Fisheries and Oceans Canada / Pêches et Océans Canada

Science / Sciences

C S A S

Canadian Science Advisory Secretariat

S C C S

Secrétariat canadien de consultation scientifique

Research Document 2010/066

Document de recherche 2010/066

Ecosystem status and trends report: Arctic Marine Ecozones

Rapport de l'état des écosystèmes et des tendances : écozones marines de l'Arctique

Andrea Niemi, Joclyn Paulic and Don Cobb

Fisheries and Oceans Canada / Pêches et Océans Canada
Central & Arctic Region / Région du Centre et de l'Arctique
501 University Crescent / 501, University Crescent
Winnipeg, MB
R3T 2N6

ISSN 1499-3848 (Printed / Imprimé)
ISSN 1919-5044 (Online / En ligne)

Canada

TABLE OF CONTENTS / TABLE DES MATIÈRES

FIGURES

TABLES

Correct citation for this publication:

Niemi, A., Paulic, J. Cobb and D. 2010. Ecosystem status and trends report: Arctic Marine Ecozones. DFO Can. Sci. Advis. Sec. Res. Doc. 2010/066. viii + 66 p.

ABSTRACT

This document is in support of the national Ecosystem Status and Trends Report (ESTR), prepared under the Biodiversity Outcomes Framework for the Canadian Councils of Resource Ministers (CCRM). The ESTR reports on the assessment of 25 Canadian Ecozones (15 terrestrial, 1 freshwater, and 9 marine) supporting the Convention on Biological Diversity's (CBD) 2010 biodiversity targets.

A compilation of the current information on the condition, trends, drivers and stressors are presented for the Beaufort Sea, Canadian Arctic Archipelago and Hudson and James Bay and Foxe Basin Ecozones. The three Arctic marine Ecozones represent a very extensive and diverse area from both a geographical and ecosystem perspective. Ecosystem trends are presented when available. However, there are few long-term trends available for the Arctic Marine Ecozones and in some situations baseline conditions are lacking. Climate change is a key ecosystem driver, having significant effects on sea ice and water column characteristics thereby altering marine habitat and seasonality. Climate together with industrial development, shipping, harvesting and contaminant stressors act cumulatively to impact marine ecosystem structure and function in these Ecozones. Continued research is needed to assess trends in the rate and direction of ecosystem responses to these cumulative stressors in the Arctic marine Ecozones.

RÉSUMÉ

Le présent document est présenté à l'appui du rapport national de l'état des écosystèmes et des tendances, rédigé en vertu du cadre axé sur les résultats en matière de biodiversité pour le Conseil canadien des ministres des ressources (CCME). Les rapports de l'état des écosystèmes et des tendances sur l'évaluation de 25 écozones du Canada (15 terrestres, 1 d'eau douce et 9 marines) appuient les cibles en matière de biodiversité de 2010 de la Convention sur la diversité biologique (CDB).

Une compilation de l'information actuelle sur l'état, les tendances, les facteurs et les agresseurs environnementaux est présentée pour les écozones de la mer de Beaufort, de l'archipel Arctique canadien, de la baie d'Hudson et de la baie James, et du bassin Foxe. Les trois écozones marines de l'Arctique représentent une zone très vaste et diversifiée du point de vue géographique et de l'écosystème. Les tendances de l'écosystème sont présentées lorsqu'elles sont disponibles. Cependant, peu de tendances à long terme sont disponibles pour les écozones marines de l'Arctique et, dans certains cas, les conditions de base sont inexistantes. Le changement climatique est un facteur clé de l'écosystème, ayant des effets importants sur la glace de mer et les caractéristiques de la colonne d'eau modifiant l'habitat marin et le cycle saisonnier. Le climat et les agresseurs environnementaux tels que le développement industriel, l'expédition, la récolte et les contaminants ont des effets cumulatifs sur la structure et la fonction de l'écosystème marin dans ces écozones. Des recherches continues sont nécessaires pour évaluer les tendances du taux et de la direction des réactions de l'écosystème à ces agresseurs cumulatifs dans les écozones marines de l'Arctique.

OVERVIEW OF ARCTIC ECOZONES

The Marine Arctic Ecozones are comprised of the Beaufort Sea Marine (BSME), Canadian Arctic Archipelago (CAA) and Hudson & James Bay and Foxe Basin (HJBFB) Ecozones (Figure 1). The Marine Arctic Ecozones cover an impressive and diverse area, from well below the Arctic Circle to the North Pole. When available, status and trends specific to these Ecozones are presented as will marine trends for the entire Arctic. The Marine Arctic Ecozones are closely linked to the terrestrial Arctic Ecozones chapter.

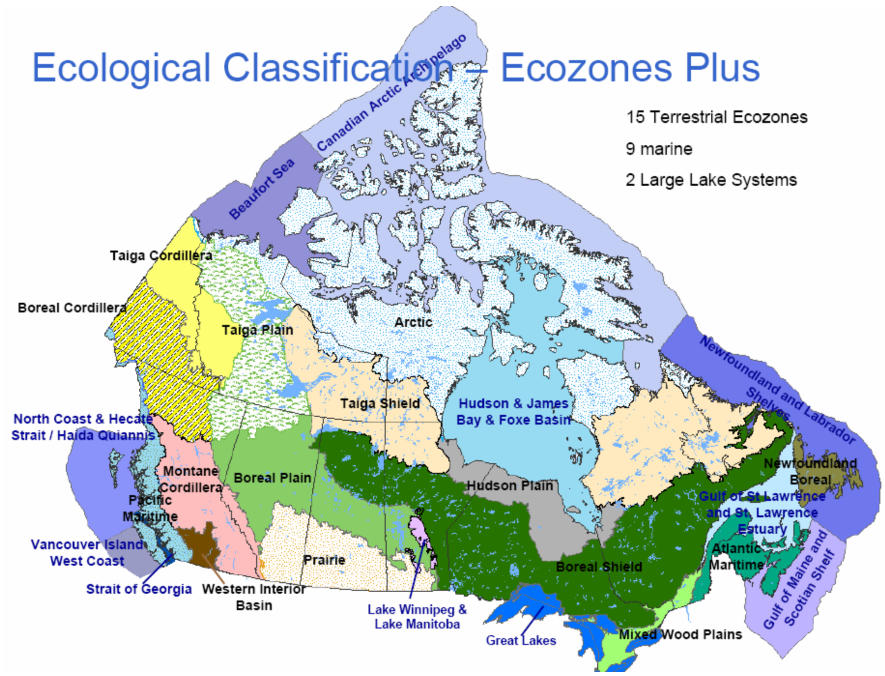


Figure 1: Marine Arctic Ecozones consisting of the Beaufort Sea, Canadian Arctic Archipelago and Hudson & James Bay & Foxe Basin Ecozone

DESCRIPTION OF THE ECOZONES

Beaufort Sea Marine Ecozone (BSME)

The BSME covers approximately 540 938 km^2 and includes four distinct geographical regions; the Beaufort Sea, Mackenzie Delta, Yukon North Slope and Arctic Islands. The Beaufort Sea region refers to marine offshore waters, whereas the Mackenzie Delta and Yukon North Slope refer to the coastal waters along the Canadian mainland. The Arctic Islands region includes the coastal waters of Banks Island and of western Victoria and Prince Patrick Islands.

The most significant geological feature within the BSME is the Beaufort Continental Shelf. The width of the shelf ranges between 10 and 200 km and the slope of the shelf can extend for up to 250 km (e.g., off the Tuktoyaktuk Peninsula). Important bathymetric features on the Beaufort Shelf include the Mackenzie and Kugmallit troughs, gas vents, mud volcanoes, ice scours and underwater pingos. The shelf is usually covered with land-fast and bottom-fast ice by November. A stamukhi zone forms at the 20 m depth contour where the convergence of drifting and landfast ice creates a division between nearshore and offshore dynamics. The Mackenzie River outflow is impounded nearshore of the stamukhi zone forming a freshwater “lake” that extends up to 12 000 km^2 (Macdonald *et al.* 1995). Offshore of the stamukhi zone lies open water of the flaw lead polynya.

Along the Yukon North Slope, the coastal bathymetry has a steep gradient creating a very narrow coastal zone. Amundsen Gulf and Prince of Wales Strait, at the eastern extent of the BSME, are relatively shallow channels (<200 m), while Viscount Melville Sound, north of Victoria Island, is connected to the Beaufort Sea by M'Clure Strait, which is 400 m deep. Sediments on the shelf consist predominantly of clay or silt, with relatively little gravel. The gravel deposits that do occur may originate from ice rafting, or from drowned beaches where erosion has removed the finer sediments (Carmack and Macdonald 2002). Sediments in the BSME are greatly influenced by the inflow of the Mackenzie River which transports approximately $130x10^6$ tonnes of inorganic sediments annually (Macdonald *et al.* 1998). The river also supplies 2.1 $x10^6$ and 1.3 $x10^6$ tonnes/y of particulate and dissolved terrestrial organic carbon, respectively. Approximately 50% of the sediments are trapped in the Mackenzie Delta, 40% remains on the shelf and the remaining 10% is transported off the shelf (Macdonald *et al.* 1998).

The Mackenzie River supplies ~330 km^3/y of freshwater, with peak discharge between mid-May and June. The freshwater input covers ~60 000 km^2 of the shelf area to depths >6 m (Macdonald *et al.* 1989), driving surface currents on the inner shelf. Overall, the surface currents are weak and wind-driven. Tidal amplitudes are generally <0.5 m with currents of <5 cm/s (Carmack and Macdonald 2002). Stratification and mixing of water masses are discussed in section 2.

<u>Canadian Arctic Archipelago Ecozone (CAA)</u>

The CAA is the largest Marine Ecozone in Arctic Canada. It encompasses an area of over $1.4x10^6$ km^2 and includes >36 000 islands and a myriad of passages, straits, sounds and bays. Water depths in the central archipelago are generally <100m, although depths up to 800 m occur in eastern Lancaster Sound. Shorelines are composed mainly of cobble, pebbles or exposed bedrock, with sand, silt or mud at greater depths (Thompson 1982). Ice scouring is an important feature of nearshore sediments in this and both of the other Marine Arctic Ecozones. This natural disturbance influences benthic invertebrate assemblages. Studies in Barrow Strait have followed recolonization trends with ice scours 8 to 9 years old being 65 to 84% recolonized, as compared to undisturbed sediments (Conlan and Kvitek 2005).

The CAA is a major pathway connecting the Pacific and Atlantic Oceans. The freshwater and heat exchange through the Archipelago has consequences for global climate patterns. Surface waters that flow through the CAA and into Baffin Bay follow one of three main pathways; 1) Lancaster Sound/Barrow Strait, 2) Jones Sound or 3) Nares Strait. During the summer, the highest flow occurs through Nares Strait (46%) (Kleim and Greenberg 2003). As surface waters move through the Archipelago they are biochemically altered by mixing and thermodynamic processes. Fluxes in volume, fresh water, and heat through the CAA show extensive seasonal and interannual variability (Prinsenberg and Hamilton 2005).

Currents in the CAA are strongly tidal (e.g., peak flow 50 cm/s in Barrow Strait) and can also be influenced by differences in sea-surface elevations between the BSME and CAA. In Resolute Passage, high current rates (10-30 cm/s) cause turbulent mixing at the ice-water interface such that surface waters are resupplied with nutrients, supporting abundant sea-ice biomass and production (Prinsenberg and Bennet 1987; Cota *et al.* 1987; Smith *et al.* 1997).

