categories: autochthonous, which are obligate ice users throughout their life cycle and therefore dependent on MYI, and allochthonous, which facultatively use the sea ice and can thrive in seasonal ice environments (Gulliksen and Lønne 1991; Barber et al. 2015). Autochthonous ice assemblages are dominated by the macrofaunal amphipods *Gammarus wilkitzkii* (Figure 16a)*, Onisimus nanseni, O. glacialis* and *Apherusa glacialis* (Figure 16b; Buchanan et al. 1977; Hop et al. 2000; Hop and Pavlova 2008; Gradinger et al. 2010) but can also include

meiofaunal nematodes, turbellarians, polychaetes, rotifers, and other crustaceans (Grainger and Hsiao 1990; Nozais et al. 2001; Barber et al. 2015). Allochtonous invertebrates in the High Arctic are numerically dominated by the copepods *Calanus glacialis, and Calanus hyperboreus* which utilize ice algae to reproduce and build sufficient wax ester storage to enter diapause during the winter months (Daase et al. 2013; Visser et al. 2017). Other allochtonous species include pelagic amphipods like *Themisto spp.,* pteropods, and gelatinous zooplankton which inhabit the upper portion of the water column under sea ice (Søreide et al. 2003; Hop et al. 2011).
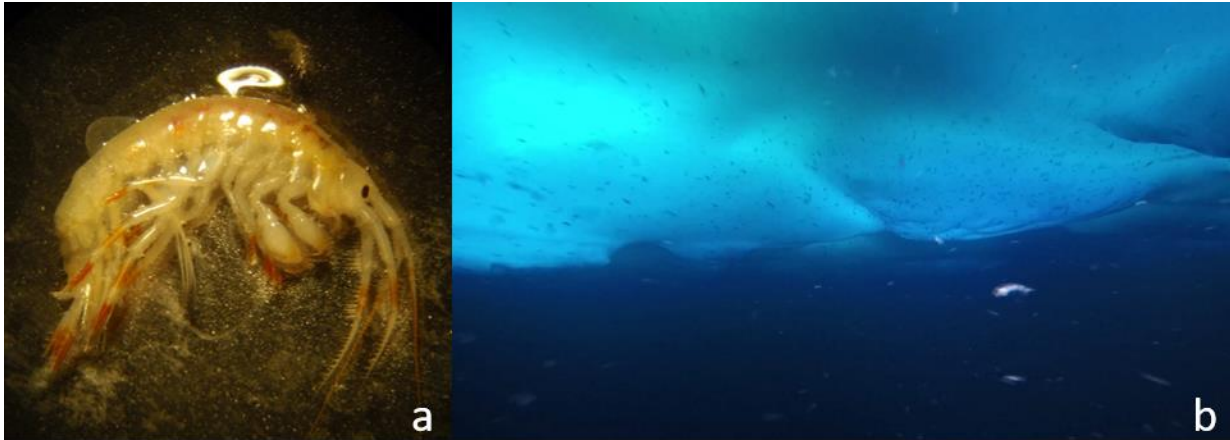
Figure 16. *Gammarus wilkitzkii* (a) and Remotely Operated Vehicle footage of a swarm of *Apherusa glacialis* under MYI (b) during the MAP-Last Ice 2019 field campaign. Photo credits: S. Duerksen, DFO

G. wilkitzkii has a complex feeding strategy, preying on other invertebrates, subsisting on detritus or even suspension feeding (Poltermann 2001; Beuchel and Lønne 2002). A long lived species, females can survive up to 7.5 years. *G. wilkitzkii* have been found in areas of seasonal ice, but at 10-100 times lower biomass than MYI; furthermore, the growth rates of individuals in FYI areas were also lower than in older ice regions indicating that young ice is a low quality habitat for these amphipods (Beuchel and Lønne 2002). *A. glacialis* is herbivorous-detritivorous and the most numerically abundant ice-associated species (Hop et al. 2000; Poltermann 2001). They have a relatively short life span, usually surviving for about 2 years, but have a high fecundity with females producing up to 554 offspring per year (Beuchel and Lønne 2002). *A. glacialis* may be some of the first animals to colonize new ice due to its extreme motility, and is often found in areas of first year ice (Gulliksen and Lønne 1989). There is recent evidence that this species may be better classified as allochthonous as they may leave the sea ice to over-winter at depths >200 m (Kunisch et al. 2020). *Onisimus sp.* are detritovorous-necrophagous and generally have low abundances (ca. 1 individual m^{-2}) (Arndt and Beuchel 2006). Their maximum life span is approximately 2.5-3.5 years (Arndt and Beuchel 2006). For all ice associated amphipods, evidence suggests that food is rarely a limiting resource, and large scale population changes are therefore likely to be caused by abiotic factors such as loss of sea ice habitat (Poltermann 2001; Arndt et al. 2005; AMAP 2017). There are no published studies that have examined ice associated invertebrate communities and their abundances in Tuvaijuittuq, however there is some evidence that the replacement of MYI

with FYI has already impacted ice-associated amphipod species such as *G. wilkitzkii* elsewhere in the Arctic (Melnikov et al. 2002; AMAP 2017).

Allocthonous zooplankton assemblages in the Arctic are dominated by a mix of Arctic endemic species and Atlantic species, while those of Pacific origin are generally unable to thrive in Arctic waters (Nelson et al. 2009). The total diversity has been estimated at 372 species, which is similar to the Atlantic Ocean, but less than the Pacific (Archambault et al. 2010; Darnis et al. 2012). In the spring and summer, zooplankton biomass throughout the High Arctic is generally dominated by copepods of the genus *Calanus* (*C. glacialis*, *C. hyperboreus,* and *C. finmarchicus*), which can make up to 80% of mesozooplankton biomass (Falk-Petersen et al. 2009; Darnis and Fortier 2012). In shelf areas, *Metridia longa* has also been shown to contribute substantially to the total biomass (Kosobokova and Hirche 2009). During the polar night, *C. glacialis* and *C. hyperboreus* descend to deep water for diapause and smaller copepods such as *Pseudocalanus* spp*.* and *Oithona* sp. become the most abundant (Kosobokova and Hirche 2009; Grenvald et al. 2016; Gluchowska et al. 2017). Larger zooplankton (>1500 μm) such as euphausids, chaetognaths, and ctenophores are also common throughout the year (Grenvald et al. 2016; Gluchowska et al. 2017).

Ice-associated fauna and zooplankton consume diatom algae from under the ice either *in situ* or as the algae sinks through the water column (Conover et al. 1986; Poltermann 2001; Michel et al. 2002), with a shift from ice-associated to phytoplankton sources as the season progress (Brown and Belt 2012). Uptake and storage of large quantities (up to > 50% dry weight) of lipids during ice algae and phytoplankton blooms is essential to the survival of these Arctic zooplankton (Søreide et al. 2010; Record et al. 2018). Early and rapid growth of zooplankton is aided by early ice-associated algal blooms (Søreide et al. 2010). *C. hyperboreus* and *C. glacialis* time their reproductive cycles around the ice algal blooms to take advantage of high quality polyunsaturated fatty acids produced by ice diatoms, which are important for reproduction and to build reserves for the diapause during the winter months (Falk-Petersen et al. 2009; Record et al. 2018). *C. hyperboreus* is a capital breeder and reproduces using its energy stores at the start of the bloom in early spring (Halvorsen 2015). *C. glacialis* on the other hand, is an income breeder, and uses the spring ice algae bloom to fuel reproduction, and spawning occurs towards the end of the bloom (Conover and Huntley 1991; Søreide et al. 2010).

In the early 1960s, qualitative zooplankton sampling was conducted in Tuvaijuittuq and adjacent areas (Grainger 1965; Mohammed and Grainger 1974). Table 4 lists the taxa identified during these surveys. In Strand Fiord, east of Tuvaijuittuq, a handful of species were identified and the copepod *Oithona similis* was especially abundant, accounting for 65% of the zooplankton catch from 0–50 m depth (Mohammed and Grainger 1974). Zooplankton abundances in Nansen Sound and Strand Fiord were very low (89 and 259 individual m^{-3}, respectively).

Table 4. List of zooplankton and ice-associated invertebrate taxa from marine waters within Tuvaijuittuq and adjacent areas of MYI.

Taxonomic Nomenclature	Within Tuvaijuittuq? (Y/N)	Location(s)[1]	Source(s)
Cnidaria			
Aeginopsis laurentii	Y	CB	Grainger 1965
Aglantha digitale	N	CB	
Mollusca			
Gastropoda			
Clione limacina	N	CB	Grainger 1965
Limacina helicina	Y	AHI, KB, MgI	Grainger 1965; Longhurst et al. 1984; Van Wagoner et al. 1989
Annelida			
Polychaeta			
Larvae	Y	CB, NSo	Grainger 1965; Mohammed and Grainger 1974
Arthropoda			
Amphipoda			
Gammaracanthus loricatus		CB continental shelf	Grainger 1965
Onisimus nanseni	Y	CB	Grainger 1965
Themisto abyssorum	N	KB, SF	Grainger 1965; Mohammed and Grainger 1974; Longhurst et al. 1984
Themisto libellula	Y	CB, KB	Grainger 1965; Longhurst et al. 1984
Copepoda			
Calanus finmarchicus	N	KB	Longhurst et al. 1984
Calanus glacialis	Y	CB, KB, NSo, SF	Grainger 1961, 1965; Mohammed and Grainger 1974; Longhurst et al. 1984; Schmid and Fortier 2019
Calanus hyperboreus	Y	CB, KB, NSo, NSt, SF	Grainger 1965; Longhurst et al. 1984; Schmid and Fortier 2019 Mohammed and Grainger 1974
Euchaeta norvegica	N	KB	Longhurst et al. 1984
Gaetanus brevispinus	N	CB	Grainger 1965
Gaetanus tenuispinus	N	CB	Grainger 1965
Metridia longa	Y	CB, KB, NSo, SF	Grainger 1965; Mohammed and Grainger 1974; Longhurst et al. 1984
Microcalanus pygmaeus	Y	CB, KB, NSo, SF	Grainger 1965; Mohammed and Grainger 1974; Longhurst et al. 1984
Oithona similis	Y	CB, KB, NSo, SF	Grainger 1965; Mohammed and Grainger 1974; Longhurst et al. 1984
Paraeuchaeta glacialis	Y	CB, NSo	Grainger 1965
Pseudocalanus minutus	Y	CB, KB, NSo, SF	Grainger 1965; Mohammed and Grainger 1974; Longhurst et al. 1984
Spinocalanus magnus	N	CB	Grainger 1965
Triconia borealis	Y	CB	Grainger 1965
Mysida			
Mysis sp.	Y	CB	Grainger 1965
Ostracoda			

Taxonomic Nomenclature	Within Tuvaijuittuq? (Y/N)	Location(s)[1]	Source(s)
Boroecia maxima	N	CB	Grainger 1965
Chaetognatha			
Eukrohnia hamata	Y	CB	Grainger 1965
Parasagitta elegans	Y	CB, SF	Grainger 1965; Mohammed and Grainger 1974
Tunicata			
Fritillaria borealis	Y	CB, NSo, SF	Grainger 1965; Mohammed and Grainger 1974
Oikopleura vanhoeffeni	Y	CB, NSo, SF	Grainger 1965; Mohammed and Grainger 1974

[1] AHI = Axel Heiberg Island, CB = Canada Basin, KB = Kane Basin, MgI = Meighen Island, NSo = Nansen Sound, NSt = Nares Strait, SF = Strand Fiord

Very few studies have examined zooplankton communities in the Ellesmere Island Ice Shelves region. Milne Ice shelf in Tuvaijuittuq is the location of perhaps the last deep epishelf lake in the Arctic, although there are several shallower epishelf lakes along the northern coast of Ellesmere island (Jungblut et al. 2017). Zooplankton sampling of the Milne Ice Shelf epishelf lake found eight copepod species, 6 marine taxa, and 2 freshwater/brackish taxa (Veillette et al. 2011). The marine species *Pseudocalanus minutus* was numerically dominant in both of the sampling tows (Veillette et al. 2011).

Current and Future Trends

There is evidence that the diversity and distribution of ice-associated fauna are dependent on ice type, with potentially more diversity in MYI than FYI (Hop et al. 2000; 2011; Barber et al. 2015). The replacement of structurally complex MYI by smoother and more transient FYI likely has already caused population declines in obligate ice associated invertebrates, particularly gammarid amphipods (AMAP 2017). *Apherusa glacialis* may be less vulnerable to ice loss due to their higher mobility, and preference for smoother ice (Kunisch et al. 2020). It must be stressed however, that the lack of information on species that inhabit MYI makes future predictions very difficult.

Shifts in zooplankton community composition from higher to lower quality forage species have important implications to Arctic marine food webs. Generally, lipid content in *Calanus* and other Arctic zooplankton is highest in summer and tied closely to algal blooms, both ice-associated and phytoplanktonic, and lowest in winter (Connelly et al. 2016). As such, changes to the timing and extent of ice cover can affect blooms, which may alter the annual cycle of lipid uptake and storage in zooplankton (Søreide et al. 2010). To highlight the complexity of this system, for pelagic zooplankton, the loss of thick, older ice will likely lead to an overall increase in resources due to an increase in production (Arrigo and van Dijken 2011). A population increase however, may be modulated by a concurrent increase in top-down pressure by predators during the increased ice-free periods (Darnis et al. 2019). Increasing temperatures have also been shown to shift zooplankton community composition to smaller, less lipid rich species (Garzke et al. 2015; Møller and Nielsen 2020), although it is unclear if this process will affect Tuvaijuittuq.

BENTHIC COMMUNITIES

Benthic diversity across the Arctic is estimated at 1,470 species (Bluhm et al. 2011; CAFF 2013), with approximately 1,000–1,300 taxa occurring in Canadian Arctic marine waters (Archambault et al. 2010; Darnis et al. 2012; Snelgrove et al. 2012). Arthropoda and Annelida are the most diverse Arctic phyla (Archambault et al. 2010). Benthic community composition can be influenced by substrate, depth, ice cover and thickness, water and sediment chemical properties, and food availability.

Historical records from the Canada Basin include bivalves, representing nearly two-thirds of the diversity, arthropods, gastropods, and chordates (Roy and Gagnon 2016). In some of these samples, arthropods comprise roughly one-third of the diversity. In the Canadian Arctic Archipelago, including QEI, Nansen Sound, Greely Fiord, Lincoln Sea and Kane Basin, the benthic community is generally dominated by arthropods and bivalves (approximately 70% of the taxa), but also include gastropods, echinoderms, bryozoa, and a small number of cnidaria, ascidiacea and porifera (Roy and Gagnon 2016). A benthic community primarily dominated by polychaetes (75%), but also echinoderms, ascidiacea and porifera is present at other sites of this region. Both Piepenburg et al. (2011) and Kędra et al. (2015) asserted that the ecoregion to which Tuvaijuittuq belongs requires further investigation.

Very few benthic studies have focused specifically on Tuvaijuittuq compared to adjacent regions and the southern Canadian Arctic Archipelago and western Canadian Arctic (Cusson et al. 2007; Archambault et al. 2010), and as such almost nothing is known about the structure, abundance or diversity within Tuvaijuittuq itself. Van Wagoner et al. (1989) identified diverse benthic communities from western Ellesmere Island to Meighen Island in water shallower than 130 m. These communities were supported by large siliceous sponges that formed mounds up to 10 m in height. Sponges were rare or absent from 130–300 m. Additional areas in the QEI were surveyed in the 1960s, 1970s and 1980s, but they were selective primarily for molluscs and arthropods (Table 5; Powell 1968; Squires 1968; MacPherson 1971; Lubinsky 1976; McLaren 1982; Thomson et al. 1986).

Table 5. List of benthic and epibenthic taxa from marine waters within Tuvaijuittuq and adjacent areas of MYI.

Taxonomic Nomenclature	Within Tuvaijuittuq? (Y/N)	Location(s)[1]	Source(s)
Foraminifera			
Cassidulina laevigata	Y	CPM north of AHI and MgI	Van Wagoner et al. 1989
Cassidulina reniforme	Y	CPM north of AHI and MgI	Van Wagoner et al. 1989
Epistominella arctica	Y	CPM north of AHI and MgI	Van Wagoner et al. 1989
Islandiella helenae	Y	CPM north of AHI and MgI	Van Wagoner et al. 1989
Neogloboquadrina pachyderma	Y	CPM north of AHI and MgI, CB continental shelf north of ERI	Van Wagoner et al. 1989; El Bani Altuna et al. 2018
Planispirinoides bucculentus	Y	CPM north of AHI and MgI	Van Wagoner et al. 1989
Quinqueloculina vulgaris	Y	CPM north of AHI and MgI	Van Wagoner et al. 1989
Robertinoides charlottensis	Y	CPM north of AHI and MgI	Van Wagoner et al. 1989
Saccammina sphaerica	Y	CPM north of AHI and MgI	Van Wagoner et al. 1989
Porifera			
Demospongiae			
Geodia phlegraei	Y	CPM north of AHI and MgI	Van Wagoner et al. 1989

Taxonomic Nomenclature	Within Tuvaijuittuq? (Y/N)	Location(s)[1]	Source(s)
Haliclona sp.	Y	CPM north of AHI and MgI	Van Wagoner et al. 1989
Myxilla sp.	Y	CPM north of AHI and MgI	Van Wagoner et al. 1989
Cnidaria			
Anthozoa			
Gersemia rubiformis	Y	Arctic Archipelago biogeographic unit[2]	Roy and Gagnon 2016
Hydrozoa			
Abietinaria turgida	N	ERI	CMN 2018
Bryozoa			
Aquiloniella scabra	N	KB	Powell 1968
Cheilopora sincera	N	KB	Powell 1968
Cystisella elegantula	N	KB	Powell 1968
Cystisella saccata	N	KB	Powell 1968
Dendrobeania murrayana	N	KB	Powell 1968
Escharella immersa	N	BMC	McLaren 1982
Escharoides jacksonii	N	ERI	Powell 1968; CMN 2018
Eucratea loricata	N	ERI	Powell 1968; CMN 2018
Kinetoskias arborescens	N	ERI	CMN 2018
Leieschara coarctica	N	KB	Powell 1968
Membranipora sp.	Y	CPM north of AHI and MgI	Van Wagoner et al. 1989
Membranipora serrulata	N	KB	Powell 1968
Posterula sarsii	N	KB	Powell 1968
Pseudoflustra solida	N	ERI	Powell 1968; CMN 2018
Rhamphostomella costata	N	ERI, PPI	CMN 2018
Tegella armifera	N	ERI	Powell 1968; CMN 2018
Tricellaria gracilis	N	ERI, KB	Powell 1968; CMN 2018
Tubulipora sp.	Y	CPM north of AHI and MgI	Van Wagoner et al. 1989
Mollusca			
Bivalvia			
Arca sp.	Y	CPM north of AHI and MgI	Van Wagoner et al. 1989
Astarte borealis	N	AHI,BMC, ERI	McLaren 1982; CMN 2018
Bathyarca glacialis	N	SF, SIF	CMN 2018
Cuspidaria glacialis	Y	CPM north of AHI and MgI	Van Wagoner et al. 1989
Dacrydium vitreum	Y	CPM north of AHI and MgI	Van Wagoner et al. 1989
Delectopecten vitreus	Y	CPM north of AHI and MgI	Van Wagoner et al. 1989
Hiatella arctica	Y	Arctic Basin biogeographic unit[3] Arctic Archipelago biogeographic unit[2]	Roy and Gagnon 2016
Limatula subauriculata	Y	CPM north of AHI and MgI	Van Wagoner et al. 1989
Lyonsiella abyssicola	Y	CPM north of AHI and MgI	Van Wagoner et al. 1989
Macoma moesta	N	SF, SIF	CMN 2018
Mya truncata	N	BMC	McLaren 1982
Parathyasira dunbari	Y	North of EI, ERI, GF, NSo	Lubinsky 1976
Portlandia arctica	Y	CPM north of AHI and MgI	Van Wagoner et al. 1989
Gastropoda			
Alvania moerchi	N	WS	MacPherson 1971
Anatoma crispata	N	ERI	MacPherson 1971
Buccinum spp.	Y	Arctic Basin biogeographic unit[3] Arctic Archipelago biogeographic unit[2]	Roy and Gagnon 2016
Buccinum undatum	N	ERI	CMN 2018

Taxonomic Nomenclature	Within Tuvaijuittuq? (Y/N)	Location(s)[1]	Source(s)
Buccinum hydrophanum	Y	KB, NSo	MacPherson 1971
Buccinum undatum	N	ERI	CMN 2018
Colus sabini	Y	AHI, EIIS, PGAS	MacPherson 1971
Erginus rubellus	N	WS	MacPherson 1971
Margarites groenlandicus umbilicalis	Y	AF, North of EI, KB	MacPherson 1971
Margarites olivaceus	N	ERI, KB, WS	MacPherson 1971
Scissurella sp.	Y	CPM north of AHI and MgI	Van Wagoner et al. 1989
Solariella obscura	Y	CPM north of AHI and MgI	Van Wagoner et al. 1989
Velutina velutina	N	ERI, SIF	MacPherson 1971
Annelida			
Polychaeta			
Axionice flexuosa	N	BMC	McLaren 1982
Capitella capitata	N	BMC	McLaren 1982
Pista maculata	N	BMC	McLaren 1982
Scoletoma fragilis	N	BMC	McLaren 1982
Arthropoda			
Amphipoda			
Acanthostepheia malmgreni	Y	Arctic Archipelago biogeographic unit[2]	Roy and Gagnon 2016
Calliopiidae sp.	N	BMC	Thomson et al. 1986
Gammarus setosus	N	BMC	Thomson et al. 1986
Hippomedon gorbunovi	N	BMC	McLaren 1982
Onisimus glacialis	N	BMC	Thomson et al. 1986
Onisimus litoralis	N	BMC	Thomson et al. 1986
Onisimus nanseni	N	BMC	Thomson et al. 1986
Paroediceros lynceus	N	BMC	Thomson et al. 1986
Pleustidae sp.	N	BMC	Thomson et al. 1986
Weyprechtia pinguis	Y	BrI, North of EI,	CMN 2018
Decapoda			
Eualus gaimardii	N	BC	Squires 1968
Lebbeus groenlandicus	N	MI	Squires 1968
Lebbeus polaris	N	HS	Squires 1968
Pandalus sp.	N	ERI	CMN 2018
Sabinea septemcarinata	N	AHI	Squires 1968
Sclerocrangon boreas	N	BC, HS	Squires 1968
Spirontocaris phippsii	Y	Arctic Archipelago biogeographic unit[2]	Roy and Gagnon 2016
Isopoda			
Caecognathia elongata	Y	CPM north of AHI and MgI	Van Wagoner et al. 1989
Saduria entomon	N	AHI, ERI	CMN 2018
Mysida			
Mysis litoralis	N	AHI, ERI, SIF	CMN 2018
Mysis relicta	N	AHI, ERI, SIF	CMN 2018
Ostracoda			
Acetabulastoma arcticum	Y	CPM north of AHI and MgI	Van Wagoner et al. 1989
Cytheropteron bronwynae	Y	CPM north of AHI and MgI	Van Wagoner et al. 1989
Eucytherura sp.	Y	CPM north of AHI and MgI	Van Wagoner et al. 1989
Henryhowella sp.	Y	CPM north of AHI and MgI	Van Wagoner et al. 1989
Polycope sp.	Y	CPM north of AHI and MgI	Van Wagoner et al. 1989

Taxonomic Nomenclature	Within Tuvaijuittuq? (Y/N)	Location(s)[1]	Source(s)
Pseudocythere caudata	Y	CPM north of AHI and MgI	Van Wagoner et al. 1989
Pycnogonida			
Boreonymphon abyssorum	N	ERI, SlF	CMN 2018
Boreonymphon compactum	N	BMC	McLaren 1982
Boreonymphon ossiansarsi	N	ERI, SlF	CMN 2018
Nymphon hirtipes	N	ERI, SlF	CMN 2018
Nymphon longimanum	N	ERI	CMN 2018
Nymphon stroemi	N	ERI, SlF	CMN 2018
Echinodermata			
Asteroidea			
Icasterias panopla	N	ERI, SlF	CMN 2018
Echinoidea			
Strongylocentrotus droebachiensis	Y	AHI, BMC, ERI, NSo, SlF	Thomson et al. 1986; CMN 2018
Crinoidea			
Heliometra glacialis	Y	CPM north of AHI and MgI	Van Wagoner et al. 1989
Ophiuroidea			
Gorgonocephalus sp.	Y	CPM north of AHI and MgI	Van Wagoner et al. 1989
Ophiacantha bidentata	Y	Arctic Archipelago biogeographic unit[2]	Roy and Gagnon 2016
Ophiocten sericeum	Y	Arctic Archipelago biogeographic unit[2] NSo, SlF, SF	Roy and Gagnon 2016 CMN 2018 Thomson et al. 1986
Chordata			
Ascidacea			
Ascidia spp.	Y	Arctic Archipelago biogeographic unit[2] Arctic Basin biogeographic unit[3]	Roy and Gagnon 2016

[1] AF = Archer Fiord, AHI = Axel Heiberg Island, BMC = Byam Martin Channel, BrI = Brock Island, CB = Canada Basin, CPM = Canadian Polar Margin (continental slope and shelf off QEI), EI = Ellesmere Island, EIIS = Ellesmere Island Ice Shelves, ERI = Ellef Ringnes Island, GF = Greely Fiord, HS = Hazen Strait, KB = Kane Basin, LS = Lincoln Sea, MgI = Meighen Island, MI = Melville Island, NSo = Nansen Sound, PGAS = Prince Gustav Adolf Sea, PPI = Prince Patrick Island, QEI = Queen Elizabeth Islands, SF = Strand Fiord, SlF = Slide Fiord, WS = Wilkins Strait

[2] from Roy and Gagnon (2016); includes sampling sites in QEI, NSo, GF, LS and KB

[3] from Roy and Gagnon (2016); includes sampling sites on the continental slope/in the CB north of the QEI