Hudson & James Bay and Foxe Basin Ecozone (HJBFB)

The HJBFB, extends between 51° and 71°N latitude, has a surface area of ~$0.8x10^6$ km^2 and a drainage area of >$4x10^6$ km^2. Within this semi-enclosed Ecozone, the average residence time of water is estimated to range from 1 to 6.6 years (Prinsenberg 1984; Drinkwater 1988; Jones and Anderson 1994; Ingram and Prinsenberg 1998). Hudson Bay has two basins separated by a ridge-like feature that rises to a depth of <40 m at the Midbay Bank (Stewart and Lockhart 2005). For such a large area, the Hudson Bay Ecozone is surprising shallow (~250 m deep), except for Hudson Strait which drops to a depth of 1000 m. Circulation is generally characterized by a relatively small inflow of cold saline waters to Foxe Basin via Fury and Hecla Strait and a larger outflow of more dilute surface waters from Hudson Bay to the Labrador Sea via Hudson Strait. The marine surface waters in Hudson Bay are diluted due to a combination of seasonal ice melt, freshwater runoff and rainfall. Stratification and circulation are strongly influenced by the dynamics of these freshwater sources, with runoff contributing 940 km^3/y of freshwater mostly between May and October (Déry *et al.* 2005; Straneo and Saucier 2008).

The HJBFB is underlain by Paleozoic sedimentary or Precambrian crystalline rock (Norris 1986; Stewart and Lockhart 2005). Where Paleozoic sedimentary rock occurs, the slope is often gradual with marshy coastal plains, shallow nearshore waters, and wide tidal flats (Martini 1986). The Nelson, Churchill, Albany, Moose, Nottaway, and Nettilling rivers flow into these low-lying coastal areas. In areas of Precambrian rock the coasts and seafloor are more rugged with exposed bedrock (Dionne 1980; Martini 1986, Stewart and Lockhart 2005). Seafloor sediments are composed of glacial till or glacio-marine deposits that range from coarse gravel nearshore to silts and clay offshore (Dionne 1980; Henderson 1989; Josenhans and Zevenhuizen 1990). A variety of glacial deposits are evident along the coasts and inland due to post-glacial isostatic rebound from the Laurentide Ice Sheet (Webber *et al.* 1970).

The HJBFB Ecozone has an impressive tidal range and holds the world record for the highest spring rise (16.7 m in Leaf Bay at the head of Ungava Bay, Kuzyk *et al.* 2008). Powerful tides that originate in the North Atlantic Ocean surge into the Ecozone twice daily via Hudson Strait (Dohler 1968; Drinkwater 1988). These strong tides override local tides and any Arctic Ocean tidal influences. At Kimmirut on the north shore of Hudson Strait, the spring tide increase to 12.5 m whereas within Hudson Bay spring tides range from 0.5 to 3 m (Dohler 1968; Godin 1974). These tides result in impressive current speeds up to 2 m/s at the eastern entrance to Hudson Strait and 0.3 m/s in Foxe Basin and in Hudson Bay (Stewart and Lockhart 2005 and references therein).

GENERAL CLIMATE

The availability of Canadian Arctic climate data is greatly skewed towards coastal stations with few offshore trends available. The arctic has been generally viewed as a polar desert with a uniform climate and harsh weather throughout the year. However, different climate zones have been identified within the area of the Marine Arctic Ecozones (e.g. Maxwell 1981) based on consistencies or alterations in cyclonic/anticyclonic activity, ice-water regimes, net radiation and changes from the higher mountainous terrain in the east to the lower terrain of the western arctic. The Marine Arctic Ecozones are characterized by low temperatures with average annual daily air temperatures below 0°C and mean monthly temperatures above freezing from June to September. Seasonal sea-ice formation generally begins in September and is a key component of the Marine Arctic Ecozones, with multiple feed-backs to the climate system. Of the three Ecozones discussed herein, only the HJBFB is completely ice-free during the summer. The marine areas are both a heat sink and a heat source. During spring, ocean waters are cooler than the land and therefore delay the progress of spring in coastal areas. During winter, ocean waters are warmer than the land resulting in delayed freeze-up near the coast. Climate trends are discussed in further detail in the terrestrial Arctic Ecozones chapter.

HISTORY OF USE

Hunting and Fishing

Hunting and fishing provide food and materials for Northern communities and are economically and socially important to Northern cultures. Plants, invertebrates, fishes, birds and their eggs, and marine mammals are harvested. In the HJBFB Ecozone, communities traditionally harvest kelp and seaweed for subsidence as well as several species of invertebrates (e.g. mussels, scallops, sea urchins, starfish and the brown sea cucumber, Stewart and Howland 2009). Shrimp are also harvested commercially in the CAA.

Fishes are harvested for subsistence, commercial sale and sport. There are harvest quotas on commercial fisheries and catch and possession limits for sport fishing but subsistence harvest are formally unregulated. The majority of the harvested fish are anadromous species such as Arctic Char (*Salvelinus alpinus*) and whitefish (*Coregonus* spp.). The only commercial fishery is for turbot (i.e. Greenland Halibut, *Reinhardtius hippoglossoides*) in the CAA. This fishery includes both a winter inshore fishery (Cumberland Sound, DFO 2008) and the offshore summer fishery in Baffin Bay.

Commercial whaling greatly reduced Bowhead whale (*Balaena mysticetus*) populations in the Marine Arctic Ecozones prior to 1907 (Figure 2). This whaling ended when baleen was no longer in demand for the fashion industry, and whale oil was no longer needed for lamps. Currently, Ringed (*Phoca hispida*) and Bearded (*Erignathus barbatus*) seals, Beluga (*Delphinapterus leucas*), Narwhal (*Monodon monoceros*), Bowhead and Atlantic walrus (*Odobenus rosmarus rosmarus*) are all harvested for subsistence. Polar bears (*Ursus maritimus*) are also harvested and are discussed in the Terrestrial chapter. In recent years there appears to be some declines in the harvest of marine mammals, for example, Beluga whales (Figure 3), and Atlantic walrus in the HJBFB Ecozone (COSEWIC 2006). Reductions in community harvests do not necessarily reflect declines in total abundances of mammals. Declining harvests could be linked to environmental effects, social factors such the availability of alternative foods (Harwood *et al.* 2002), declining use of dog teams (DFO 2002), and/or changes in harvest reporting by communities.

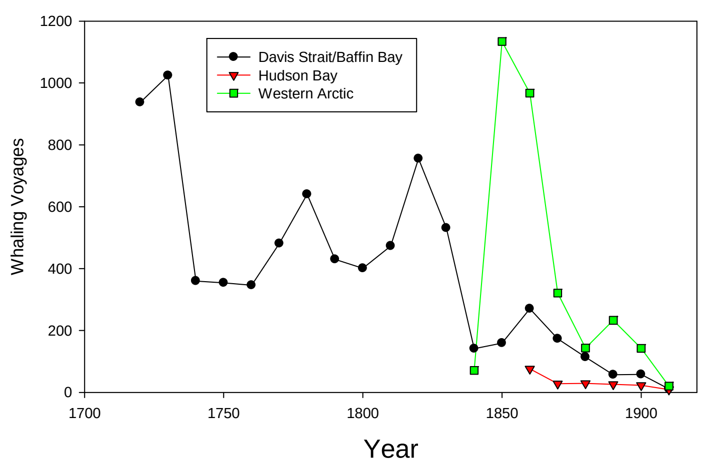


Figure 2. History of whaling voyages in the Marine Arctic Ecozones (data from Barr 2008)

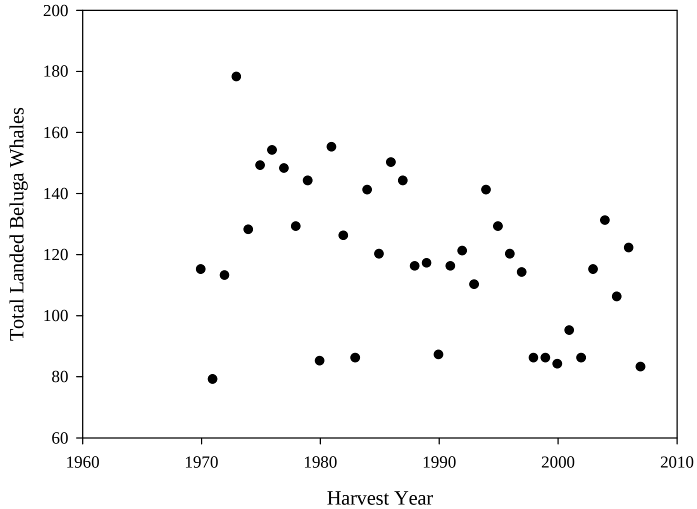


Figure 3. Landed Beluga in BSME 1970 to 2007 (data from Harwood et al. 2002, FJMC)

<u>Transport</u>

Curiosity and the search for the Northwest Passage led to the first ship traffic in the Marine Arctic Ecozones. Martin Frobisher was the first European explorer to reach the Arctic in 1576, and the first successful transit of the Northwest Passage was completed in 1906 by Roald Amundsen. Since then the number of ship transits the Northwest Passage has steadily increased (Figure 4). The early presence of ships in the eastern and western Arctic was also related to whaling as shown in Figure 2. Today, ships visit the Marine Arctic Ecozones to resupply remote communities (sealift) with dry goods and fuel, to support exploration and development for renewable (fishing) and non-renewable (mining and oil/gas) resources, conduct marine research, support tourism, and for National defense.

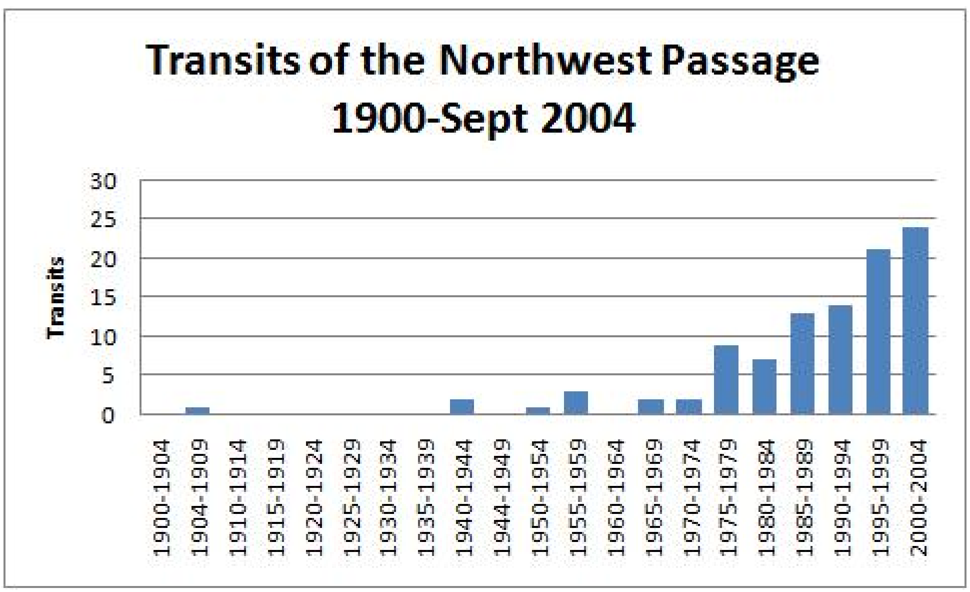


Figure 4. Ship transits of the Northwest Passage between 1906 and 2004 (Brigham and Ellis 2004)

Oil & Gas
Marine oil and gas development in the Beaufort Sea began during the 1970's. The first wells were drilled from artificial islands developed by Dome Petroleum and Gulf Canada Resources. Drilling and seismic exploration was also conducted in HJBFB in the 1970s and 1980s (Stewart and Lockhart 2005), and seismic exploration in the CAA in the Lancaster Sound region during the 1970s. Marine oil and gas development is now concentrated in the BSME and current oil and gas rights and potential areas of development are summarized in Figure 5. The current trend in marine oil and gas is an increase in offshore compared to coastal activity, especially in the BSME (Cobb *et al.* 2008) where there are currently 53 significant discovery licenses and 183 exploratory wells. The new exploratory leases have resulted in seismic activity and studies in preparation for drilling along the Beaufort Sea shelf break.

DESCRIPTION OF THE ARCTIC ECOZONES CONDITION

DRIVERS OF CHANGE

Without good long-term data, the natural variability of Arctic ecosystems makes it difficult to distinguish natural patterns of change from changes that are anthropogenically driven. The lack of baseline data for many regions and/or species also complicates the assessment of changes as the initial natural status may not be known. Local and global human activity as well as natural variability in the atmospheric-ice-ocean system, drives changes within the Marine Arctic Ecozones. Over harvesting, contaminants, flow regulations and other habitat disruptions can have local impacts on the Ecozones. Climate is also an important driver of change and is discussed in detail in the Terrestrial Arctic Ecozones chapter. The Arctic climate follows natural cycles on an annual to decadal scale that are driven by patterns of atmospheric circulation such as the North Atlantic Oscillation and Arctic Oscillation. Episodic events such as storms can also have great impacts on surface waters and coastal habitats through processes such as erosion and flooding (e.g. Mason and Solomon 2007). Recent reductions in sea ice, and other apparently unidirectional trends, suggest that global warming is affecting the region and may be accelerating.

Freshwater input into the Arctic, and the temperature and salinity of ocean water masses are important regulators of ecosystem structure and function. In addition, these two features in combination with air temperature have complex effects on the extent, quality and seasonality of sea ice which is a key driver of ecosystem change. On a larger scale, climate-driven changes to freshwater input, water masses and sea ice can influence deep water formation, which feeds back to thermohaline circulation and the global climate. Reductions in sea ice and snow cover also reduce surface reflectance, thereby influencing the availability of solar light energy and solar heating. These changes in albedo are part of complex climate feedbacks in the Arctic that challenge our prediction of future scenarios (Deser *et al.* 2000).

Human activity can also drive changes in the Marine Arctic Ecozones directly. The potential for increased shipping and oil and gas development in the Arctic increases the risk for spills or other contamination including invasives from ballast water as well as introduces noise and other visual disturbances. Contaminants originating from human activity outside of the Arctic capable of long range transport also enter the Arctic food chain. These contaminants and their potential impacts are discussed later in this chapter. Flow alteration in associated watersheds as has occurred due to hydroelectric development around Hudson/James Bay, also has the potential to impact the Arctic Marine Ecozones.

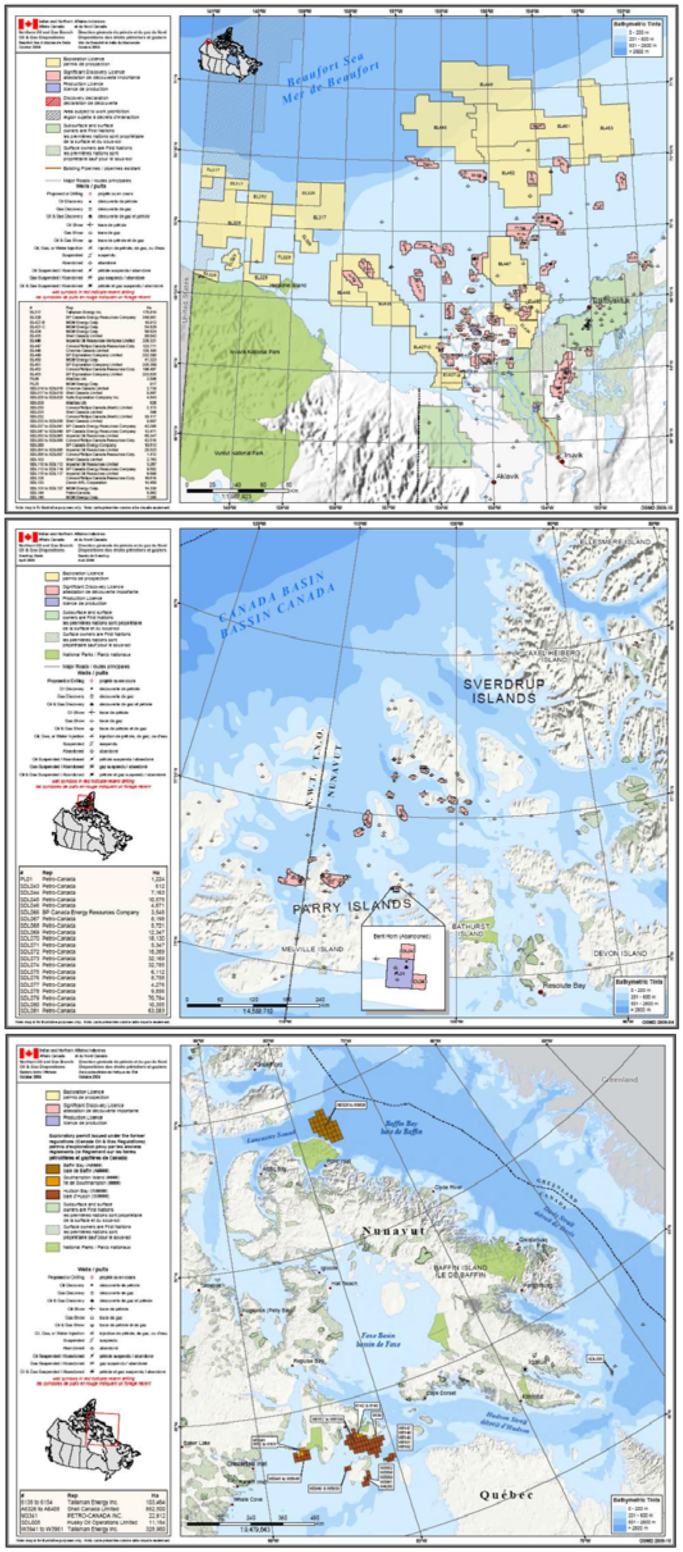


Figure 5. Location of current oil and gas rights and potential oil development areas in the Marine Arctic Ecozones (Source: INAC).

ECOSYSTEM FUNCTION AND PROCESSES

Physical Oceanography

Large-scale atmospheric circulation patterns influence trends in climate, ocean circulation, sea ice, and many other aspects of these ecosystems. In the Arctic basin, atmospheric circulation patterns naturally fluctuate (decadal or longer scales) between positive and negative trends in vorticity. Under a positive North Atlantic Oscillation or Arctic Oscillation phase, surface winds produce a clockwise (anticyclonic) rotation of waters and ice, whereas in a negative mode, counter clockwise (cyclonic) rotation occurs. In the early 1990's there was a strong positive phase, but in recent years there has been a rapid transition between positive and negative phases.

In the BSME these atmospheric patterns influence the Beaufort Gyre which drives the movement of surface waters and sea ice. Below the surface, the Beaufort Undercurrent moves the water in a counter-clockwise direction resulting in an eastward movement of Pacific waters towards the CAA. Nearshore, winds and the Mackenzie River influences surface circulation with the Mackenzie plume generally spreading eastward in response to the Coriolis force. Easterly winds induce upwelling nearshore, whereas offshore the topography and currents create areas of upwelling >100 km wide (Carmack and Macdonald 2002). Large scale atmospheric and Arctic Ocean circulation patterns impact the Beaufort Gyre as described in the following section on water temperature and salinity.

The CAA is an important transit zone for Pacific waters flowing to the Atlantic Ocean (Jones *et al.* 2003). During the current positive phase of Arctic atmospheric circulation it is hypothesized that there is a greater flow of Pacific and fresh waters through the CAA than during the negative phase (McLaughlin *et al.* 2002). Water circulation within the CAA is influenced by glacial-shaped topography and the exchange of water on the expansive shelves. Research continues to describe CAA circulation and the current understanding for surface circulation is summarized in Michel *et al.* 2006.

Surface waters circulate counterclockwise around Hudson Bay with deeper water generally following the same pattern except when diverted by the seafloor topography (Prinsenberg 1986). The coldest waters enter Hudson Bay from Foxe Basin and some of this water eventually enters James Bay. This extreme southerly occurrence of Arctic waters is a unique feature of HJBFB compared to other waters at similar latitude (Stewart and Lockhart 2005).

Water temperature

Sea Surface Temperatures (SST) in the Arctic show variable trends and in recent years, have declined relative to a large anomaly of ~0.9°C in the Arctic Ocean. Trends in SST for the Beaufort Sea and Hudson Bay are presented in Figure 6. In the Marine Arctic Ecozones the largest SST anomalies have been observed on the Beaufort Sea/Chukchi Sea border and in the southwestern Foxe Basin/northwestern Hudson Bay area (Figure 7).

Changes in deep water temperatures reflect the movement of water masses. The heat content of the Beaufort Gyre, for example, has increased significantly since the 1970s, and this has been related to a twofold increase in the temperature of the Atlantic Water layer (Proshutinsky *et al.* 2009, Figure 8). Warmer Atlantic water has also entered the Arctic via Fram Strait, contributing to the net warming of Arctic waters (Schauer *et al.* 2004).

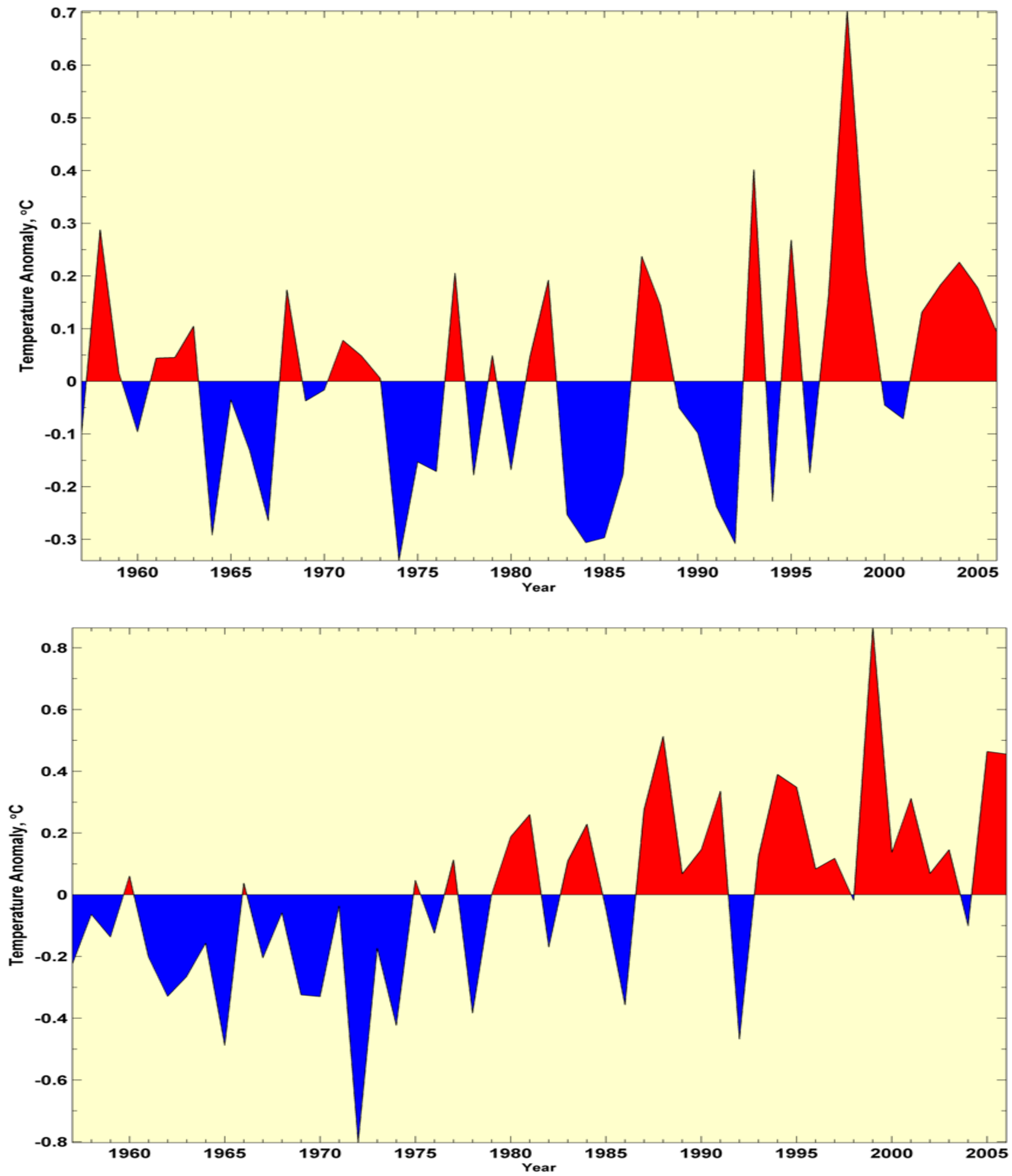
A
B


Figure 6. Sea Surface Temperature (SST) anomalies for the Beaufort Sea (1957-2006, A) and Hudson Bay (1957-2006, B), note different y-axis (Belkin et al. 2009)

Water salinity

Surface water salinities in the Marine Arctic Ecozones are influenced by ice formation/melt, freshwater runoff from the land, precipitation, wind and tidal mixing, and circulation patterns. Salinity influences the presence of marine species directly, through salinity preferences and tolerances. It also influences them indirectly by dictating density and water column stratification, which affects water and nutrient movements and thereby phytoplankton productivity. Over the past century the surface salinity of the central Arctic Ocean has generally increased, with a 239 ± 270 km^3/decade loss of freshwater (Polyakov *et al.* 2008).