Opportunistic ROV dives were carried out as part of the MAP-Last Ice 2018 and 2019 field campaigns. which revealed diverse assemblages of benthic organisms underneath the ice-covered ocean. Crinoid congregations, brittle stars and basket stars (Ophiuroidea), star fish (Asteroidea), beds of scallops, glass sponges, soft corals, sea fans, anemones, and sea snails were commonly observed. Several species of benthic fish, including sculpins (Cottoidea) and fish doctors (Gymnelus spp.) as well as cuttlefish (Sepia spp.) and octopus (Bathypolypus arcticus) were also detected. Numerous types of sea spiders (Pycnogonida) were very abundant and one individual was observed carrying a brood of young. There are no quantitative surveys of the benthos in the region (Figure 17).
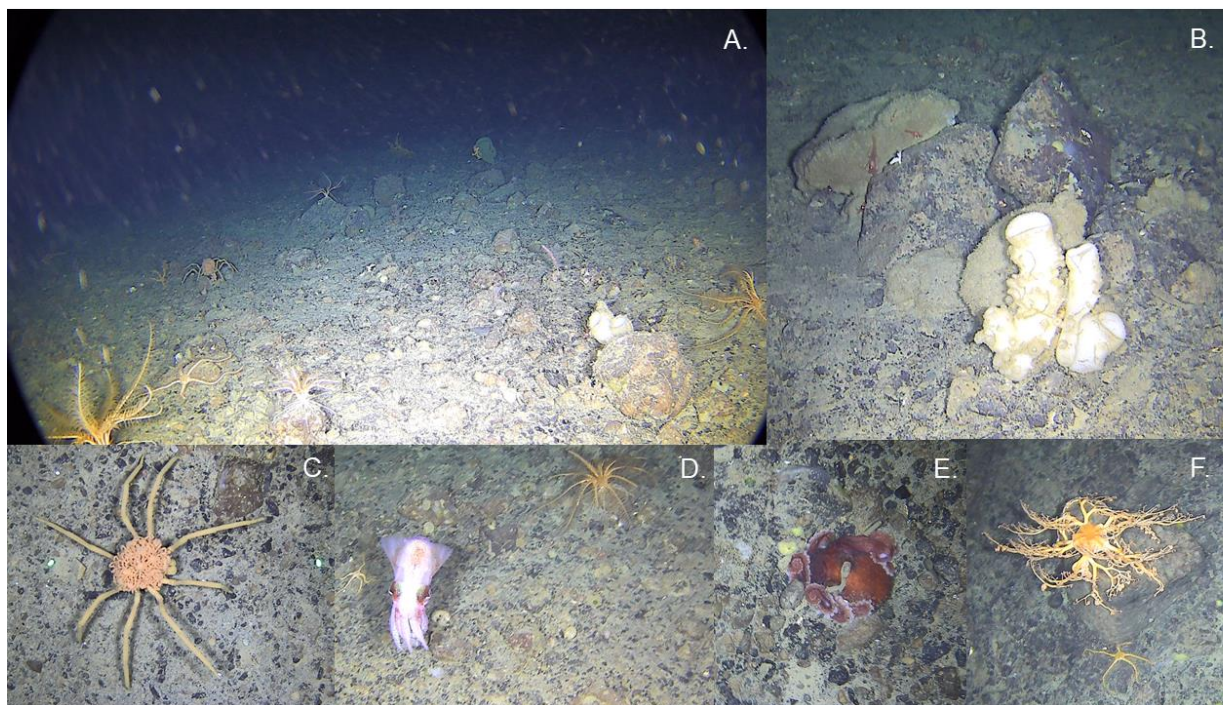
Figure 17. ROV footage from the MAP-Last Ice 2019 field campaign; (a) benthos of Tuvaijuittuq, (b) sponges and shrimp, (c) a pycnogonid (sea spider) carrying its brood on its back, (d) a cuttlefish and crinoid, (e) an octopus, and (f) gorgon's head star and brittle star.

Current and Future Trends

Information on benthic communities across the Canadian Arctic Archipelago are scarce, and in Tuvaijuittuq, essentially lacking (Mäkelä et al. 2017). It is therefore difficult to determine the nature and magnitude of changes they may experience due to climate change. Benthic communities derive most of their carbon from sinking organic material, which, under MYI in the High Arctic, can include large deposits from sinking ice algae (Wiedmann et al. 2020). Therefore the direction of changes in ice-associated primary production and its export to the benthos will influence the future productivity of benthic communities in Tuvaijuittuq.

ICE-PELAGIC-BENTHIC COUPLING

Ice-pelagic-benthic coupling refers to the connectivity of energy and nutrients between these respective communities. Much of the carbon in pelagic zooplankton and benthic communities in the High Arctic can be traced using stable isotopes and fatty acid biomarkers to ice associated primary productivity, consumed as it sinks through the water column to the seafloor (Kohlbach et al. 2016; Wiedmann et al. 2020). The importance of pelagic production will likely increase however as MYI continues to decrease and open water becomes more common (Arrigo and van Dijken 2011). These linkages have not been studied in Tuvaijuittuq, but due to their potential importance, a general description of potential interactions is provided here.

Varying amounts of ice-pelagic (France et al. 1998; Michel et al. 2002; Søreide et al. 2006; Yamamoto et al. 2014), ice-benthic (Conover et al. 1990; Tamelander et al. 2006;

Renaud et al. 2007; Boetius et al. 2013), and pelagic-benthic (Bluhm et al. 2015; Stasko et al. 2018) coupling have been observed in the Arctic marine environment. The flux of carbon from the ice and water column to the benthos is determined by several factors, including the productivity of the area, sinking flux of the organic matter, structure of water masses and the hydrogeography near the sea floor (Stasko et al. 2018). As such, the strength of factors that determine benthic community structure will be very different for deeper environments compared to those that are shallower (Wiedmann et al. 2020).

It is also important to recognize that the fluxes between the sea ice, water column and benthos are not necessary linear, or unidirectional. Søreide et al. (2013) found high levels of ice algal diatom biomarkers in benthic organisms, but little input from pelagic phytoplankton. *Calanus* sp. were found to have equal amounts of ice and pelagic biomarkers, and ice associated amphipods had high levels of *Calanus* biomarkers (Søreide et al. 2013). Kohlbach et al. (2016) had similar findings: ice algae in the Eurasian Basin of the Arctic Ocean contributed substantially to ice-associated amphipod diets (87–91% of carbon), but less so to pelagic amphipod and copepod diets (39–55% of carbon).

The loss of MYI may also directly increase the flux of carbon to the benthos in the short term. While present in areas of FYI, the greater structural complexity of MYI may foster large accumulations of the colonial diatom *Melosira arctica* (Poulin et al. 2014). When the ice melts, *M. arctica* quickly sink, and Boetius et al. (2013) observed strands of ice algae along the ocean floor of the Arctic Basin as deep as 4,400 m, covering up to 10% of the seafloor in some regions. Carbon contributions from these strands were estimated to be as high as 156 g C m^{-2}, and were higher than pelagic production at the time of the survey (Boetius et al. 2013). These contributions amounted to at least 45% of total primary production and more than 85% of total carbon export (Boetius et al. 2013). Renaud et al. (2007) found that ice algae exported to the bottom during spring increased benthic activity in the Beaufort Sea, showing a tight coupling between ice algae as a food source and benthic grazers. As ice retreats earlier on Arctic shelves, the contribution of ice algae to shelf benthos, in particular, may lose early season inputs of organic matter from ice algal blooms and the strength of the coupling may potentially lessen. The outcomes of these changes is still unknown and some predict these processes will result in possible local extirpations (Carroll et al. 2008), while there is also the suggestion that an increase in pelagic production may make up the loss (Wiedmann et al. 2020). The actual outcomes will likely be determined by local factors such as water masses, hydrogeography, and food web structure. In Tuvaijuittuq, the persistence of sea ice is likely to provide some stability to the ice-benthic or pelagic coupling that supports food web transfers and higher trophic levels. Despite the lack of data on sinking export in Tuvaijuittuq, there is indication of tight ice-pelagic-benthic coupling. For example, in Archer Fiord the presence of walruses and bearded seals indicates a productive benthic community for that area.

Polynyas, which are generally some of the most biologically productive areas, have been observed to have strong pelagic-benthic linkages. Studies from the early 1990s conducted in the Northeast Water Polynya (NOW) on the East Greenland Shelf suggested that infaunal density, polychaete biomass (Ambrose and Renaud 1995) and diets of benthic grazers and filter-feeders (Hobson et al. 1995) were all strongly linked to the advection of phytoplankton, and less so to ice algae. The ice-pelagic coupling is also

strong in the NOW area where up to 75% of ice algal carbon was exported to the water column (Michel et al. 2002).

The magnitude of flux between these habitats has direct effects on community structure, and determines the number of trophic levels these areas can support. Arctic cod (*Boreogadus saida*) is a keystone species (see Section below), and rely on sea ice during their development. The contribution of ice-derived fatty acids to Arctic cod appears to vary seasonally, by location, and with body size. In the Central Arctic Kohlbach et al. (2017), utilized a combination of bulk stable isotope analysis and compound specific isotope analysis and determined that that young Arctic cod derive the majority of their total carbon (up to 90%), as well as their lipids (up to 65%), from ice algal sources. Budge et al. (2008) likewise found ice algal diatoms to be a major part of Arctic cod diets near Alaska, but that the contribution was significantly different between the two populations sampled, and that cod feeding on copepods only derived ca. 32% of their lipids from ice associated sources in comparison to cod feeding on ice associated amphipods (ca. 62%). Lastly, when cod were examined at the end of the open water season, long after the ice algal bloom, turnover had reduced the ice associated biomarker levels to ≤ 2% total contribution (Graham et al. 2014). This highlights the importance of timing of these fluxes to arctic ecosystems. There is concern that as the Arctic warms, the timing of blooms will change such that invertebrate consumers may miss critical oportunities to forage, particularily earlier in the season (Søreide et al. 2010). The resulting decoupling between ice and pelagic realms would have far reaching and unpredictable consequences for the entire Arctic marine food web.

FISHES

There is very little information about fish diversity and abundance in Tuvaijuittuq and the surrounding areas. In the Canadian Arctic, a total of 221 species constitute the marine ichtyofauna (Coad and Alfonso 2018). Within the High Arctic Archipelago and the Arctic Basin ecozones, 25 and 11 species were recorded respectively (Coad and Alfonso 2018). Notably, polar cod (*Arctogadus glacialis)*, arctic cod (*Boreogadus saida)*, arctic char (*Salvelinus alpinus*), fourhorn sculpin (Myoxocephalus quadricornus), Greenland halibut (*Reinhardtius hippoglossoides*) have been confirmed above 83° N, within the boundaries of the Tuvaijuittuq (Table 6; Coad and Reist 2018). Water depths and ice conditions within Tuvaijuittuq likely mean the area is appropriate habitat for *R. hippoblossoides,* but no direct observations have been made (Coad and Reist 2018, K. Hedges, DFO, pers. comm.). The International Union for the Conservation of Nature (IUCN) includes portions of Tuvaijuittuq for the range of Greenland shark (*Somniosus microcephalus)* (Kyne et al. 2006*).* Nansen Sound also hosts many fish species, especially *cottidae* (Coad and Reist 2018). Glacial eelpout (*Lycodes frigidus*) were recorded in Canada Basin, in the deep water just outside Tuvaijuittuq (Coad and Reist 2018).

Warmer waters, sea ice loss and changes in stratification resulting from climate change are expected to bring shifts in fish distribution throughout the Arctic as sub-Arctic, Atlantic and Pacific species moving northwards (Beamish 2002; Archambault et al. 2010; Cheung et al. 2011). However, northward range expansions for fish species are highly unlikely in the Tuvaijuittuq ecosystem. Advection has been shown to dictate poleward expansions of sub-arctic pelagic species (Fossheim et al. 2015; Eriksen et al. 2017; Oziel et al. 2020;

Spies et al. 2020). Tuvaijuittuq is not directly connected to either of the Pacific or North Atlantic gateways, and Atlantic waters of the west Greenland current do not reach Tuvaijuittuq. Tuvaijuiituq is upstream of Baffin Bay, which means that water (and ice) from Tuvaijuittuq flow through Nares Strait into Baffin Bay, and no direct route of advection is likely to bring sub-Arctic plankton or fish species into the region. Possible range expansions in Tuvaijuittuq would be for marine mammals and birds, the former benefiting from sea ice declines in 'bottle neck' regions such as Nares Strait, and the latter from longer open water seasons (see Marine Mammals and Birds Sections).

Arctic cod are circumpolar, highly dependent on sea ice (Welch et al. 1993; Benoit et al. 2008; Mecklenburg et al. 2011) and are ecologically pivotal as both predator and prey in pelagic and benthic food webs of Arctic marine systems (Cobb et al. 2008; Loseto et al. 2008a; 2008b; 2009; Crawford et al. 2012; Majewski and Reist 2015; David et al. 2016; Kohlbach et al. 2017; Coad and Reist 2018). Despite being an ecologically and biologically important species, little is known the ecology and movement of Arctic cod, particularly in areas with high concentrations of MYI. Arctic cod likely spawn under the ice and their eggs float to the surface and hatch near the ice-water interface (Bain et al. 1977). cod larvae use the subsurface of the ice and its brine channels and wedges for feeding and predator avoidance (Bain et al. 1977; Gradinger and Bluhm 2004). Arctic cod larvae and juveniles are also epipelagic and concentrate in shallow waters (< 50 m) along the Beaufort Shelf southwest of Tuvaijuittuq (Hunter 1979; Ponton et al. 1993; Sareault 2009). Adult cod are strongly associated with sea ice, and David et al. (2016) found in the central Arctic that higher abundances were linked with thick ice cover and higher densities of the amphipod *Apherusa glacialis*. Cod diet consists mainly of ice-associated species such as calanoid copepods, amphipods and mysids (David et al. 2016; Kohlbach et al. 2017). Arctic cod, in turn, are important in the diets of other fishes, marine mammals, and sea birds, all of which concentrate at floe edges to feed (Bradstreet and Cross 1982; Welch et al. 1993; Kovacs et al. 2011), and they represent a key link between Arctic primary production and higher trophic levels.

MYI loss in the Arctic will likely have complex effects on Arctic cod populations: it may reduce the availability of critical shelter from predators and/or reduce the availability of foraging habitat by dispersing cod over a larger area (Gradinger and Bluhm 2004; Marz 2010; Meier et al. 2014). There is however evidence that earlier breakup of sea ice will increase recruitment success of juvenile cod due to longer growing seasons (LeBlanc et al. 2019). Arctic cod are unlikely to be replaced by southern species in Tuvaijuittuq, and the persistence of sea ice in the region can offer refuge for cod populations.

Within Tuvaijuittuq, Arctic char have been observed off the northern tip of Ellesmere Island and in Nansen Sound and Greely Fiord (Coad and Reist 2004, 2018). While no significant rivers are present in Tuvuijuittuq, numerous lakes along this coastline that interact with the sea to varying extents, including many that drain to the sea (such as the Taconite Inlet lakes; Ludlam 1996; Ward Hunt Lake, Bégin et al. 2020; Stuckberry Valley Lakes, Klanten et al. Under review), some that contain Arctic char that likely migrate between marine and freshwater habitats (Veillette et al. 2012). Moreover, anadromy is usually limited in populations in extreme latitudes, so the presence of large freshwater spawning sites for anadromous char is unlikely with fjords instead expected to act as an important habitat for char within Tuvaijuittuq (Stephenson and Hartwig 2010). While Arctic

char is the most commonly harvested fish species in Nunavut, an average of 198,611 fish were taken each year from 1996-2001 (Priest and Usher 2004), there are no commercial or subsistence fisheries within or near Tuvaijuittuq (Nunavut 2016). Existing exploratory licenses operating in Nunavut also do not include Tuvaijuittuq (Nunavut 2016).

Table 6. List of fish taxa from marine waters within Tuvaijuittuq and adjacent areas of MYI.

Family & Common Name	Species	Within Tuvaijuittuq? (Y/N)	Location(s)[1]	Source(s)
Rajidae				
Darkbelly skate	*Amblyraja hyperborea*	N	QEI	Coad and Reist 2018
Salmonidae				
Arctic char	*Salvelinus alpinus*	Y	AF, North of EI, GF, NSo, NSt, QEI	Ratynski and de March 1988; Coad and Reist 2004, 2018
Gadidae				
Arctic cod	*Boreogadus saida*	Y	AF, CB, North of EI, GF, NSo, NSt, QEI	Ratynski and de March 1988; Coad and Reist 2004, 2018; Mecklenburg et al. 2011
Polar cod	*Arctogadus glacialis*	Y	AF, North of EI, GF, LS, QEI	Ratynski and de March 1988; Ouellet 1990; Coad and Reist 2004, 2018
Gasterosteidae				
Three-spine stickleback	*Gasterosteus aculeatus*	N	QEI	Coad and Reist 2004, 2018
Cottidae				
Arctic staghorn sculpin	*Gymnocanthus tricuspis*	Y	KB, NSo, QEI	Ratynski and de March 1988; Coad and Reist 2004, 2018
Twohorn sculpin	*Icelus bicornis*	Y	AF, North of EI, KB, NSo, NSt, QEI	McAllister et al. 1981; Coad and Reist 2004, 2018
Spatulate sculpin	*Icelus spatula*	Y	NSo, QEI	Coad and Reist 2004, 2018
Fourhorn sculpin	*Myoxocephalus quadricornis*	Y	AF, CB, North of EI, NSt, QEI	Ratynski and de March 1988; Coad and Reist 2004, 2018
Shorthorn sculpin	*Myoxocephalus scorpius*	Y	AF, AHI, North of EI, ERI, GF, NSo, QEI	Ratynski and de March 1988; Coad and Reist 2004, 2018; Mecklenburg et al. 2011
Bigeye sculpin	*Triglops nybelini*	Y	NSo, QEI	Coad and Reist 2004, 2018
Ribbed sculpin	*Triglops pingelii*	Y	KB, NSo, QEI	Coad and Reist 2004, 2018
Agonidae				
Arctic alligatorfish	*Aspidophoroides olrikii*	N	QEI	Coad and Reist 2018
Psychrolutidae				
Polar sculpin	*Cottunculus microps*	N	QEI	Coad and Reist 2018
Cyclopteridae				
Leatherfin lumpsucker	*Eumicrotremus derjugini*	N	KB, QEI	Coad and Reist 2004, 2018
Spiny lumpsucker	*Eumicrotremus spinosus*	N	KB, QEI	Coad and Reist 2004, 2018

Family & Common Name	Species	Within Tuvaijuittuq? (Y/N)	Location(s)[1]	Source(s)
Liparidae				
Sea tadpole	*Careproctus reinhardti*	N	QEI	Coad and Reist 2018
Gelatinous snailfish	*Liparis fabricii*	Y	AF, North of EI, KB, NSt, QEI	Coad and Reist 2004, 2018
Variegated snailfish	*Liparis gibbus*	N	QEI	Coad and Reist 2018
Kelp snailfish	*Liparis tunicatus*	Y	KB, North of EI, QEI	Coad and Reist 2004, 2018
Black seasnail	*Paraliparis bathybius*	Y	North of EI, QEI	Mecklenburg et al. 2011
Threadfin snailfish	*Rhodichthyes regina*	N	QEI	Coad and Reist 2018
Zoarcidae				
Aurora pout	*Gymnelus retrodorsalis*	Y	NSo, QEI	McAllister et al. 1981; Coad and Reist 2004, 2018
Fish doctor	*Gymnelus viridis*	Y	KB, LS, NSo, QEI	Coad and Reist 2004, 2018
Doubleline eelpout	*Lycodes eudipleurostictus*	N	QEI	Coad and Reist 2018
Glacial eelpout	*Lycodes frigidus*	N	CB	Coad and Reist 2004, 2018
White Sea eelpout	*Lycodes marisalbi*	N	QEI	Coad and Reist 2004, 2018
Saddled eelpout	*Lycodes mucosus*	Y	KB, NSo, QEI	Coad and Reist 2004, 2018
Pale eelpout	*Lycodes pallidus*	N	QEI	Coad and Reist 2018
Polar eelpout	*Lycodes polaris*	N	QEI	Coad and Reist 2004, 2018
Arctic eelpout	*Lycodes reticulatus*	Y	North of EI, QEI	Coad and Reist 2018
Stichaeidae				
Slender eelblenny	*Lumpenus fabricii*	N	CB, QEI	Coad and Reist 2004, 2018
Pholidae				
Banded gunnel	*Pholis fasciata*	N	QEI	Coad and Reist 2018
Anarhichadidae				
Northern wolffish	*Anarhichas denticulatus*	N	QEI	Coad and Reist 2018
Pleuronectidae				
Greenland halibut	*Reinhardtius hippoglossoides*	Y	North of EI, QEI	Coad and Reist 2004, 2018
Somniosidae				
Greenland shark	*Somniosus microcephalus*	Y	North of EI, QEI	Kyne et al. 2006

[1] AF = Archer Fiord, AHI = Axel Heiberg Island, CB = Canada Basin, EI = Ellesmere Island, ERI = Ellef Ringnes Island, GF = Greely Fiord, KB = Kane Basin, LS = Lincoln Sea, NSo = Nansen Sound, NSt = Nares Strait, QEI = Queen Elizabeth Islands

MARINE MAMMALS

Bearded Seal (*Erignathus barbatus*)

Bearded seals are circumpolar and occur at low densities throughout their range (Bengtson et al. 2005). There have been no recent population surveys of bearded seals, however Cleator (1996) estimated 190,000 individuals in Canadian waters. Bearded seals are strongly associated with sea ice at all life history stages and are primarily benthivores

(Cameron et al. 2010; Kovacs 2016). Bearded seals give birth on small, FYI floes in free-floating pack or at the white edges of land-fast, and are always within 1 m of the water while birthing, rearing pups, moulting, and resting (Kovacs et al. 1996; 2011). As such, they are found in areas with moderate or low ice cover (floes or rotten ice) and high benthic productivity (Smith 1981; Kingsley et al. 1985). Bearded seals are considered data deficient by the Committee of the Status of Endangered Wildlife in Canada (COSEWIC) (COSEWIC 2007) and Least Concern by the IUCN (Kovacs 2016).

Detailed studies focused on bearded seal habitat use, distribution and population size within Tuvaijuittuq and surrounding areas have not been conducted. Although their distributional range includes Tuvaijuittuq (Figure 18; Stephenson and Hartwig 2010; Kovacs 2016; Lomac-MacNair et al. 2018), the total number of bearded seals inhabiting the area is unknown. The dense, thick MYI found throughout most of Tuvaijuittuq likely limits their local distribution and abundance. Two bearded seals have been observed in Archer Fiord during aerial surveys conducted in recent years. A few individuals have also been observed in the region during ship-based surveys in 2015 (Lomac-MacNair et al. 2018; Yurkowski et al. 2019).

Figure 18. Distribution of bearded seals in the Canadian Arctic. Adapted from Stephenson and Hartwig (2010).

Ringed Seal (*Pusa hispida*)

Ringed seals are circumpolar and their distributions are closely linked to sea ice (Figure 19; Smith et al. 1979; Frost and Lowry 1981; Kingsley et al. 1985; Stephenson and Hartwig 2010; Lowry 2016b). Existing estimates suggest that there are approximately three million ringed seals around the world (Reeves 1998; Lowry 2016b).They are one of the few marine mammals that regularly occupy extensive land-fast ice (Tynan and DeMaster 1997; Laidre et al. 2008). Research conducted in Baffin Bay suggests that this species inhabits coastal fast ice habitat and offshore pack ice at similar densities, but the majority of animals in offshore habitat were smaller and likely sub-adults unable to secure high quality habitat (Finley et al. 1983; Stephenson and Hartwig 2010). Ringed seal diets consist of many ice associated species such as Arctic cod and marine invertebrates (mysids,*O. glacialis*, *A. glacialis* and G. *wilkitzkii* , copepods and shrimp) (Bradstreet and Cross 1982; Smith and Harwood 2001; Yurkowski et al. 2016). The status of ringed seals was listed as Least Concern by IUCN in 2016 due to large population size and broad distribution; however, loss of sea ice habitat due to climate change is expected to negatively impact this species in the southern parts of its range (Lowry 2016b). The latest assessment by the COSEWIC in 2019 increased ringed seals designation to Special Concern under the Species At Risk Act (SARA).
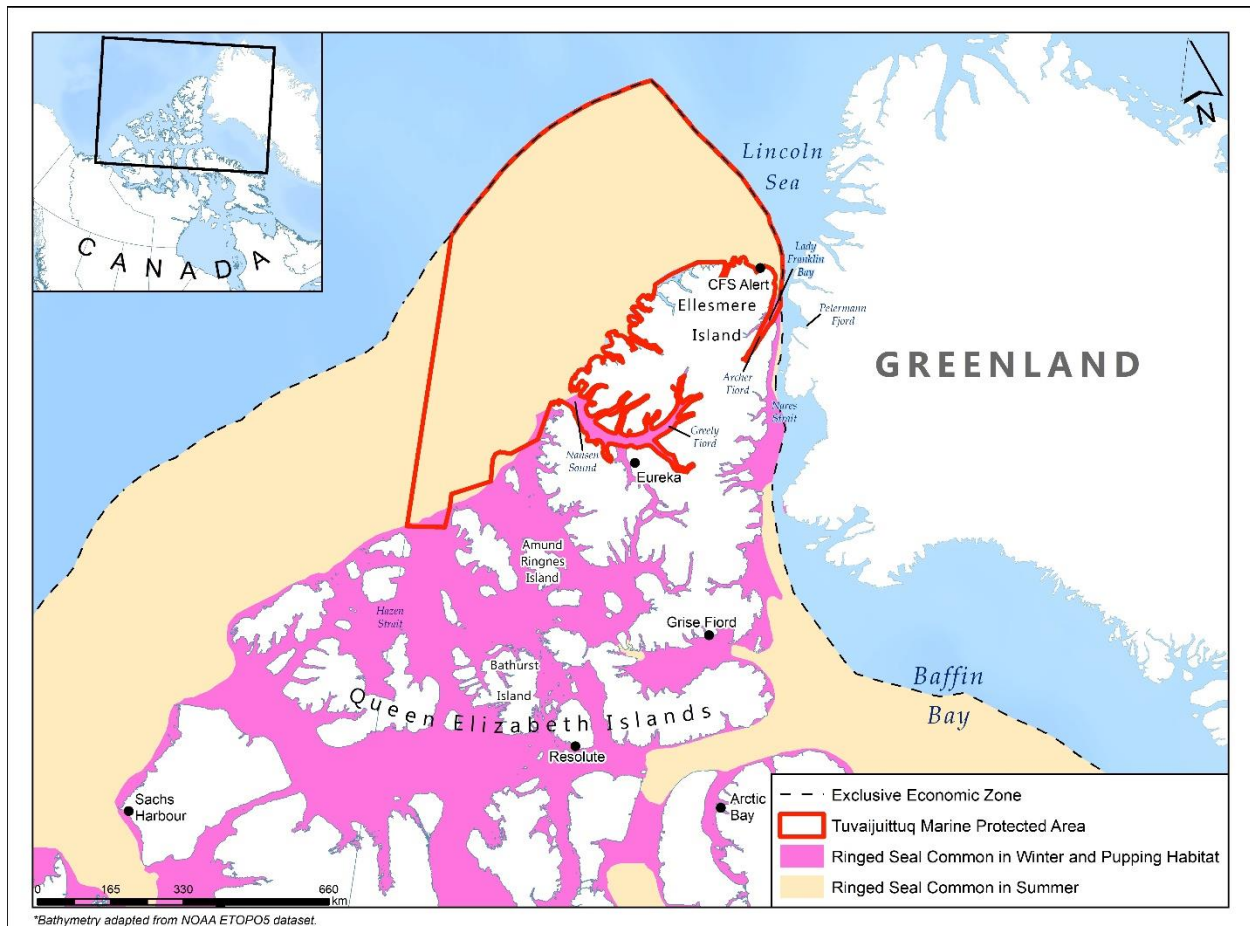

Figure 19. Distribution of ringed seals in the Canadian Arctic. Adapted from Stephenson and Hartwig (2010).