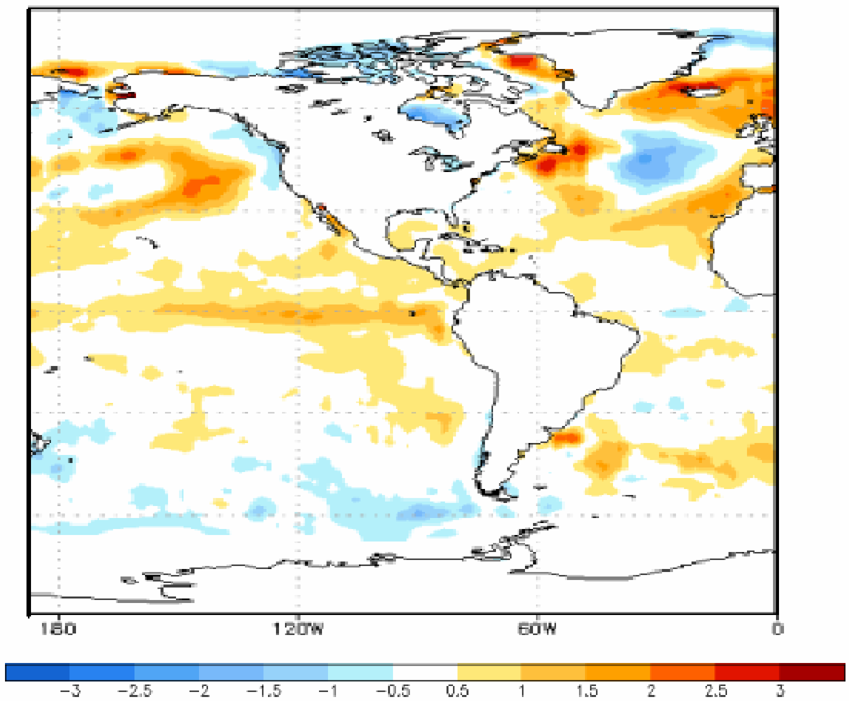


Figure 7. Sea Surface Temperature (SST) anomalies in July 2009. Scale is in °C (Source: NOAA)

However, in recent years, there has been a shift in the amount and distribution of freshwater in surface layers. In 2008 there was an unprecedented amount of freshwater in the surface layer of the Arctic Ocean due to melting of sea ice (Arctic report card 2009). Since the 1970s, there has been a general freshening of surface waters on the Pacific side of the Arctic, which alters the transport of freshwater into the Beaufort Gyre (Figure 8) (McPhee *et al.* 2009). Deeper water layers in the Beaufort Gyre also continued to freshen in 2008 (Proshutinsky *et al.* 2009). Long term trends in salinity and freshwater in the CAA and HJBFB are unknown.

Temperature and salinity trends in the Arctic Ocean have been accompanied by an increase in sea level. The rate of this increase has accelerated since 1990. Between 1954 and 1989 the sea level in the Arctic Ocean increased at a rate of 1.94 ± 0.47 mm/y (Arctic Report Card 2008). When the years 1990 to 2007 are included (i.e., 1954-2007) the rate of increase is higher at 2.61 ± 0.45 mm/y.

<u>Nutrient Cycling</u>

Long-term tends in nutrient concentrations and distributions are not available for the Marine Arctic Ecozones, although numerous studies provide point measurements of nutrients in the water column and sea ice from the BSME, CAA and HJBFB. During the summer, primary production in the surface waters can become nutrient limited, as primary producers use up the available nutrients while water column stratification limits vertical mixing and thereby nutrient replenishment. Nitrate generally becomes the limiting nutrient for primary production, although production by diatoms may be limited by the silicate they require for cell walls (Smith *et al.*1997).

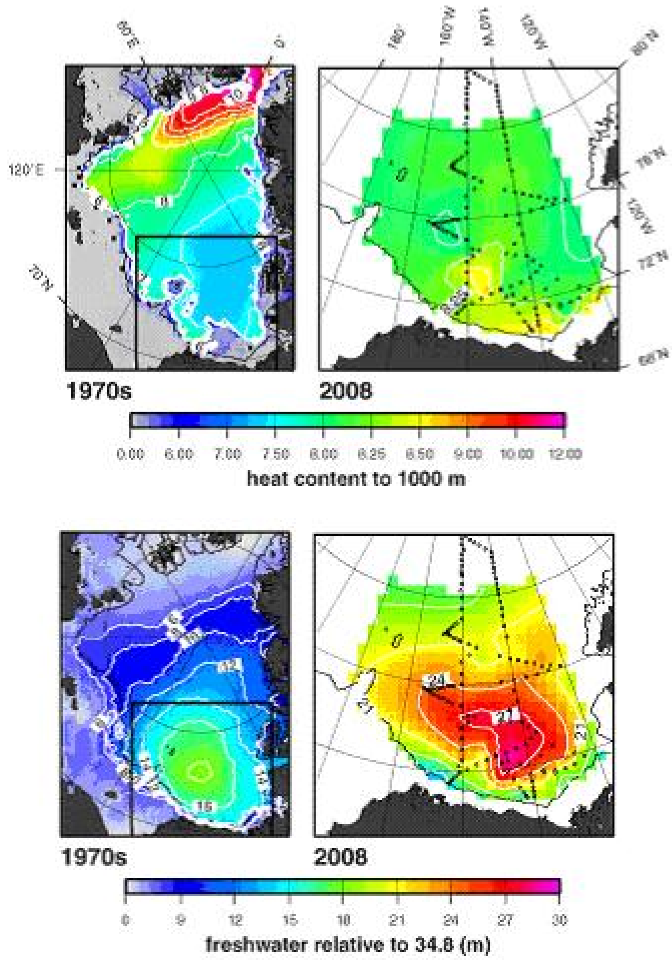


Figure 8. Warming and freshening of the Beaufort Sea in 2008 compared to the 1970s. The 2008 areas are outlined in black in the 1970s panels. Warming and freshening are measured as summer heat units (1×10^{10} J m^{-2}) and meters of freshwater content, respectively (adapted from Proshutinsky et al. 2009; Arctic report card 2009)

New primary production relies on nutrients that are transported into surface waters. Brine rejection during ice formation is an important process that reduces density stratification and enables mixing of nutrient rich bottom waters into the surface waters. Rivers are also an important source of nutrients for surface waters in the Marine Arctic Ecozones. River input can supply nitrogen and silicate but generally contains low concentrations of phosphate (Macdonald *et al.* 1987). Consequently, primary production may be phosphate limited in brackish nearshore waters. Changes in the quantity and constituents of river flow will influence nutrient cycling in coastal areas of the Marine Arctic Ecozones.

Upwelling is also a key process that replenishes nutrients by mixing deep waters into surface layers. It takes place along the coast, in areas of elevated seafloor topography and at ice edges, in response to wind-driven currents or storms. During the ice covered period, upwellings may also be driven by tides and density-driven currents. Upwellings occur locally throughout the Marine Arctic Ecozones. Upwellings in polynyas support phytoplankton blooms in the exposed surface waters and at the ice edges. Ice-edge phytoplankton blooms can be very important for the total primary productivity of that area. For example, in the Beaufort Sea a single ice-edge phytoplankton boom contributed double the annual amount of primary production previously estimated for that area (Mundy *et al.* 2009). These ice-edge phytoplankton blooms are not well documented but could become increasingly important with decreasing ice thickness and increasing ice deformation, which enhance the opportunities for wind-driven upwelling of nutrient rich waters during the winter.

Observed changes in water masses in the Arctic, such as increased inflow of Atlantic waters (Dickson *et al.* 2000), shifting boundaries between Atlantic and Pacific waters (McLaughin *et al.* 1996) and the warming and freshening of water masses, impact nutrient concentrations. These impacts may be direct, by affecting nutrient import from the Pacific, or indirect, by modifying water stratification and mixing regimes. Changing wind and storm patterns will also influence stratification, mixing and upwelling processes that affect nutrient distributions/availability and primary productivity.

CO_2 and Ocean Acidification

The Arctic Ocean is considered to be undersaturated with carbon dioxide (CO_2) relative to the atmosphere indicating that the Arctic Ocean has the capacity to absorb atmospheric CO_2. The CO_2 can be absorbed during the open water period and drawn down into ocean waters through sea ice (Rysgaard *et al.* 2009). The uptake of CO_2 on the Beaufort Sea Shelf and in the CAA are estimated at ~2 and 16-24 Tg (10^{12} grams) C/y, respectively (Murata and Takizawa 2003; Bates and Mathis 2009). The total drawdown of CO_2 in the Arctic Ocean is estimated between 65 and 175 Tg C/y, representing 5-14% of the global balance of CO_2 sinks and sources (Bates and Mathis 2009). Unlike other shelf areas in the Marine Arctic Ecozones, HJBFB appears to release CO_2 to the atmosphere during the ice-free season (Else *et al.* 2008).

The recent loss of sea ice (e.g., 2007, 2008) may have increased CO_2 uptake in the Arctic Ocean by an additional 33 ± 10 Tg C/y. A complete loss of sea ice in the central basin of the Arctic Ocean could increase surface water CO_2 absorption by 280 to 1200 Tg during the summer (Bates and Mathis 2009). The resulting decrease in surface water pH would lead to ocean acidification with an undersaturation in calcium carbonate. Under these conditions, plankton, invertebrates and fishes that use calcium to build their skeletons, shells and tests would be negatively impacted (Comeau *et al.* 2009). Ocean acidification is expected to impact the Arctic before other regions (Steinacher *et al.* 2009). In fact, in 2008 surface waters in the Canada Basin of the Arctic Ocean were undersaturated in a soluble form of calcium carbonate (i.e., aragonite) that is required for both planktonic and benthic fauna. This trend towards undersaturation is linked to both the melting of sea ice and enhanced upwelling that brings deep aragonite-undersaturated waters onto the shelf areas (Yamamoto-Kawai *et al.* 2009).

Primary Productivity

Overall, primary production is low in the Arctic compared to other oceans around the world (Figure 9) with higher Ocean Primary Productivity (OPP) around coastal areas. Rates of primary production are controlled primarily by the availability of light and nutrients, which are in turn controlled by the physical and biological processes of the marine environment (Tremblay and Smith Jr. 2007). There is considerable regional variation in OPP within the Arctic (Figure 10). This variation in OPP is influenced by latitude, seasonal and multi-year sea ice and snow cover, shading by sea-ice algae, polar night, discharge of inorganic sediments (i.e. light attenuation) and nutrients from rivers, vertical stratification and water circulation patterns (Smith *et al.* 1988; Gosselin *et al.* 1997; Pabi *et al.* 2008). Areas with heavy ice cover can be characterized by low biomass and small size classes of phytoplankton (Tremblay & Smith Jr. 2007).