The number of ringed seals in Tuvaijuittuq is unknown, and only a small percentage of the total fast ice area in Tuvaijuittuq meets the criteria for preferred ringed seal habitat (i.e., first-year pressure ridges), which potentially limits their distribution and abundance within the area (Furgal et al. 1996). Within Tuvaijuittuq, winter and pupping habitat occurs in the Nansen Sound and Greely Fiord areas to the west, as well as on nearshore shelf habitat off northern QEI (Figure 19; Stephenson and Hartwig 2010). In the east, Archer Fiord is also considered winter and pupping habitat. Summer habitat includes much of the Canada Basin portion of the Tuvaijuittuq and, based on the results of a recent ship-based survey, extends into northern Nares Strait at the entrance to Archer Fiord and, in particular, Petermann Fiord on the Greenland side (Lomac-MacNair et al. 2018). In August 2018, Yurkowski et al. (2019) conducted the first-ever aerial survey for marine mammals in the Lincoln Sea, Nares Strait and Lady Franklin Bay. In August 2019, 34 ringed seals sightings were recorded in Archer Fiord during aerial survey (D. Yurkowski, pers. comm.). A reduced extent of sea ice in portions in the Canadian Arctic Archipelago, as well as potential increases in FYI within Tuvaijuittuq, may result in higher ringed seal densities in the area.

Narwhal (*Monodon monoceros*)

Narwhals in the Canadian High Arctic are part of the Baffin Bay population (Figure 20; Petersen et al. 2011; DFO 2015). The most recent population estimate for the Canadian stocks of Baffin Bay narwhals, based on a robust data set and analyses, is 141,909 (Doniol-Valcroze et al. 2015). This population shows high fidelity for four main summering areas: East Baffin Island, Eclipse Sound, Admiralty Inlet and Somerset Island (Heide-Jørgensen et al. 2003; Richard 2010; Heide-Jørgensen et al. 2013; DFO 2015). These narwhals winter in Baffin Bay and Davis Strait (DFO 2011a, 2014, 2015) but current evidence suggests the narwhals using these different summering areas represent four distinct stocks (de March and Stern 2003; Heide-Jørgensen et al. 2003; Dietz et al. 2008; Richard 2010; Petersen et al. 2011; Heide-Jørgensen et al. 2013). Additional narwhal from the Baffin Bay population migrate to Jones Sound, Smith Sound and Parry Sound in summer (DFO 2015). These groups potentially represent additional Canadian stocks, but they are not yet officially recognized.

Narwhal habitat preferences are deep, steep-sided inlets with partial ice cover in summer, presumably to provide protection from killer whales (Kingsley et al. 1994; Petersen et al. 2011; Breed et al. 2017) and broken pack ice or leads along the fast ice edge of continental shelves (Koski and Davis 1994; Heide-Jørgensen et al. 2002; COSEWIC 2004b; Dietz et al. 2008; Stephenson and Hartwig 2010). Narwhal diets are variable, but typically include Arctic cod, polar cod, decapods, squid and Greenland halibut (Hay 1984; Watt et al. 2017). Cod is more prevalent in the diet during spring, when narwhals are found at the ice edge, while demersal fish are more common during the winter (Watt et al. 2017).

The global narwhal population was listed as Least Concern by the IUCN (Lowry et al. 2017). In Canada, the Baffin Bay stock was designated as Special Concern by the COSEWIC (COSEWIC 2004a), and Traditional Knowledge (TK) suggests that the population is stable (Furgal and Laing 2012). The current annual total allowable landed

catch for Baffin Bay narwhals is 1,540 (Doniol-Valcroze et al. 2015) and none are currently harvested in Tuvaijuittuq or adjacent areas of MYI.

Figure 20. Distribution of narwhals in the Canadian Arctic. Adapted from Doniol-Valcroze et al. (2015).

While the known use of habitat by narwhals in Tuvaijuittuq is limited to two bays in the southern extremity of Archer Fiord, they are present in Eureka Sound and Kennedy Channel (Lowry et al. 2017). Moreover, narwhals that summer in Smith Sound are in close proximity to the site of the ice arch that forms in Smith Sound in most winters (DFO 2015; Ryan and Münchow 2017). While there have been occasional narwhal sightings within the QEI, there is no evidence that narwhal use habitat within Tuvaijuittuq and adjacent areas. An analysis conducted by Higdon (2017) indicated that there are no critical calving or nursing areas, no important foraging habitat, migration routes, or overwintering habitat for narwhal within the High Arctic areas of MYI in Canada. However, sightings of a pod of narwhals including a yearling in Archer Fiord during aerial surveys conducted in 2019 (C. Carlyle, DFO, pers. comm.) may suggest otherwise. A total of 29 narwhals were observed in Archer Fiord in August 2019.

A sensitivity index created by Laidre et al. (2008) identified narwhal as the most sensitive Arctic marine mammal to climate change due to high site fidelity, low growth rates, globally limited range and population size (i.e., eastern Canadian Arctic and Greenland), migration requirements, and low diet diversity. The potential effects of climate change on

narwhals and their relationship with Tuvaijuittuq are unknown but evidence suggests that narwhals could be adaptable to changing Arctic food webs and that they may take advantage of changes to the thick ice cover (Watt et al. 2013; 2015).

Walrus (*Odobenus rosmarus*)

Walrus have low abundances and discontinuous distributions in the Canadian High Arctic (Figure 21; Stephenson and Hartwig 2010; COSEWIC 2017). Three management stocks (Penny Strait-Lancaster Sound, West Jones Sound and Baffin Bay) form a distinct genetic cluster called the Canadian High Arctic-Northwest Greenland population with an estimated population size of 2,480 walrus (Born et al. 1995; Andersen and Born 2000; de March et al. 2002; Shafer et al. 2014; Stewart et al. 2014a; 2014b; Shafer et al. 2015; Higdon and Stewart 2016). Walruses require productive benthic communities with abundant bivalves, reliable open water and haul out sites (preferably on ice) near the open water (Lowry 2016a). Terrestrial haul out sites become critically important to walruses during summer and early fall periods of sea ice minima (Higdon 2016; DFO 2019a). This species is particularly sensitive to disturbance at these locations and has been known to abandon them for less favourable locations (DFO 2019a). Atlantic walrus is listed as Vulnerable by the IUCN (Lowry 2016a) due to predicted substantial changes to their sea ice habitat. The High Arctic population was designated Special Concern by the COSEWIC in 2017 (COSEWIC 2017).

The known distribution ranges of these three stocks do not extend into Tuvaijuittuq. The lack of reliable open water in highly productive benthos would limit walrus distribution within Tuvaijuittuq. There are only two areas within in Tuvaijuittuq that are not ice-covered year-round: Nansen Sound/Greely Fiord, along the west coast of Ellesmere Island, and Nares Strait along the northwestern shoreline of Ellesmere Island (CIS 2018). Walrus have not been observed in Nansen Sound or Greely Fiord, but a total of 36 walrus sightings were recorded in Archer Fiord off Nares Strait during the 2019 photographic and visual aerial marine mammal surveys. In 2018, , a single adult walrus was detected through photography on an ice floe at the head of Archer Fiord, and an additional seven were observed slightly farther west within Archer Fiord on an ice floe (Yurkowski et al. 2019). These sightings confirm the presence of Atlantic walruses in Canadian waters much further north than their documented distribution range. These walruses are likely from either the west Jones Sound or Baffin Bay stocks of the High Arctic population, as the high sea ice concentrations north of Greenland and sheer distance (ca. 930 km) likely prevents movements between the East Greenland stock and Tuvaijuittuq. The new observations of Atlantic walruses in Archer Fiord cannot be unambiguously attributed to range extension as it could also reflect the lack of knowledge with respect to the distribution and habitat use of Tuvaijuittuq by walruses and other marine mammals.

Although walrus have occasionally been observed within the MYI of the QEI (on the north coast of Melville Island and southeast coast of Prince Patrick Island), they were considered to be outside their normal range (Harington 1966). Walruses southwest of Tuvaijuittuq are most likely from the Penny Strait-Lancaster Sound stock (Harington 1966; Stephenson and Hartwig 2010; Stewart et al. 2014a; 2014b; Higdon and Stewart 2016; Lowry 2016a). Traditional hunting for walrus occurs in Jones Sound and Lancaster Sound/Austin Channel.

Figure 21. Known distribution of walrus in the Canadian Arctic. Adapted from Stephenson and Hartwig (2010).

Polar Bear (*Ursus maritimus*)

Polar bears are circumpolar in 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 subpopulations recognized by the IUCN Polar Bear Specialist Group (PBSG) and 14 of those occur fully or partially within Canada (Obbard et al. 2010; Wiig et al. 2015; COSEWIC 2018). Open water, land and MYI represent barriers to gene flow for polar bears because all three are unsuitable habitats for their main prey, the ringed seals (Paetkau et al. 1999; Taylor et al. 2001; Malenfant et al. 2016). As a result, interactions between subpopulations appear to be limited (Paetkau et al. 1995). Only the Arctic Basin subpopulation overlaps with Tuvaijuittuq. Population densities have not been measured, but are likely very low (Obbard et al. 2010; COSEWIC 2018). Paetkau et al. (1999) suggested that approximately 200 bears occur in the Arctic Basin. This subpopulation remains poorly understood because insufficient data were collected from the sparsely populated Arctic Basin to allow for genetic comparison (Malenfant et al. 2016).

Ringed seals, particularly pups and young seals, are among the most important prey items for high central and eastern Arctic polar bears (Smith 1980). While some regional

or subpopulation variations in diet have been identified (Thiemann et al. 2008; Galicia et al. 2015), dietary studies have not been conducted for the Arctic Basin subpopulation. It is assumed that ringed seals, where present, remain an important prey item. Bears will opportunistically feed on other prey types, particularly when they are forced ashore during the fall (Lunn and Stirling 1985; Stempniewicz 2006; Dyck and Romberg 2007), and fatty acid biomarkers have revealed beluga whales, bearded seals, walrus and narwhal are also potential prey items (Thiemann et al. 2008; Galicia et al. 2015). Opportunities for these alternate prey types may be scarce within Tuvaijuittuq.

During spring and summer, bears are highly dependent on land-fast FYI in shelf and coastal island waters or on moving ice floes where seal pupping is most likely to occur (Stirling et al. 1999; Ferguson et al. 2000; Schliebe et al. 2006). Continuous access to such habitats enable polar bears to hunt throughout the year. Ice concentrations less than 50% will typically send bears ashore, likely due to increasing energetic costs of ice use due to greater travel/swim distances (Stirling et al. 1999; Derocher et al. 2004). On land, they subsist primarily on stored fat reserves until freeze-up (Obbard et al. 2010). Evidence suggests that while some polar bears use MYI in the Arctic Basin, they occur at low densities (Obbard et al. 2010).

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) and the *Convention on the Conservation of Migratory Species of Wild Animals* (CMS 2017). The IUCN listed polar bears as Vulnerable (Wiig et al. 2015) due to a predicted population decline of more than 30% (probability of 0.71) over the next 45 years as their area of occupancy, extent of occurrence, and habitat quality decrease with climate change (Schliebe et al. 2008; Wiig et al. 2015). Polar bears are also listed as Special Concern by the COSEWIC (COSEWIC 2018). Polar bears are among the most sensitive Arctic marine mammals to climate change (Derocher et al. 2004; Laidre et al. 2008; Atwood et al. 2016). In addition to being highly specialized Arctic predators, polar bears have low reproductive rates and long generations, making facultative adaptation to the rapid changes in sea ice habitat unlikely. If current trends continue, extirpation across much of their range appears likely within 100 years (Schliebe et al. 2008; Wiig et al. 2015).

The range for the Arctic Basin subpopulation includes, but is not limited to, the entirety of Tuvaijuittuq: the northern coasts of Ellesmere, Axel Heiberg, Meighen and Ellef Ringnes islands and the adjacent Canada Basin, as well as the Lincoln Sea and the northwestern shoreline of Nares Strait south to Archer Fiord. The Arctic Basin is believed to support both resident bears that remain within its boundaries (i.e., do not utilize regions outside of the Arctic Basin) and bears from other subpopulations that use it for summer feeding (Obbard et al. 2010; AMAP et al. 2013; COSEWIC 2018). Five subpopulations have ranges that include portions of the MYI adjacent to Tuvaijuittuq (Figure 22): Northern Beaufort Sea; Viscount Melville; Lancaster Sound; and Norwegian Bay; Kane Basin. Jungblut et al. (2017) observed polar bear footprints on the surface of the Ward Hunt and Milne Ice Shelves.
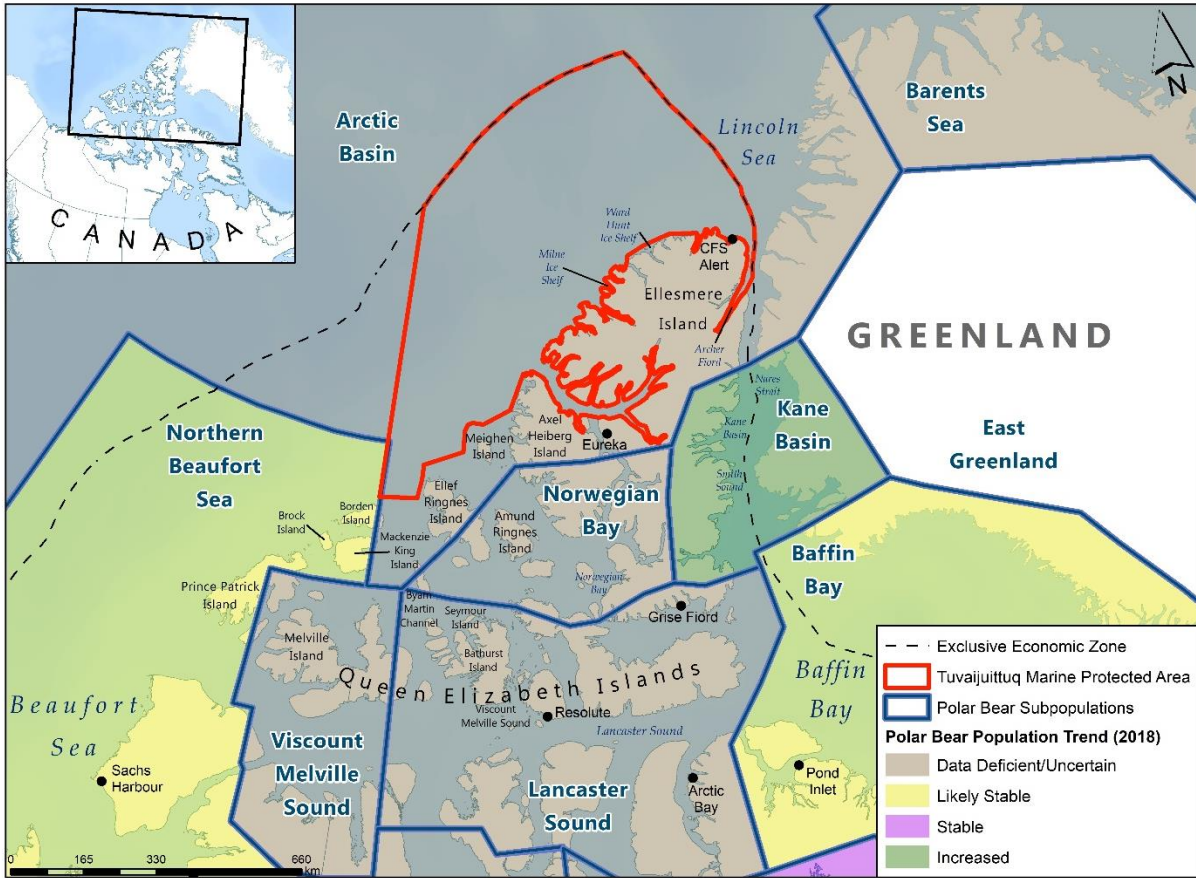
Figure 22. Distribution of the polar bear subpopulations in the Canadian Arctic. Adapted from ECCC (2018a).