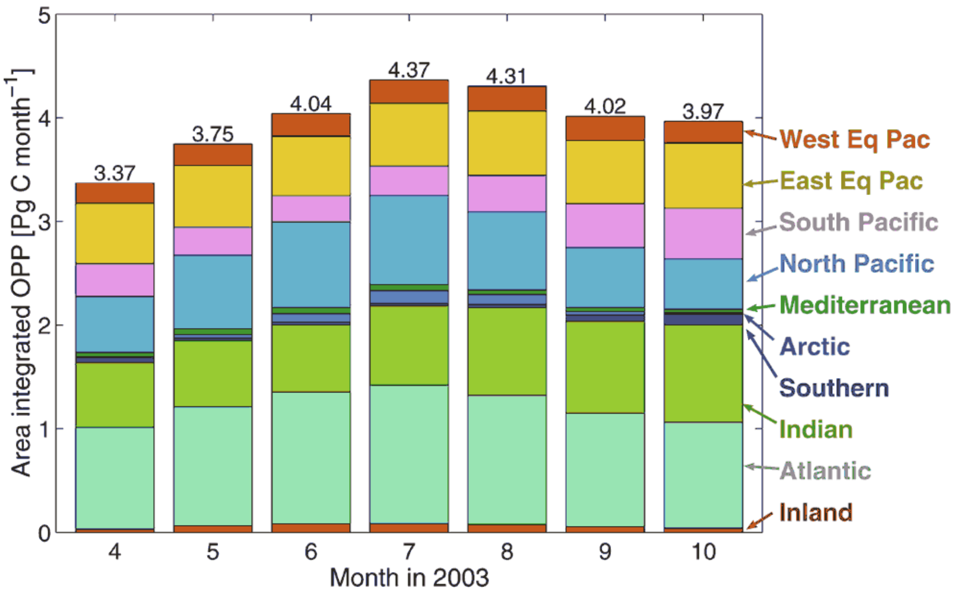


Figure 9. Monthly mean ocean primary productivity (OPP) for 2003 estimated from chlorophyll-a concentration of phytoplankton, sea surface temperature, photosynthetically available radiation and ocean bio-optical models. (Source: Japan Aerospace Exploration Agency Website, April 5, 2004)

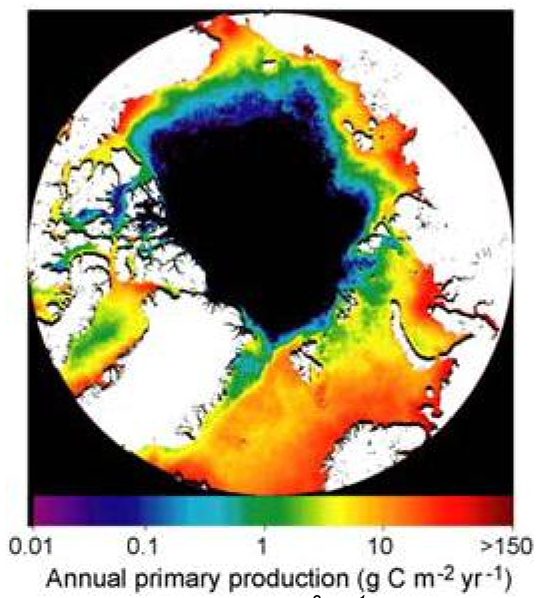


Figure 10. Pan-Arctic annual primary production (g C m^{-2} yr^{-1}) in the marine environment estimated using remotely sensed sea-surface temperature, chlorophyll a and sea ice. (Source: Pabi et al. 2008)

Since 1998, pan-Arctic values of primary production have varied between 356-459 Tg C/yr with an average pan-Arctic value of 419 ±33 Tg C/yr (1998-2006, Pabi *et al.* 2008). Since 2003 there has been a yearly average increase of 27.5 Tg C/yr and in particular a 35 Tg C/yr increase between 2006-2007. This trend was found to be a statistically significant increase of 40% in annual primary production over the last decade (Figure 11). Between 2006 and 2007 production is estimated to have increased by >15% and both 2007 and 2008 were recorded as the most productive years on record (Figure 12). The direction of changes in primary production varies among Arctic regions reflecting the heterogeneous nature of local oceanographic features and changes in climate/sea ice. The greatest increase in Canadian Arctic primary production has been observed in the Beaufort Sea, Lancaster Sound, Foxe Basin and Baffin Bay/Davis Strait (Figure 12). Most of these locations are associated with recurrent polynyas and major shore leads.

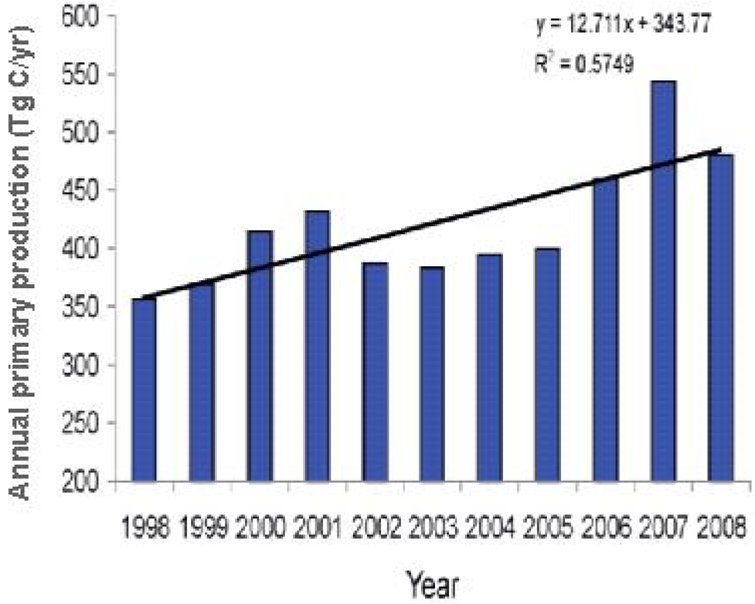


Figure 11. Trends in annual primary production (Tg C/yr) for the Arctic (1998-2008). (Source: Pabi et al. 2008; Arrigo et al 2008)

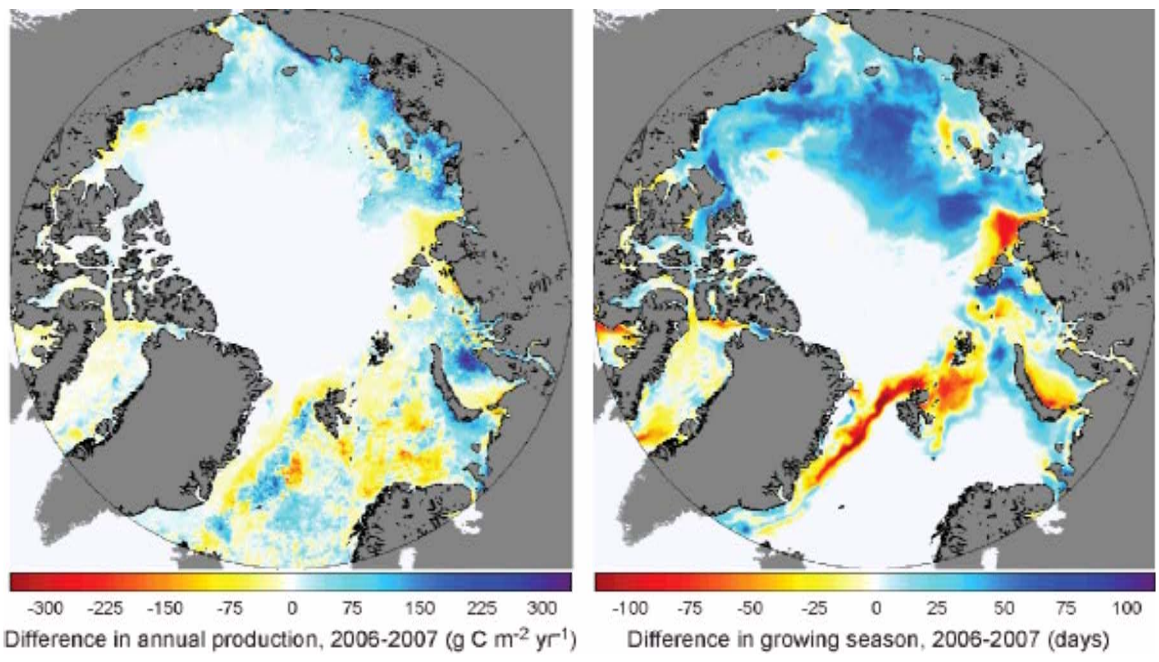


Figure 12. Differences in annual production (g C m-2/yr) and length of growing season (days) between 2006 and 2007 in the Arctic. (Source: Arrigo et al. 2008)

Polynyas represent hotspots of productivity and diversity relative to other ice covered areas in Arctic marine ecosystems. The physiochemical characteristics of a polynya can influence both the taxonomic composition of phytoplankton as well as their growth and production rates (Tremblay and Smith Jr. 2007).

The ongoing and anticipated changes in global climate (temperature, precipitation) and other associated characteristics (nutrients and circulation patterns) may alter phytoplankton community structure and overall production rates of the world's oceans (Tremblay and Smith Jr. 2007). Rates of production may continue to increase as open water habitat increases and the extent of sea ice declines (Arrigo *et al.* 2008). However, Arrigo *et al.* (2008) only attributed 30% of this increase to open water habitat and nearly 70% to the increased length of the growing season. Therefore, annual mean open water area is a better predictor of changes in annual primary production than summer minimum ice cover (Arrigo *et al.* 2008). Changes in the magnitude and fate of primary productivity can strongly influence atmospheric CO_2 levels and therefore climate trends.

Beaufort Sea

The Beaufort Sea is an oligotrophic environment with primary production on the shelf estimated at between 12 and 16 g C m^{-2}/y (Carmack *et al.* 2004), but an order of magnitude higher in the Cape Bathurst polynya (175 g C m^{-2}/y, Arrigo and van Dijken 2004). Phytoplankton production tends to be higher in nearshore waters (Hsiao 1976; Carmack *et al.* 2004) with the timing of production linked to snow and ice melt/breakup (Lavoie *et al.* 2009). On the outer shelf, primary production is lower and controlled by the return of nutrients to surface waters by wind mixing during the previous fall and winter (Lavoie *et al.* 2009). Localized increases in production in the BSME are the result of interactions between water circulation and ocean floor topography that cause upwelling of nutrient rich waters (Cobb *et al.* 2008; Mundy *et al.* 2009).

Trends in ice algae in any of the Ecozones are difficult to discern due to the inherent variability caused by snow cover, ice type and age, and differences in underlying surface waters. Ice algae in the BSME may contribute up to two-thirds of total primary production (Horner and Schrader 1982), and contribute significantly to the dissolved organic carbon pool (Riedel *et al.* 2008). Ice algal assemblages are dominated by diatoms (Rozanska *et al.* 2009). On average, 46% of the ice algae exported from the ice (measured as chlorophyll *a*) is consumed in the upper 25 m of the water column (Juul-Pedersen *et al.* 2008). However, enough ice algae reach the benthos to stimulate benthic production (Renaud *et al.* 2007).

Canadian Arctic Archipelago

The CAA supports high diatom productivity and accounts for about 32% of the total primary production on Arctic shelves (Michel *et al.* 2006). Rates of primary production range from 5 to 60 Mt C/y (Nemoto and Harrison 1981; Macdonald *et al.* 2004; Michel *et al.* 2006), about 90% of which is produced by phytoplankton and 10% by ice algae (Bergmann *et al.* 1991; Welch *et al.* 1992). Integrated fluorescence, which is a proxy for phytoplankton concentrations, shows strong seasonal and interannual variations in phytoplankton concentrations in surface waters of Barrow Strait (Figure 13, Hamilton *et al.* 2009). These differences can be linked to variability in the timing of ice break up, which influences current speeds and the transport of phytoplankton into Lancaster Sound.

Ice algal communities in the CAA are diverse and have the highest biomass in the Marine Arctic Ecozones (Michel *et al.* 2006; Riedel *et al.* 2003; Nemoto and Harrison 1981; Bradstreet and Cross 1982). Interannual variability in ice algal biomass and productivity is high due to changes in precipitation, timing of snow melt and the distribution of snow cover (Smith *et al.* 1988; Smith and Herman 1991; Welch and Bergmann 1989; Agnew and Silis 1995; Fortier *et al.* 2002; Mundy *et al.* 2005). Ice algae play an important ecological role by providing planktonic grazers with an early and concentrated food source before phytoplankton are readily available (Bradstreet and Cross 1982; Michel *et al.* 1996). The time at which algae are released from the ice each spring has varied by over a month, during a six year period (Figure 14). This variability has significant implications for trophic linkages to zooplankton and benthic communities.

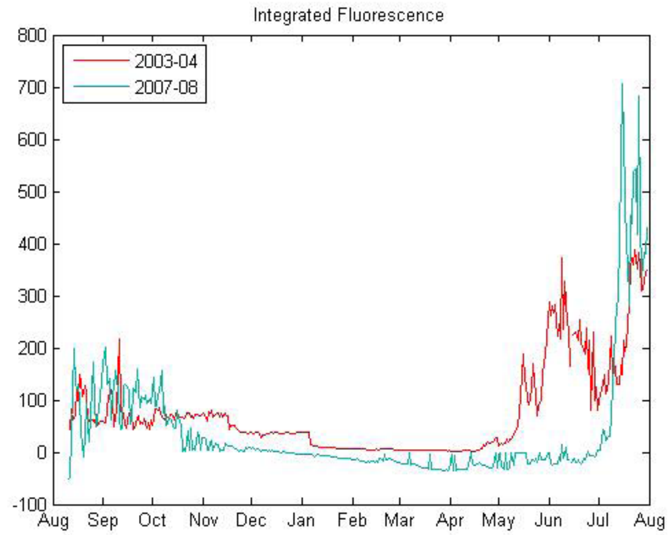


Figure 13. Surface water (<46 m) integrated fluorescence values (mg/m2) from Barrow Strait. Fluorescence values are a proxy for phytoplankton concentrations. (Source: Hamilton et al. 2009)

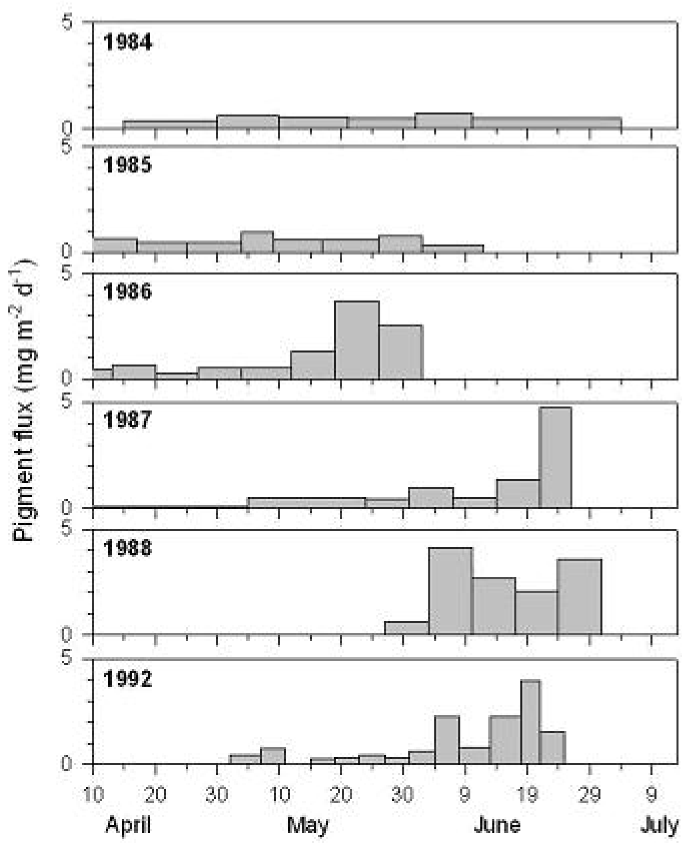


Figure 14. Algal sinking fluxes in Resolute passage between 1984 and 1992 (Source: Michel et al. 2006)

Hudson Bay, James Bay and Foxe Basin

Primary production in Hudson Bay is comparable to the seasonally open-water areas of the CAA (Subba Rao and Platt 1984), and low relative to other oceans at the same latitudes. Offshore phytoplankton production is higher in Hudson Strait (46 g C m^{-2}/y) than in Hudson Bay (14-40 g C m^{-2}/y,) and Foxe Basin (Harvey *et al.* 2006; Lapoussière *et al.* submitted). Phytoplankton biomass and production are highest on the eastern side of Hudson Bay and along the southern side of Hudson Strait (Lapoussière *et al.*, submitted). The upwelling of nitrogen in nearshore areas of Hudson Bay can lead to phytoplankton production of ca. 35 g C m^{-2}/yr, and total inshore primary production rates may reach 70 g C m^{-2}/yr (Roff and Legendre 1986). Phytoplankton, ice algae, benthic (micro and macro) algae and vascular plants (e.g., eelgrass) would together contribute to total primary production. Vascular plants are of particular importance in James Bay where extensive beds of eelgrass are found along the coast. Ice algae display a patchy distribution in HJBFB with highest biomass in areas with little snow accumulation on the sea ice (Gosselin *et al.* 1986; Roff and Legendre 1986). As in the other Marine Arctic Ecozones, the ice algae are an important food source for zooplankton, especially copepods, during and immediately following the ice algal bloom *(*Runge and Ingram 1991).

Trophodynamics

The Marine Arctic Ecozones may be sensitive to change in trophic dynamics such as increased primary productivity, due to the low number of trophic linkages (Grebmeier *et al.* 2006). Primary production in the ice or water column is transferred to pelagic or benthic secondary consumers such as zooplankton, invertebrates and larval fish. This transfer is usually highly efficient, with little organic carbon becoming buried in the sediments. In turn, these secondary consumers support fishes, birds, and mammals either directly or through higher level trophic linkages. Arctic Cod (*Boreogadus saida*) is a key species linking lower and higher trophic levels (Craig 1984; Welch *et al.* 1992). Marine mammals are at the top of the foodweb and are dependent on sea ice, water column and benthic habitats for their prey items. Table 1 summarizes key feeding habitats and main prey items for common marine mammals in the Marine Arctic Ecozones (Bluhm and Gradinger 2008). Note that polar bears are addressed in the terrestrial chapter.

Table 1. Summary of Arctic marine mammal feeding habitats and primary prey items (Adapted from Bluhm and Gradinger 2008).

Species	Feeding habitats	Primary prey
Bowhead whale	Pelagic, hyperbenthic	Copepods, euphausiids, mysids
Beluga whale	Pelagic, benthic	Arctic cod, various other fish and invertebrates
Narwhal	Pelagic, benthic	Turbot, Arctic cod, squid, other invertebrates
Atlantic walrus	Benthic, pelagic	Benthic invertebrates especially *Mya spp*.
Bearded seal	Benthic, pelagic	Various fishes, mollusc, crustaceans
Ringed seal	Pelagic	Arctic cod, amphipods, euphausiids

Due to the scarcity of long-term data sets, trends in trophic interactions are largely unknown. One exception is for Thick-billed Murres (*Uria lomvia*) at Coats and Digges islands in Hudson Bay. The diets of Thick-billed Murre nestlings at Coats and Digges Island have been monitored since the 1980s. In the early years, the diet at both colonies was dominated by Arctic Cod but since 1994 the capelin *Mallotus villosus* has made up about half the diet at Coats Island, with cod falling to less than 20% after 2000 (Gaston *et al.* 2003, Figure 15). At Digges Island, Capelin made up 85% of the nestling diet in 2004. Arctic Cod is an ice-associated fish and these changes may be linked to progressively earlier break-up of sea-ice in Hudson Bay since the early 1990s (Gaston *et al.* 2005).

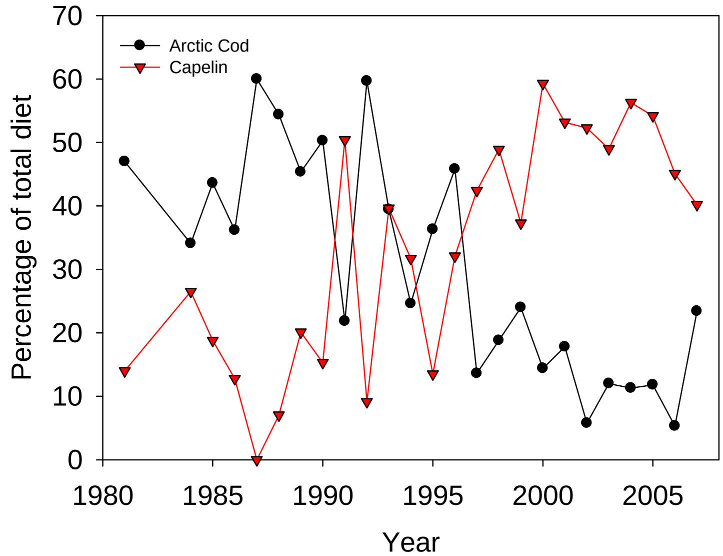


Figure 15. Proportion of Arctic Cod Boreogadus saida and Capelin Mallotus villosus fed to nestling Thick-billed Murres at Coats Island between 1981-2007 (no data for 1982 and 1983) (Source: Gaston et al. 2003 and AJG unpublished)

<u>Disease</u>
Another important trophic interaction is between pathogenic viruses /bacteria and fish or marine mammals. The study of disease in marine mammals is a relatively new in the Marine Arctic Ecozones yet vitally important since outbreaks can reduce marine mammal populations. Infections currently known to be in Canadian Arctic marine mammals include, brucellosis (Nielsen *et al.* 1996), morbillivirus (Duignan *et al.* 1997), influenza A (Nielsen *et al.* 2001), canine adenovirus, dolphin rhabdovirus (Philippa *et al.* 2004), and a new species of virus (SePV-1) that appears to have a high prevalence among hunted Ringed seal populations (Kapoor *et al.* 2008).

DFO has been monitoring two diseases of importance to marine mammals in Arctic Canada using samples from subsistence hunts for over ten years. Brucellosis is a serious zoonotic disease of livestock world-wide that occurs in marine mammals. The disease is caused by bacteria from the genus *Brucella*. Marine mammals are infected by different species of the disease than those affecting terrestrial animals. Two species of marine mammal Brucella are presently recognised, *B. pinnipedialis* which infects predominately seals, and *B. ceti* which infects predominately dolphins and porpoises. Marine mammal Brucellae bacteria have been found in Beluga, Atlantic walruses and Ringed seals (Nielsen *et al.* 1996). Research is ongoing to identify the serological prevalence in all species of marine mammals in the Arctic as well as to isolate and characterize the species of *Brucella* responsible, and to determine the risk of infection to Inuit who harvest these animals, and sometimes eat them raw.

Morbilliviruses are a group of viruses that are capable of causing the disease distemper in infected hosts. Distemper is also a serious disease of marine mammals. Though not transmissible to humans it has been associated with large scale die-offs in both seals and whales world-wide. Mortalities of 40-60% are not uncommon when the virus is introduced into an immunologically naïve population of susceptible animals. No large scale die–offs of marine mammals due to distemper have so far been recorded in Canada. Research is ongoing in Canada by DFO staff to serologically identify past exposure to viruses using samples from subsistence hunts The goal is to develop methods to grow, characterize and compare viral isolates from North America and elsewhere, and to evaluate the risks, if any, that Canadian marine mammal populations face if and when these viruses make their way into Canadian waters.