Although studies directly involving Arctic Basin bears have not been conducted, modeling of the relationship between bears and habitat parameters such as latitude, available shelf habitat, prey diversity, sea ice extent, and length of ice-free season suggest that this subpopulation is one of the more vulnerable to climate change (Hamilton and Derocher 2019). However, with current and predicted Arctic sea ice changes, habitat within Tuvaijuittuq, the western half of the Canada Basin and the QEI may become more suitable for both polar bears and their prey. In addition, as Tuvaijuittuq (and northern Greenland) remain as the only Arctic area with persistent sea ice cover, it will likely become a refuge for polar bears, a species strongly adapted to sea ice (Vongraven et al. 2011; Atwood et al. 2016).

BIRDS

There is very little scientific knowledge on the distribution of birds and their habitat usage within Tuvaijuittuq. There are several observations of seabirds, shorebirds, and waterfowl in the region and some records of utilization of land surrounding Tuvaijuittuq for breeding and migration (Table 7; Gudmundsson et al. 2002; Lai et al. 2018; 2019). Birds have been observed in three main areas, i.e., offshore of Ellef Ringnes Island, on the Ellesmere Island ice shelves and in the vicinity of CFS Alert. Seabirds, including gulls (ivory gull (*Pagophila eburnea)*, sabine's gull (*Xema sabini*), glaucous gull (*Larus hyperboreus*),

thayer's gull (*Larus thayeri*)), long-tailed jaeger (*Stercorarius longicaudus*), Arctic tern (*Sterna paradisaea*) , northern fulmar (*Fulmarus glacialis*), black guillemot (*Cepphus grille*) and thick-billed murre (*Uria lomvia*), were observed flying over different areas of Tuvaijuittuq (Gudmundsson et al. 2002; Jungblut et al. 2017; Lai et al. 2018; 2019). The presence of gulls (species unknown) was noted in Archer Fiord during a marine mammal aerial survey in August 2018 (Yurkowski et al. 2019). Some seabirds, i.e., glaucous and thayer's gulls, Arctic tern and long-tailed jaeger, are also known to breed on northern Ellesmere Island, nearby CFS Alert (Lai et al. 2018; 2019). Long-tailed jaegers of northern Ellesmere Island are hardly feeding on marine environment when nesting, as they shift from a marine diet during winter, to a more generalist diet, with a preference for lemmings when nesting in the Arctic (Julien et al. 2014). There are currently no known major seabird colonies within Tuvaijuittuq.

Table 7. List of bird taxa that use marine or nearshore habitat within the QEI and Canada Basin.

Common Name	Latin Name	Within Tuvaijuittuq? (Y/N)	Location(s)[1]	Source(s)
Anatidae				
Snow goose	*Anser caerulescens*	Y	AHI, BI, North of EI, MI	Maltby 1978; Godfrey 1986; Lai et al. 2018; 2019
Greater white-fronted goose	*Anser albifrons*	N	MI	Maltby 1978
Brant goose	*Branta bernicla*	Y	AHI, BI, North of EI, MI	Maltby 1978; McLaren and Alliston 1985; Godfrey 1986; Lai et al. 2018; 2019
Canada goose	*Branta canadensis*	N	MI	Maltby 1978
Long-tailed duck	*Clangula hyemalis*	Y	AHI, BI, North of EI, MI	Godfrey 1986; Maltby 1978; Lai et al. 2018, 2019
White-winged scoter	*Melanitta fusca*	N	MI	Maltby 1978
Common eider	*Somateria mollissima*	N	DI, MI	Maltby 1978; McLaren and Alliston 1985; Godfrey 1986
King eider	*Somateria spectabilis*	Y	AHI, BI, MI, North of EI	Maltby 1978; McLaren and Alliston 1985; Godfrey 1986; Lai et al. 2018, 2019
Gaviidae				
Red-throated loon	*Gavia stellata*	Y	AHI, BI, North of EI, MI, PPI	Maltby 1978; Godfrey 1986; Lai et al. 2018, 2019
Charadriidae				
Common ringed plover	*Charadrius hiaticula*	Y	North of EI	Lai et al. 2018, 2019
Lesser golden plover	*Pluvialis dominica*	N	BI, MI	Maltby 1978; Godfrey 1986
Black-bellied plover	*Pluvialis squatarola*	Y	BI, DI, North of EI, MI, RI	Maltby 1978; Godfrey 1986; Gudmundsson et al. 2002; Lai et al. 2018
Scolopacidae				
Ruddy turnstone	*Arenaria interpres*	Y	AHI, BI, DI, North of EI, MI	Maltby 1978; Godfrey 1986; Lai et al. 2018, 2019
Sanderling	*Calidris alba*	Y	AHI, BI, DI, North of EI, MI, PPI	Maltby 1978; Parmelee and Payne 1973; Godfrey 1986; Lai et al. 2018, 2019

Common Name	Latin Name	Within Tuvaijuittuq? (Y/N)	Location(s) [1]	Source(s)
Baird's sandpiper	*Calidris bairdii*	Y	Widespread	Maltby 1978; Godfrey 1986; Gudmundsson et al. 2002; Lai et al. 2018, 2019
Red knot	*Calidris canutus*	Y	AHI, BI, North of EI, MI	Maltby 1978; Godfrey 1986; Lai et al. 2018, 2019
White-rumped sandpiper	*Calidris fuscicollis*	N	BI, DI, MI	Maltby 1978; Godfrey 1986
Purple sandpiper	*Calidris maritima*	N	BI, DI, MI	Maltby 1978
Pectoral sandpiper	*Calidris melanotus*	N	BI, MI	Maltby 1978
Least sandpiper	*Calidris minutilla*	N	MI	Maltby 1978
Red phalarope	*Phalaropus fulicarius*	Y	AHI, BI, DI, North of EI, MI, RI	Maltby 1978; Godfrey 1986; Gudmundsson et al. 2002; Lai et al. 2018, 2019
Buff-breasted sandpiper	*Tryngites subruficollis*	N	BI, MI	Maltby 1978; Godfrey 1986
Laridae				
Iceland gull	*Larus glaucoides*	N	BI, MI	Godfrey 1986
Glaucous gull	*Larus hyperboreus*	Y	AHI, BI, DI, North of EI, MI, NSt, RI	Maltby 1978; Godfrey 1986; Gudmundsson et al. 2002; Lai et al. 2018, 2019
Thayer's gull	*Larus thayeri*	Y	AHI, North of EI, MI	Maltby 1978; Godfrey 1986; Lai et al. 2018, 2019
Ivory gull	*Pagophila eburnea*	Y	BI, North of EI, EIIS, KB, PI, SI	Godfrey 1986; Thomas and MacDonald 1987; Gudmundsson et al. 2002; Jungblut et al. 2017; Lai et al. 2018
Ross's gull	*Rhodostethia rosea*	N	CI	AMAP et al. 2013
Arctic tern	*Sterna paradisaea*	Y	AHI, BI, DI, North of EI, MI, NSt, RI	Maltby 1978; Godfrey 1986; Gudmundsson et al. 2002; Lai et al. 2018, 2019
Sabine's gull	*Xema sabini*	Y	BI, DI, North of EI	Godfrey 1986; Lai et al. 2018, 2019
Procellariidae				
Northern fulmar	*Fulmarus glacialis*	Y	RI	Gudmundsson et al. 2002
Stercorariidae				
Long-tailed jaeger	*Stercorarius longicaudus*	Y	Widespread	Maltby 1978; Godfrey 1986; Lai et al. 2018, 2019
Parasitic jaeger	*Stercorarius parasiticus*	N	BI, DI, MI	Maltby 1978; Godfrey 1986
Pomarine jaeger	*Stercorarius pomarinus*	N	BI, DI, MI	Maltby 1978; Godfrey 1986
Alcidae				
Black guillemot	*Cepphus grylle*	Y	DI, RI	Godfrey 1986; Gudmundsson et al. 2002
Thick-billed murre	*Uria lomvia*	Y	RI	Gudmundsson et al. 2002

[1] AHI = Axel Heiberg Island, BI = Bathurst Island, CI = Cheyne Islands, DI = Devon Island, EI = Ellesmere Island, EIIS = Ellesmere Island Ice Shelves, MI = Melville Island, NSt = Nares Strait, PI = Perley Island, PPI = Prince Patrick Island, RI = Ringnes Islands (Ellef Ringnes Island and Amund Ringnes Island), SI = Seymour Island

Shorebirds species have also been observed in Tuvaijuittuq, including red knots (*Calidris canutus*), ruddy turnstone (*Arenaria interpres*), sanderling (*Calidris alba*), red phalarope (*Phalaropus fulicarius*), baird's sandpiper (*Calidris bairdii*) and plovers

(common ringed plover (*Charadrius hiaticula*), black-bellied plover (*Pluvialis squatarola*)) (Gudmundsson et al. 2002; Jungblut et al. 2017; Lai et al. 2018; 2019). Red knots, ruddy turnstones and sanderlings breed at the northern tip of Ellesmere Island, close to CFS Alert (Lai et al. 2018; 2019). Red knots and ruddy turnstones have a terrestrial diet during the breeding period in northern Ellesmere Island, so their utilization of marine resources inTuvaijuittuq might be limited during this period (Morrison and Hobson 2004). Red-throated loon (*Gavia stellate*), king eider (*Somateria spectabilis*), geese (brant goose (*Branta bernicla*) and snow goose (*Anser caerulescens*)) and long-tailed duck (*Clangula hyemalis*) are also bird species that can use the marine environment and that have been observed in Tuvaijuittuq (Gudmundsson et al. 2002; Jungblut et al. 2017; Lai et al. 2018; 2019). All of these species, except the long-tailed duck, breed and nest on northern Ellesmere Island (Lai et al. 2018; 2019).

Based on the current knowledge, bird diversity is thought to be higher in the QEI than in Tuvaijuittuq with additional species noted from islands bordering Lancaster Sound (Maltby 1978; Nettleship 1980; McLaren and Alliston 1985; Godfrey 1986; Circumpolar Seabird Working Group 1997; Mallory and Gilchrist 2003; Lanctot et al. 2010; Maftei et al. 2015). Gudmundsson et al. (2002) observed relatively few bird tracks close to Ellef Ringnes Island compared to sites farther south. Moreover, ross's gulls (*Rhodostethia rosea*) were not observed within the Tuvaijuittuq region, but their largest population nests on Cheyene Island, located in Penny Strait, southeast of Tuvaijuittuq (AMAP et al. 2013).

Trends associated with climate changes may affect bird distribution and use of habitat in the high Arctic. It is unknown if seabird colonies will migrate northwards, following potential changes in prey distribution or if they will adapt to possible dietary changes. Seabirds (fulmars and murres) eat predominantly Arctic cod and smaller proportions of zooplankton (e.g., *Themisto*), which are tightly associated with ice algal blooms. In the Canadian Arctic, important changes in seabird diet have been linked to the changing sea ice regime (Gaston and Elliott 2014). As the ice edge retreats further from bird colonies, a shift from a diet dominated by Arctic cod, an ice-associated species, to capelin (*Mallotus villosus),* a pelagic species, has been linked to reduced chick growth rates in thick-billed murres (Gaston and Elliott 2014).

In terms of conservation, the ivory gull, which have been observed in Tuvaijuittuq and nesting in adjacent regions, is listed as an Endangered species under Canada's Species at Risk Act and is is designated as Near Threatened by the International Union for the Conservation of Nature (COSEWIC 2006; Bird Life International 2018). In the 1980s, the population of ivory gulls in Canada was estimated at 2,400 adult birds (Thomas and MacDonald 1987). Recent surveys indicate that Canada's ivory gull population has now declined by 80 % (Gilchrist and Mallory 2005; Mallory et al. 2006; Latour et al. 2008). The cause of this decline is unknown, but elevated contaminant levels, particularly mercury, in birds and their eggs could negatively affect chick development (Braune et al. 2006; 2007; Mallory et al. 2015). This decline has also been attributed to the loss of sea ice and harvesting in Greenland during migration (Strøm et al. 2019). Ivory gulls are among the longest-lived marine bird species in Arctic, with a record age estimate of ca 28 years (Mallory et al. 2012).