Currently, distemper antibodies have been detected in Walrus and Ringed seal. No distemper antibodies have been detected in Beluga harvested at Hendrickson or Kendall Islands (BSME), indicating their susceptibility to infection by cetacean morbillivirus (CMV). Brucella antibodies as well as bacterial isolations have been made from Beluga sampled at Hendrickson and Kendall Islands, however, infection prevalence seems to fluctuate (Table 2).

Table 2. Prevalence of Brucellosis hunter harvested Beluga in the BSME (2004-2007).

Year	Total Number Harvested	Number Tested Positive (%)
2004	42	6 (14.3)
2005	33	2 (6.1)
2006	70	11 (15.7)
2007	18	1 (5.5)

Brucellosis is also present in Ringed seals in the Beaufort Sea, but the prevalence is much lower and the disease it causes in seals seems to be much less severe. *Bartonella henselae* the causative agent of “cat scratch fever” in humans has been discovered in samples of Beluga from the Beaufort Sea. This is a new finding and the significance to both human and Beluga health is presently unknown. Over 90% of the Beluga tested from 2007 were positive for various species of *B. henselae.* While this disease can kill captive animals, more research will be needed to determine its effect on animals in the wild.

Ecological effects of changing trophodynamics

Although specific trends in trophodynamics are not yet evident, different scenarios in response to climate driven changes have been proposed (e.g., Pipenburg 2005; Michel *et al.* 2006; Bluhm and Gradinger 2008). One scenario suggests that earlier sea ice melt and corresponding longer growing season could result in a greater flux of primary production to the benthos, as an earlier or sudden release of algal production may not correspond with high zooplankton abundances. Alternatively, there may be a shift away from ice-benthic linkages to phytoplankton-zooplankton linkages, such that a pelagic rather than benthic-dominated mode of energy transfer will prevail (Pipenburg 2005; Grebmeier *et al.* 2006).

The ecological consequences of the multifaceted effects of climate change and variability could propagate through all trophic levels of the Arctic foodweb. The ecological consequences could include changes to cellular physiology, species composition, rates of productivity, carbon and contaminant fluxes, prey size and distribution, and ultimately standing stocks of higher trophic levels. The sensitivity of species or groups to change will depend on their ecology and how their prey and/or habitat are affected. There may, for example, be a greater effect on species that have very specific prey or habitat requirements (e.g., Walrus) versus those that feed opportunistically on a variety of species or occupy a variety of habitats (e.g., Beluga). Additional challenges could also arise for species that depend upon seasonal pulses of production either due to migratory patterns or life history strategies (Arrigo *et al.* 2008). Given the diverse characteristics of the Marine Arctic Ecozones, trends in trophodynamics may also vary spatially among the different ecosystems.

ECOSYSTEM STRUCTURE

CHANGES IN EXTENT AND QUALITY OF IMPORTANT BIOMES

Sea Ice

Sea ice is a critical component of the Marine Arctic Ecozones and can influence ecosystems and climate on local and global scales. The impacts of sea ice are related to its effects on albedo, atmospheric-ocean exchanges and ocean circulation via brine expulsion, ice melting effects and the transport of cold, low salinity waters with ice drift. In some regions of the Ecozones there have been rapid changes in sea-ice characteristics with domino effects expected to occur throughout the sea-ice associated ecosystems.

Ice extent (regions with minimum 15% sea-ice coverage) usually reaches its maximum in March and minimum in September. Since satellite monitoring began in 1979, the lowest sea-ice extent recorded in the Arctic occurred in 2007, and the third lowest in 2009 (Figure 16). The average sea-ice extent in September declined 11.7% per decade over the period 1979-2008; and in March declined 2.7% per decade over the period 1979-2009 (Fetterer *et al.* 2009). In September 2009, sea-ice extent was 23% below the 1979-2000 average. The observed reduction in sea-ice extent is occurring faster than predicted by climate models. However, there are numerous estimates and the complexity of the changes makes prediction difficult.

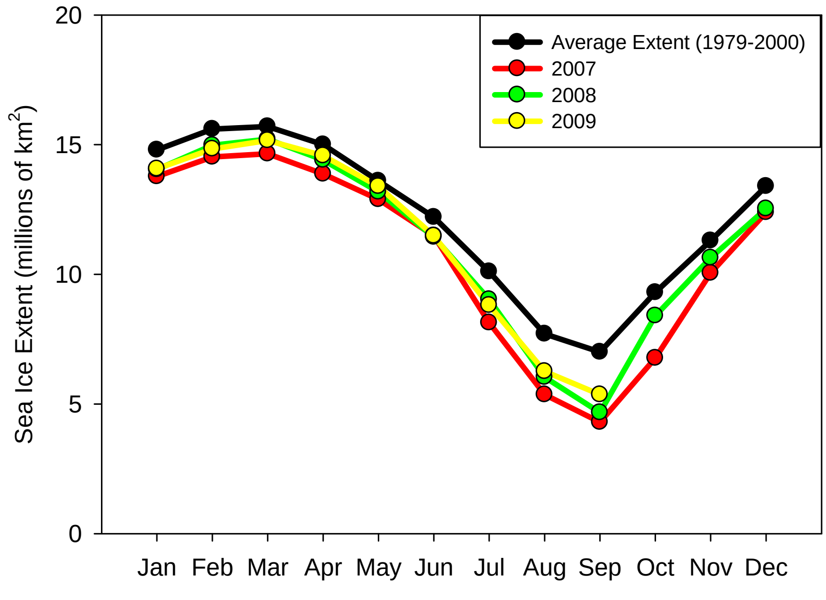


Figure 16. Arctic sea-ice extent by month for 2007 to 2009, compared to the 1979-2000 average extent. (Source: Fetterer, F., and K. Knowles. 2002, updated 2008. Sea ice index. Boulder, CO: National Snow and Ice Data Center. Digital media.)

Seasonal trends in sea-ice extent and area (area covered by ice in regions with minimum 15% sea-ice coverage) between 1979 and 2006 for the CAA, HJBFB and Arctic Ocean (which includes the BSME) are presented in Table 3. HJBFB and BSME areas show significant decreases in both extent and area whereas the CAA shows a significant decline in area only (Parkinson and Cavalieri 2008). Sea-ice conditions in the CAA were at a record low in 1998 (Atkinson *et al.* 2006), compared to 2007 for the Arctic Ocean. Decreasing trends in sea-ice extent and area are influenced by complex interactions of dynamic variables. The sea ice can be melted from above by increasing air temperatures, melted from below by influxes of warm water masses and exported/broken by wind forcing that is influenced by different atmospheric conditions such as the Arctic Oscillation and Dipole Anomaly (Köberle and Gerdes 2003; Steele *et al.* 2008; Wang *et al.* 2009). Consequently, the magnitude of trends in ice extent does not necessarily correlate to similar trends in ice mass (i.e., thickness, Lindsay *et al.* 2009).

Table 3. Summary of sea-ice trends between 1979 and 2006 in the Arctic Ocean, CAA and HJBFB. The BSME is included in the Arctic Ocean trends. Values in red are significant trends. See text for definitions of ice extent and area. Data from Parkinson and Cavalieri (2008).

Region	***Yearly***	***Winter (Jan-Mar)***	***Spring (Apr-Jun)***	***Summer (Jul-Sept)***	***Fall (Oct-Dec)***
	% per decade				
Extent					
Arctic Ocean	*-1.5 ± 0.3*	*0.0 ± 0.0*	*-0.2 ± 0.1*	*-4.1 ± 1.0*	*-1.8 ± 0.4*
CAA	*-0.7 ± 0.6*	*0.0 ± 0.0*	*-0.4 ± 0.2*	*-1.4 ± 2.2*	*-1.2 ± 0.6*
HJBFB	*-5.3 ± 1.1*	*0.0 ± 0.0*	*-2.8 ± 0.7*	*-19.5 ± 5.0*	*-12.9 ± 2.9*
Area					
Arctic Ocean	*-1.8 ± 0.4*	*-0.6 ± 0.1*	*-0.6 ± 0.3*	*-6.2 ± 1.0*	*-2.0 ± 0.6*
CAA	*-1.8 ± 0.9*	*-1.2 ± 0.2*	*-1.4 ± 0.6*	*-6.9 ± 3.3*	*-2.4 ± 1.0*
HJBFB	*-5.9 ± 1.2*	*-0.5 ± 0.3*	*-5.6 ± 1.3*	*-20.2 ± 6.0*	*-14.4 ± 3.6*

The timing of sea-ice freezing and melt and the duration of the melt period are also key factors shaping the structure of ecosystems in the Marine Arctic Ecozones. In the Arctic in general, the melt season duration increased by about two weeks per decade from 1979 to 2005 (Stroeve *et al.* 2006). The greatest increases have been observed in the Kara and Barents seas. In the Beaufort Sea, during the same period, the onset of melt has occurred 4.7 d/decade earlier and the melt season has increased 9.2 d/decade (Stroeve *et al.* 2006). In the CAA, between 1979 and 2008, the longest melt season occurred in 2008 and the duration of the melt season increased significantly by 7 d/decade (Howell *et al.* 2009). In HJBFB, significant trends in ice dynamics include earlier ice break-up in James Bay and western Hudson Bay, and later freeze-up dates in northern and northeastern Hudson Bay (Gagnon and Gough 2005).

The reduction in sea-ice extent and changing ice cycles will have far-reaching ecological impacts. The timing and magnitude of primary production will be affected by potentially increased light and nutrient availability in surface waters, enhanced upwelling or mixing and altered stratification of the water column. The direction, pelagic or benthic, and magnitude of carbon fluxes will change in response to shifts in primary productivity. Changes in sea ice will also impact the availability of food and habitat (ice or open water) for marine mammals as well as their ability to avoid predators.

Ice Thickness

The challenges of ice thickness measurements have limited the availability and understanding of trends in sea-ice thickness (Barber and Massom 2007). A recent estimate suggests that the thickness of Arctic Ocean sea-ice is declining at a rate of 0.57 m/decade (Lindsay *et al.* 2009). The Arctic Climate Impact Assessment (ACIA 2004) also reports reductions in ice thickness of 10 to 40% in different regions of the Arctic.

Decreasing trends in sea-ice thickness are expected to continue due to ice-albedo feedbacks, the export of ice out of the Arctic Basin via Fram Strait and sea surface pressure patterns driven by both the North Atlantic and Arctic Oscillation modes (Barber and Massom 2007). Further increases in SST could also drive these decreasing trends in ice thickness. Steele *et al.* (2008) estimated that the observed summer increases in SST since 1965 might reduce winter ice growth by up to 0.75 m. Alternatively, the additional summer heat may be released back to the atmosphere and delay fall freeze-up by a period of weeks to months.

Trends in ice thickness are correlated to changes in the age of sea ice (i.e., first-year versus multi-year sea ice). There has been a clear decline in the proportion of multi-year sea ice since the 1980's (Figure 17). In March 2009, sea-ice >2 years old accounted for less than 10% of total Arctic sea ice compared to 30% between 1981 and 2000. Figure 18 shows summer concentration trends for all ice types and multi-year ice specifically, in the Marine Arctic Ecozones between 1979 and 2008. The greatest decrease in multi-year sea ice has occurred in the CAA and in Foxe Basin (Figure 18). In the CAA, the area of multi-year sea ice is estimated to be decreasing at a rate of 6.4% per decade. This decreasing trend in the CAA may be counteracted by dynamic import of multi-year ice from the Arctic Ocean (Howell *et al.* 2009), or sustained by longer melt seasons that limit the promotion of first-year to multi-year sea ice (Howell *et al.* 2008).