Ivory gulls are generally observed during spring, along the ice edge, but have also been observed during summer near MYI (Mallory et al. 2003).Their breeding sites are remote,

mainly located on cliff of Devon, Seymour and eastern Ellesmere islands and on Brodeur Peninsula (Figure 23; Godfrey 1986; Thomas and MacDonald 1987; Mallory et al. 2003; Chardine et al. 2004). Ivory gulls have been observed close to Tuvaijuittuq, in Eureka Sound, Norwegian Bay and on reefs of Perley Island (northwest of Meighen Island), suggesting the presence of colonies in these areas (Thomas and MacDonald 1987; Chardine et al. 2004). Ivory gulls have also been observed within Tuvaijuittuq, flying over the Milne Ice Shelf and at CFS Alert at several occasions (Yannic et al. 2016; Jungblut et al. 2017; Lai et al. 2018). The extent of habitat use within Tuvaijuittuq is unknown, but Chardine et al. (2004) reported that ivory gulls in Jones Sound were observed at a maximum of 150 km away from a known breeding site, which suggest that an ivory gull colony could be present on land surrounding Tuvaijuittuq. The presence of MYI and the few sightings of ivory gulls in or adjacent to Tuvaijuittuq also suggest the possibility that the area may become more important for this Endangered species as the Arctic continues to warm.

Figure 23. Location of ivory gull breeding colonies occupied at least once since 2000 (black circles) and wintering areas (light blue). From Strøm et al. (2019).

KEY BIOPHYSICAL AND ECOLOGICAL FEATURES AND THEIR SIGNIFICANCE

Based on our limited knowledge of the region, the following key biophysical and ecological features of Tuvaijuittuq are identified:

1. Multi-year Ice

Tuvaijuittuq is a unique region of persistent MYI. Since the beginning of the satellite record in 1979, Arctic summer sea ice extent has declined more than 30% (Meier et al. 2014; Perovich et al. 2019). Old MYI (> 4 years), which represented 33% of the Arctic Ocean ice pack in March 1985, made up only 1.2% in March 2019. The remaining oldest and thickest ice is largely confined to the Tuvaijuittuq region (Tilling et al. 2018; Perovich et al. 2019).

Thick MYI accumulates in Tuvaijuittuq as a result of persistent wind and ocean currents that push the sea ice up against, and into, the QEI and northern Greenland (Howell et al. 2008; Moore et al. 2019). Tuvaijuittuq is also a source of MYI that is transported south into the QEI and into Baffin Bay via Nares Strait (Howell et al. 2008; Rasmussen et al. 2011). Southward transport of ice into the QEI occurs in summer but halts in autumn and winter as floating pack ice blocks the straits of the QEI connected to Tuvaijuittuq by forming arches (Melling 2002).

MYI is the dominating ice type in Tuvaijuittuq but FYI is also present, and it is dominant locally in Nansen Sound and the fiords of western Ellesmere Island (CIS 2016a, b). Heavy ridging, an important feature of MYI in Tuvaijuittuq, is acquired during many years at sea and is augmented locally through the action of high compressive and shearing forces. Older MYI, particularly the thick ridges and hummocks as found in Tuvaijuittuq, are known as key habitats for ice-dependent biota and also play multiple roles in Arctic ecosystems ranging from primary production to feedbacks to the climate system.

The multi-year sea ice ecosystem includes not only habitats on, within and immediately under the ice, but also the underlying water column which is connected to the sea ice through exchanges of dissolved (e.g. nutrients) and particulate materials (e.g. incorporation of organisms from the water into the ice and export from the ice), as well as properties such as heat or brine that further influence ocean dynamics. Modifications of ocean properties in the ice-covered ocean or in open leads further influence downstream ecosystems.

2. The Ellesmere Island Ice Shelves and associated fiords

Ellesmere Island, which is directly adjacent to Tuvaijuittuq, is the only location in Canada where ice shelves are found (Dowdeswell and Jeffries 2017; Mueller et al. 2017). These shelves are remnants of a larger, more contiguous shelf (8,900 km^2) that fringed the entire northern coast of Ellesmere Island from up to 5,500 years ago until the early 20th century (Vincent et al. 2001; England et al. 2008; Mueller et al. 2017). Since then, thinning ice and major calving events, usually coinciding with warmer than usual summers, have resulted in continual shelf decline (Braun 2017). From 1906 to 2015, the areal coverage of the Ellesmere ice shelves decreased from 8,597 to 535 km^2, resulting in 4 major and 9 minor ice shelves (Mueller et al. 2017). The largest existing remaining shelf is the Ward Hunt Ice Shelf (224 km^2) which, together with the McClintock Ice Shelf, is currently part

of Quttinirpaaq National Park (Parks Canada 2009; Mueller et al. 2017). The remaining ice shelves, to the west of McClintock Inlet, are all located in Tuvaijuittuq.

Ellesmere Island ice shelves provides habitat for microbial mats (Mueller et al. 2006; Jungblut et al. 2017) and are responsible for the formation of epishelf lakes that support planktonic assemblages (Veillette et al. 2011; Thaler et al. 2017). Moreover, animals were found within cavities inside the Milne Ice Shelf (WIRL 2020) suggesting that there will be other surprises ahead in exploring and mapping the biological richness of this ecosystem.

The landward side of Tuvaijuittuq is distinguished by a large number of bays, inlets and fiords. Several of the fiords and inlets contain or have recently contained the Ellesmere ice shelves and associated ecosystems. Despite their large collective expanse and diversity of forms and size, little is known about most of these coastal features, and even the most basic knowledge about their bathymetry is sparse or completely lacking. In the Milne fiord, the water column is heavily modified, with a sharp halocline present at 10 m which demarcates the bottom of the epishelf lake. Both terrestrial and marine processes are important within this fiord environment. The atmosphere has warmed substantially in the Tuvaijuittuq region over the last 50 years (White and Copland 2019) and will continue to do so, which will have profound implications on runoff to fiord ecosystems, whether they connect to ice shelves or not.

The fiords connect the land to the sea, and act as conduits for the transfer of snow and ice meltwaters from Ellesmere Island to the Arctic Ocean, along with organic carbon, nutrients and biota such as microbes and fish. There are also numerous lakes that interact with the sea to varying extent, some drain to the sea, some contain Arctic char, and several contain ancient seawater trapped within their basins.

3. Marine Mammal Habitat in Lady Franklin Bay/Archer Fiord

Ringed seals, bearded seals and polar bears are present in Tuvaijuittuq, however their abundance, distribution and habitat use are largely unknown (COSEWIC 2008; Stephenson and Hartwig 2010). The first systematic marine mammal aerial survey in Tuvaijuittuq, carried out in 2018 in the region north and northeast of Ellesmere Island, revealed the presence of walruses in Archer Fiord, much further north than their known distribution range (Yurkowski et al. 2019). These first sightings were confirmed in a subsequent survey, in 2019, which also showed the presence of narwhals including a yearling, in the same region (C. Carlyle, DFO, pers. comm.). Overall, 36 Atlantic walrus, 29 narwhal, 34 ringed seals and two bearded seals were observedindicating that Archer Fiord may be a location where marine mammals congregate, possibly due to enhanced productivity relative to surrounding areas. As Nares Strait opens up during summer sea ice break-up, the area becomes accessible to marine mammals who can travel from Pikialasorsuaq or between Greenland and Canadian waters.

4. Sea ice-associated Communities

Multi-year ice provides a unique, yet poorly studied, habitat for a number of ice-associated species ranging from ice-adapted microbes and amphipods to sea birds and polar bears. Older MYI, particularly the thick ridges and hummocks found in Tuvaijuittuq, are considered important habitat for ice-dependent biota such as key zooplankton species *Gammarus wilkitzkii* (Hop and Pavlova 2008; Gradinger et al. 2010). The thin snow cover

associated with hummocks would increase light transmittance compared to surrounding areas of higher snow cover, thereby offering suitable habitat for ice algal communities (Lange et al. 2017). Although MYI is typically considered less productive than FYI, ice cores collected from MYI hummocks in the Lincoln Sea were found to have significantly higher mean chlorophyll *a* biomass than thinner (i.e., non-hummocked) MYI and FYI (Lange et al. 2015; Lange et al. 2017). Ice algae are an essential component at the base of Arctic marine food webs, supporting zooplankton, benthic invertebrates, and under-ice fauna through processes such as ice-pelagic-benthic coupling, which is particularly important in areas of extensive annual ice-cover.

Invertebrates act as the link between primary producers and higher trophic levels, such as fishes, whales, seals, and birds, and transfer the energy through the Arctic marine food web. Arctic zooplankton uptake and store large quantities of lipids provided by ice algae and, later in the season, by phytoplankton. Ice algae provide lipids that are essential for the reproduction of key zooplankton species (Søreide et al. 2010; Brown and Belt 2012; Record et al. 2018). Ice associated invertebrates can be divided into two categories: species that are obligate ice users throughout their life cycle and therefore dependent on MYI (referred to as autochtonous), and species that facultatively use the sea ice and can thrive in seasonal ice environments (referred to as allochtonous, Gulliksen and Lønne 1991; Barber et al. 2015). For *Gammarus wilkitzkii*, an obligate ice user observed within Tuvaijuittuq (C. Michel, S. Duerksen, DFO, pers. comm.), MYI provide a higher quality habitat than FYI (Beuchel and Lønne 2002).

Arctic cod (*Boreogadus saida*) are ecologically important species, are highly dependent on sea ice (e.g. Welch et al. 1993; David et al. 2016; Kohlbach et al. 2017; Coad and Reist 2018). Arctic cod use the sea ice throughout their life cycle and their diet consist mainly of ice associated species (David et al. 2016; Kohlbach et al. 2017). Many species of fishes marine mammals, and sea birds feed on Arctic cod which represent a key link in energy transfers in Arctic marine food webs. The extensive loss of MYI in the Arctic Ocean is anticipated to have widespread and complex effects on Arctic cod populations but the persistence of sea ice in Tuvaijuittuq can offer refuge for cod populations.

To date, a variety of species of algae, bacteria, viruses and other microbes have been identified in Tuvaijuittuq as part of the Multidisciplinary Arctic Program (MAP) – Last Ice, contributing to the overall diversity of the Arctic marine ecosystem. Under-ice swarms of zooplankton and abundant and diverse benthos, observed for the first time in Tuvaijuittuq using a remotely operated underwater vehicle (S. Duerksen, DFO, pers. comm.), highlight the important connection between sea ice and the pelagic and benthic food webs.

THREATS TO KEY PHYSICAL AND BIOLOGICAL FEATURES

CLIMATE CHANGE

Climate change represents a significant threat to Tuvaijuittuq. Overall extent and thickness of Arctic sea ice, particularly during summer, have significantly declined over the past decades as MYI is replaced with thinner FYI in vast expenses of the Arctic Ocean (AMAP 2017; Perovich et al. 2019). During the past decades, the older ice has become less common (Perovich et al. 2019), so that by 2019, Arctic MYI > 3 years covered only 0.9 million square kilometers compared to 3.5 millions square kilometers in 1985. Most of

the oldest ice in the Arctic and a sizeable fraction of the remaining MYI now appears to be located in Tuvaijuittuq (Perovich et al. 2019). Recent important ice shelf calving events include the complete disappearance of the Ayles and Markham ice shelves in 2005 and 2008, respectively (Copland et al. 2007; Mueller et al. 2008; White et al. 2015a) and large losses from the Ward Hunt, Petersen, Serson and Milne ice shelves (White et al. 2015a; Copland et al. 2018; WIRL 2020). Most of the periods of extensive calving and break-up of ice shelves have coincided with warmer than usual summers in northern Ellesmere Island (White et al. 2015a; Braun 2017).

Changes to sea ice composition (e.g., MYI *versus* FYI), as well as spatial and seasonal extent affect all components of the ecosystem, including physical, chemical, and biological processes at various scales (e.g., AMAP 2017). The composition, location, timing and magnitude of ice algal and phytoplankton blooms (the foundation of Arctic marine ecosystems) are already impacted by climate and sea ice changes in the Arctic (e.g. Comeau et al. 2011; Leu et al. 2011; Ardyna et al. 2014). In turn, these changes have cascading effects on the diversity and abundance of higher trophic levels, the nature of energy transfer within the food web, carbon and elemental cycling, and overall ecosystem structure and function (e.g. Meier et al. 2014; Michel et al. 2015; Underwood et al. 2019). For example, a decrease in the abundance of the ice-associated zooplankton species *Gammarus wilkitzkii* (an important ice-associated species found in Tuvaijuittuq) in the Canada Basin has been linked to changes in sea ice conditions (Melnikov et al. 2002).

Baysian modeling shows the importance of Tuvaijuittuq as an ice-covered refugia for ice-associated species such as polar bears, as the climate continues to warm and sea ice cover declines in other regions (Atwood et al. 2016). These species are particularly sensitive to climate change and sea ice loss (e.g. Laidre et al. 2008).

Analysis of long-term temperature datasets from the Canadian Arctic identified relatively large and often significant increases in mean annual air temperature throughout the Arctic in recent decades, with Eureka experiencing one of the largest increases (Van Wijngaarden 2015). Climate model simulations suggest an increase in precipitation for the Tuvaijuittuq area by the end of the century (Šeparović et al. 2013). Increased rate of glacier melt on Ellesmere Island due to climate change is anticipated to augment the discharge of glacier melt freshwater and its constituents to the nearshore region of Tuvaijuittuq.

Additionally, atmospheric patterns influence the position of the front separating Pacific and Atlantic waters in the central Arctic Ocean, and consequently the signature of these water masses in Tuvaijuittuq. The response of these far-field ocean forcings to climate change and their influence on the marine ecosystem of Tuvaijuittuq is unknown.

VESSEL TRAFFIC/RESOURCE DEVELOPMENT

Potential resource development and associated vessel traffic in Tuvaijuittuq and adjacent areas of MYI are considered high-risk and high-cost activities due, in part, to its remoteness and the current dangers presented by operation in an area of thick MYI cover. As such, the overall potential for development in the area is limited (Gavrilchuk and Lesage 2014). Extraction of oil and gas deposits within the Sverdrup Basin of the QEI

(Adams 2014; Gavrilchuk and Lesage 2014), while unlikely until more of the MYI disappears, could result in direct and indirect negative effects to key features and biota. In addition, increase in trans-Arctic vessel traffic as shipping routes open up with the decline in sea ice, can be a stressor for the northern part of the MPA.

By the beginning of the 20th century, three expeditions had reached Tuvaijuittuq: the North Polar Expedition, the Nares Expedition and the Greely Expedition (Davis 1876; Greely 1886; Peary 1910). As MYI declines, interest in cruise ship tourism in Tuvaijuittuq may grow, but this type of activity is currently minimal due to accessibility issues and dangerous ice conditions. An analysis of vessel traffic by Maerospace Corp (2019) revealed that between 2012 and 2019, only one passenger vessel (the Kapitan Khlebnikov, in September 2016) entered Tuvaijuittuq at Greely Fiord through Eureka Sound. With the exception of this vessel, the only credible tracks identified in Tuvaijuittuq during this period were those of four ice breakers, three Canadian (CCGS Des Groseilliers, CCGS Henry Larsen and CCGS Amundsen) and one Swedish (Oden) (Amundsen Science 2019; Maerospace Corp 2019). The vessels were present only in two regions, Greely Fiord or Hall Basin and Robeson Channel.

Environmental concerns of commercial development and increased vessel traffic in the area include, but are not limited to, damage to habitat and disturbance/injury to biota as a result of noise, oil spills and release of other contaminants, ice breaking, movement underway (e.g., ship strikes), grounding/foundering, and discharge (e.g., bilge/grey water, garbage, ballast) (Adams 2014; DFO 2020).

FISHERIES AND SUBSISTENCE ACTIVITIES

Subsistence and commercial harvests are not currently conducted in Tuvaijuittuq due to its remoteness, dense MYI cover, high costs of harvesting, and hazardous travel conditions (Dawson et al. 2018; DFO 2019b; Maerospace Corp 2019). The nearest communities with natural resource harvesters, Grise Fiord and Resolute Bay, are over 600 km away from Tuvaijuittuq; however, the area represents one of cultural importance to these, and other communities within the Qikiqtani Region. The distribution and abundance of potential commercial species such as Arctic Char, Greenland Halibut and shrimp (*Pandalus borealis*) are largely unknown in the area, however, general oceanographic conditions in Tuvaijuittuq indicate the region may not be suitable habitat for these species. There is also a lack of knowledge on marine mammal distribution and use of habitat in Tuvaijuittuq, despite observations of ringed seals, bearded seals, polar bears, Atlantic walrus and narwhal in Archer Fiord in recent summers (Yurkowski et al. 2019; C. Carlyle, DFO, pers. comm.). However, for Atlantic walrus and narwhal it is unknown which populations and stocks they represent and the level of harvesting pressure they may experience during migrations to and from the MPA.

While interest in commercial fishing within Tuvaijuittuq may arise in the future, this activity is highly unlikely due to sea ice and oceanographic conditions. An assessment of the productive capacity of Tuvaijuittuq is the first step towards an evaluation of fisheries potential.

RANGE EXPANSIONS

Northward range expansions for marine sub-Arctic, Atlantic and Pacific zooplankton and fish species are highly unlikely in the Tuvaijuittuq ecosystem. There is accumulating evidence of poleward expansions of sub-arctic pelagic species, from phytoplankton to fish, in the Arctic gateways of the Pacific and European Arctic (Fossheim et al. 2015; Eriksen et al. 2017; Spies et al. 2020), largely attributed to advection (Oziel et al. 2020). Tuvaijuittuq is not directly connected to these gateways as it is located far downstream Atlantic or Pacific water influences, also acting a transit route of waters from the Beaufort Sea/Arctic Basin en route to their export through the narrow conduit of Nares Strait. Waters from Tuvaijuittuq are upstream of those from Baffin Bay, which means that Arctic waters from Tuvaijuittuq are transported into the North Water and further south to Baffin Bay whereas Atlantic waters of the west Greenland current do not reach Tuvaijuittuq. Therefore, Tuvaijuittuq is not exposed to the direct influence of range expansion via advection of sub-Arctic species, i.e. advection of planktonic species or larval stages of benthic and pelagic species. Northward range expansions in Tuvaijuittuq are anticipated for highly mobile species such as marine mammals and seabirds, including gulls and terns, that can migrate to Tuvaijuittuq, either opportunistically or based on learned/adaptive behaviour, as climate and sea ice conditions are changing. Increasing abundance and distribution of these species would impact food webs via top-down effects of predation as well as competition. For example, increased predation on potentially slow-growing benthic species in Tuvaijuittuq by accrued numbers of benthic feeders, e.g. walruses, could disproportionally impact benthic communities. Range expansions of fish species into the eastern region of Tuvaijuittuq is possible depending on ocean conditions.

LONG-RANGE POLLUTANTS

Like other areas of the Arctic, Tuvaijuittuq is considered a receiving environment for global pollutants, including persistent organic pollutants (POPs), mercury and microplastics. High trophic level species of interest for Tuvaijuittuq, such as polar bear and Ivory gull can accumulate high enough concentrations of POPs and mercury to put them at high risk of adverse reproductive and other health effects (AMAP 2018). Future monitoring and assessment of ecosystem and wildlife health for the area should consider the effects of global pollutants in combination with other current and anticipated stressors.

KNOWLEDGE GAPS

Tuvaijuittuq is one of, if not the single most data poor area of the Arctic Ocean and of the Canadian Arctic. As a result, broad knowledge gaps exist ranging from the sea ice, physical, chemical, and biochemical ocean processes, to all trophic levels within the food webs and their connections. The following are some of the more critical knowledge gaps that need addressing to improve our understanding of the region and its relative importance within the greater Arctic as potential refuge habitat for ice-dependent species as sea ice continues to decline.

- Multi-year and first-year ice concentration data based on RADARSAT synthetic aperture radar (SAR) imagery are available from the Canadian Ice Service Digital Archive, and two recent studies evaluate sea ice trends in parts of Tuvaijuittuq

(Howell and Brady 2019; Moore et al. 2019). However, there is an urgent need to characterize sea ice properties and dynamics in the region, particularly MYI thickness and trends which are necessary to improve baseline knowledge and help constrain future climate change predictions. This includes the formation and collapse of ice arches and the dynamics of the flaw lead polynya.

- Further study of the rapidly changing ice shelves (e.g. collapse of the Milne ice shelf in summer 2020), their unique biota, and their connectivity to the coastal ecosystem of Tuvaijuittuq is required in order to better understand the changing physical conditions of the shelf-ocean system and their influence on the diversity, distribution and abundance of biota. There are wide knowledge gaps on the oceanography and ecology of the Tuvaijuittuq fiords, including bathymetry.

- Overall, there are wide knowledge gaps for baseline knowledge on primary and secondary producers and their coupling, locally, regionally, and seasonally. Baseline information on the productivity, distribution, species composition, abundance, and ecosystem relationships for ice-associated and open water primary and secondary producers is required. The role of MYI as a habitat for ice-associated biological communities, their productivity and the connections with higher trophic levels is very poorly understood.

- Ice-pelagic-benthic coupling has been identified as an important carbon cycling and food web transfer mechanism in many Arctic ice-covered areas, but this essential information is lacking for Tuvaijuittuq. Similarly, there is no quantitative assessment of benthic communities that depend on this coupling, in Tuvaijuittuq.

- The exploratory ROV dives during MAP — Last Ice revealed a diversity of benthic organisms, including slow growing glass sponges. There is a complete knowledge gap regarding the diversity, abundance and distribution of benthic species in Tuvaijuittuq, as well as their connectivity with the sea ice and ocean productivity and their role in the diet marine mammals and birds.

- Fish communities have not been studied in Tuvaijuittuq. Arctic cod (*Boreogadus saida*) is an ice-associated species and an important link between lower and higher trophic levels in Arctic marine food webs. There is a complete knowledge gap for Arctic cod and other fish species in Tuvaijuittuq. There are no significant rivers in Tuvaijuittuq; it is therefore unlikely that this region would offer suitable habitat for important populations of anadromous Arctic char.

- Bird species distribution and habitat use for the bird species observed in Tuvaijuittuq is largely unknown, including for ivory gulls (*Pagophila eburnea*) and Ross's gulls (*Rhodosterhia rosea*), both classified as Endangered species (COSEWIC 2006).

- Marine mammal distribution and habitat use within Tuvaijuittuq is, at best, poorly known. Atlantic walruses and narwhal have only been observed in Archer Fiord within Tuvaijuittuq, along with ringed seals, bearded seals and polar bears also observed in the remainder of the region. However, marine mammal surveys conducted in Tuvaijuittuq are limited in space and time and the seasonal use of, and behaviour of marine mammal species in the region are largely unknown.

- Polar bears from the Arctic Basin subpopulation are considered data deficient throughout their range, including Tuvaijuittuq. Baseline data regarding polar bear use of Tuvaijuittuq and adjacent areas of multi-year ice is necessary in order to monitor changes in distribution and habitat use over time as Arctic sea ice continues to change.

- Our current knowledge of Tuvaijuittuq is based on sparse observations rather than dedicated ecosystem-based surveys and sustained ecosystem monitoring. The uniqueness and diversity of habitats within Tuvaijuittuq suggests potential high biodiversity, however, unique habitats or ecosystem types are not yet inventoried nor adequately characterized.

RECOMMENDED AREAS/FEATURES FOR PROTECTION

Fundamental to the protection/conservation of Tuvaijuittuq is the overarching persistence of the sea ice cover year-round while it is disappearing from the remainder of the Arctic. This makes Tuvaijuittuq a unique area where sea-ice associated species and food webs can continue to thrive whereas large expanses of the Arctic Ocean are becoming more similar to the Antarctic (Antarctification) and the Atlantic Oceans.

Based on the analysis of current ecological knowledge for the region and the Arctic Ocean, we identify three key/sensitive features that would inform boundaries or key areas for protection. The identification of these areas is not meant to preclude the identification of other key ecosystem components/features, as we develop a better knowledge base and understanding of species and ecosystem dynamics within Tuvaijuittuq.

1. Areas of MYI.

Tuvaijuittuq falls within a larger area of MYI in the Canadian Arctic that includes the western half of the Canada Basin and the channels, sounds and straits of the QEI (i.e., the Arctic Basin, Archipelago Multi-year Pack Ice, and Ellesmere Island Ice Shelves EBSAs) (DFO 2011b). MYI is an essential component of the Canadian High Arctic ecosystem, playing a vital role in regulating physico-chemical conditions in the Arctic Ocean (e.g., salinity, acidification) and the global climate (e.g. albedo effect), and providing critical habitat to ice-dependent and ice-associated species. The current protected area of MYI within Tuvaijuittuq, i.e., the northernmost boundary of the Canadian Archipelago, is essential to prevent habitat fragmentation associated with human activities. The area could be expanded to further MYI areas with the northern QEI. Considerations with respect to connectivity to the Arctic Ocean, differential forcings and sea ice dynamics, and evidence of different sea ice changes (Moore et al. 2019) all suggest that these regions will behave differently than the current region of Tuvaijuittuq in the future.

2. Ellesmere Island Ice Shelves and connected fiords.

The Ellesmere Island Ice Shelves are likely to vanish within a few decades at their current rate of attrition (Mueller et al. 2017; Copland et al. 2018), resulting in the extinction of their associated unique ecosystems (Vincent et al. 2001; Jungblut et al. 2017; Copland et al. 2018). While their disappearance due to climate change appears inevitable, long-term

protection in fiords and connected areas to the ocean would limit additional disruption due to human activities, while offering a unique opportunity to monitor and study the complete restructuring of ecosystems and the likely establishment of new species and food webs.

3. Archer Fiord, Lady Franklin Bay and adjacent marine habitat.

Seasonal variability in sea ice concentration in Archer Fiord and adjacent waters makes this portion of Tuvaijuittuq accessible to marine mammals, supported by the recent evidence of presence of narwhals and walruses in this region. Vessel access to the area is likely to increase as sea ice continues to decline in the eastern Arctic, potentially opening up the area to increased tourism and other human activities (ECCC 2019). Permanent protection for the portion of Archer Fiord that is not contained within Quttinirpaaq National Park is recommended.

RECOMMENDATIONS FOR PROTECTION OF ADDITIONAL ECOSYSTEM COMPONENTS

In addition to the protection of key features identified within Tuvaijuittuq identified above, the Nansen Sound/Greely Fiord region is also considered a key region for conservation. The fiord provides a pathway for the run-off of the Ellesmere Island ice caps to the coastal ecosystem of Tuvaijuittuq, and likely can be characterized by a suite of unique oceanographic and biogeophysical conditions resulting from these influences. This region is adjacent to two important features of Tuvaijuittuq that are recommended for protection (the multi-year pack ice and the ice shelves of Ellesmere Island), it is highly accessible compared to the rest of Tuvaijuittuq, and it has baseline climate data available from the neighbouring Environment and Climate Change Canada Station at Eureka. Potential nesting habitat for seabirds has been identified as an important feature of the region (C. Chambers, DFO, pers. comm.) as well as potential habitat used by Peary caribou (*Rangifer tarandus pearyi*), classified as an Endangered Species in Canada, during travel on sea ice (R. Eagleson, ECCC, pers. comm.).

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