The loss of multi-year sea ice results in increased concentrations of first-year sea ice during winter. First-year ice is thinner and thus is more susceptible to fractionation. An increase in ice deformation can decrease albedo, increase SST temperature feedback, and increase the potential for wind driven upwelling. New ice formation in the cracks and leads can also increase brine drainage thereby influencing water stratification. Rampal *et al.* (2009) found that between 1979 and 2007, the mean speed of sea ice increased by 17% and 8.5% per decade during the winter and summer, respectively, in the central Arctic Ocean. Consequently, the mean strain rate on this sea ice also significantly increased about 50% per decade during the same period. Thus, thinner sea ice induces numerous positive feedbacks that can further increase fractionation, potentially increasing export of ice out of Fram Strait (Rampal *et al.* 2009).

Increased deformation and transport, together with changing ice thickness, break-up/formation dates and extent, can have serious ecological consequences. The impact of these different sea-ice variables can be difficult to predict since their effects do not necessarily induce responses in a uniform way. For example, thinner sea ice may make accessing breathing holes easier for whales and seals. However, the unexpected movement and deformation (i.e., thick ridges) of thin ice may trap whales. In Baffin Bay there is a decreasing trend in the proportion of open water during the winter and an increasing trend in sea-ice variability. This unpredictability makes Narwhal vulnerable to entrapment and even suffocation (Laidre and Heide-Jørgensen 2005). Increasing sea-ice variability and deformation may also create serious problems for ice-obligate species such as the Hudson Bay eider (*Somateria mollissima sedentaria*), Ringed seal and polar bear. For example, the physical condition of polar bears in western Hudson Bay has declined due to earlier break-up and ice movement (Stirling *et al.* 1999). Changing sea-ice conditions also create transportation and harvesting problems for Northerners. Thinner and less abundant sea ice make it more difficult and dangerous to travel on the ice and hunt seals. In Sachs Harbour, people noticed more ice movement and changes in the distribution of leads, cracks and pressure ridges during the 1990s. In the past, they rarely had to worry about the ice but “now you really have to watch” when travelling on the ice (Berkes and Jolly 2001).

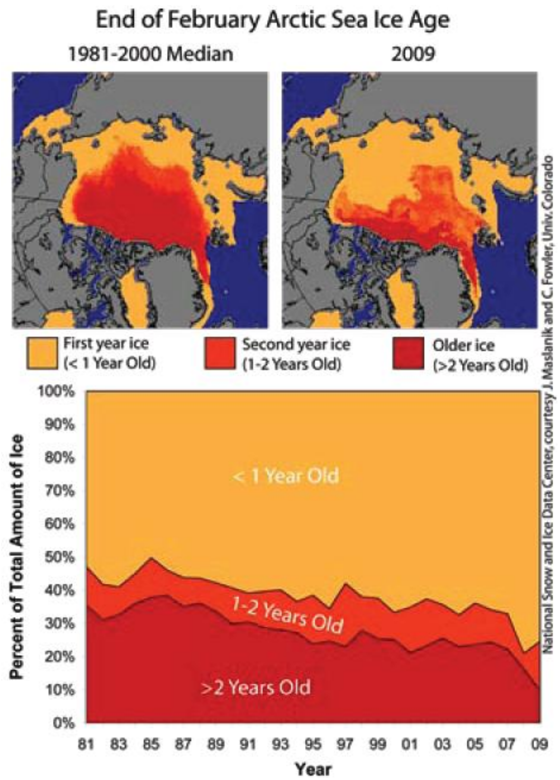


Figure 17. Distribution and relative abundance (%) of Arctic sea-ice ages in February between 1981 and 2009. Blue areas do not indicate open water but rather no data. (Source: From the National Snow and Ice Data Center, courtesy J. Maslanik and C. Fowler, University of Colorado)

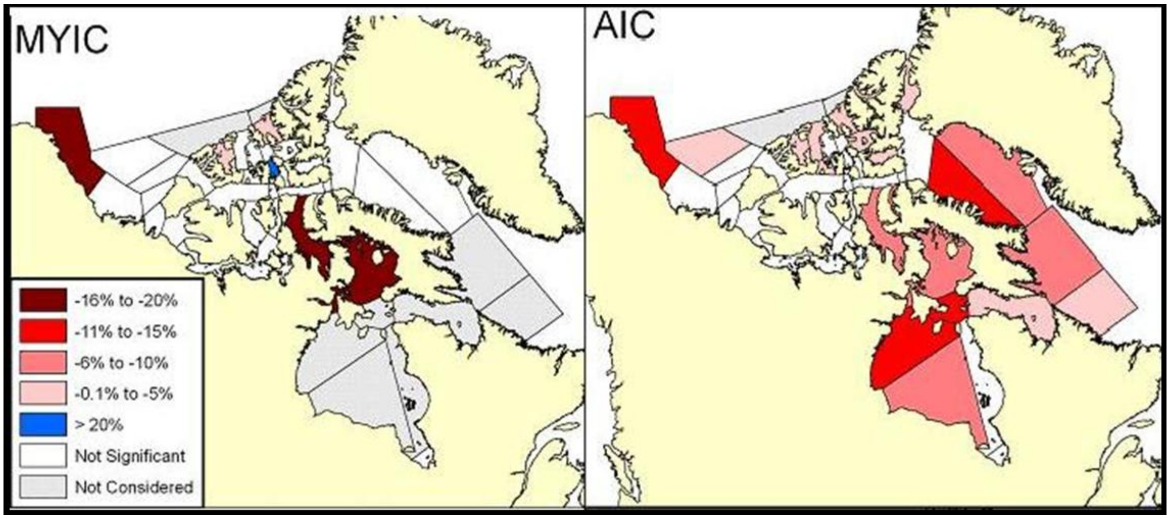


Figure 18. Trends in summer average ice concentration (June 25 to October 15) from 1979 to 2008 for all ice types combined (AIC) and multi-year ice (MYIC). Units are percent change per decade and only trends significant to the 95% confidence level are shown. (Figure courtesy of A.Tivy)

Polynyas

Polynyas are persistent and recurrent regions of open-water and/or thin ice surrounded by thicker consolidated ice. They recur in the same geographical location each year and persist for periods of weeks to months with intermittent closings and openings (Barber and Massom 2007). Polynyas are widely distributed in the Marine Arctic Ecozones (Figure 19) and are generally biologically significant habitats that have relatively high productivity and diversity (Stirling 1997). Polynyas are sustained by mechanical (e.g., winds, tides) or convective (e.g., heat fluxes) forces (Williams *et al.* 2007). Given the trends in SST, sea ice and wind forcing, polynyas may also be affected. Over a five year study of the Cape Bathurst polynya in the BSME, the average open water season was 4 months. However, in 1998, the open water period increased to seven months, likely in response to an atmospheric temperature anomaly (Arrigo and van Dijken 2004). The response of polynyas to climate change will likely be complex, with some polynyas disappearing and new ones being generated in new locations. Smith and Barber (2007) suggest that the opening of polynyas in the Arctic will generally decline. For example, in Hudson Strait a large recurring polynya used by Ivujivik and Salluit hunters started to freeze over in the 1980s and no longer opened during spring tides in the 1990s (McDonald *et al.* 1997).Thus, Northerners, marine mammals and birds that depend on polynyas will need to adapt spatially and/or temporally if they are to remain connected to these “hot spots” of production or alternatively adapt to less productive habitats (Ingram and Carmack 2006).

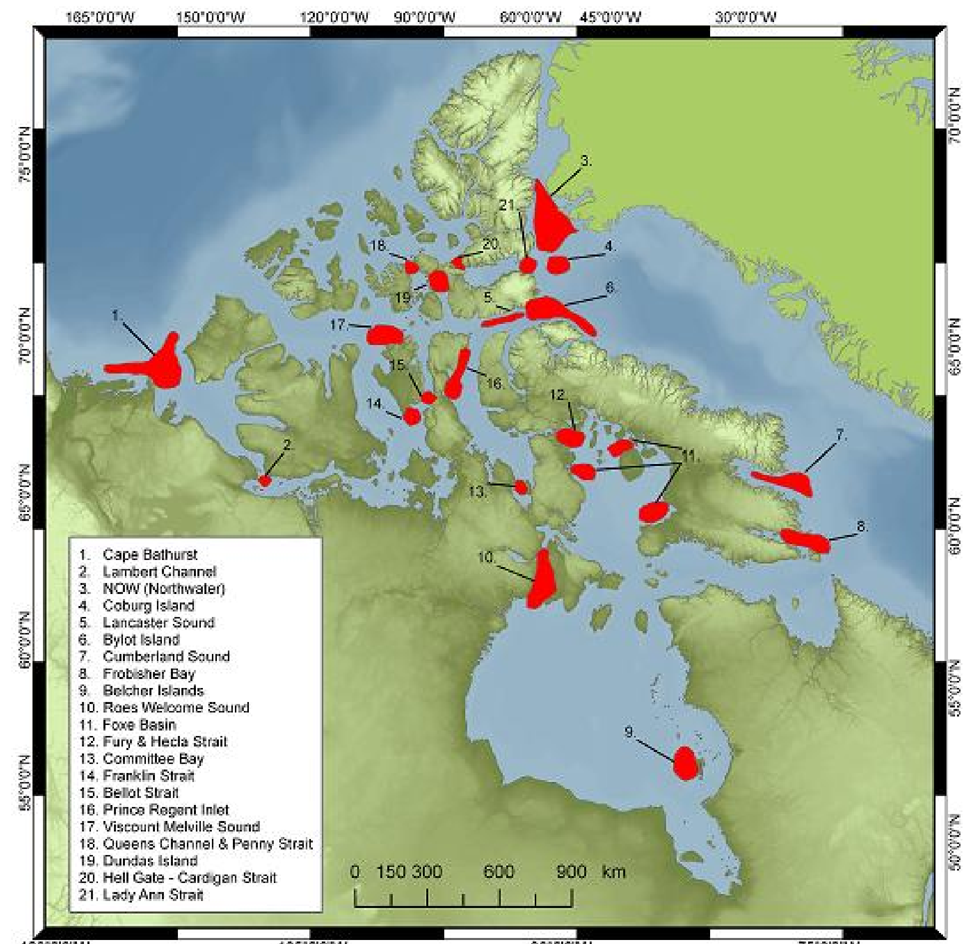


Figure 19. Approximate locations of polynyas detected and identified in the Marine Arctic Ecozones. (Modified from Barber & Massom 2007)

Shelves and Coastal Erosion

Over 50% of the total area of the Arctic Ocean is continental shelves and approximately half of the shelf area in the Arctic is located in the CAA (Jakobsson *et al.* 2004; Michel *et al.* 2006). The shelves of the Marine Arctic Ecozones are the location of polynyas and are important habitat with productive ecosystems. However, the shallow water column and presence of first-year sea ice makes these ecosystems susceptible to climate-driven change. Sea ice on the shelves plays a key role in changing water column salinity via brine expulsion or ice melt thereby altering water masses that are eventually exported from the Arctic.

The amount and timing of river discharge to the shelves is also susceptible to climate-driven changes in precipitation and air temperature, and to changes in land-use such as hydro development. Trends in river discharge are discussed in detail in the terrestrial chapter. In general river discharge to the Arctic Ocean decreased by about 10% for the period 1964 to 2003 (Déry and Wood 2005). Inflow to Hudson Bay declined by 13% between 1964 and 1994, likely in response to the terrestrial effects of the Arctic Oscillation on atmospheric circulation (Déry and Wood 2004; Déry *et al.* 2005).

Interactions of sea level rise, storms and sea ice with coastal geology and morphology, influence coastal erosion in the Arctic. Parts of the Arctic coastline are rebounding from past glaciation periods, while in the Western Arctic, the coastline is subsiding. As a result, the highest threat to coastal erosion is centred in the Western Arctic, and this has been the focal area of research and monitoring to better understand processes and effects. Erosion involves the release of icebonded, unconsolidated sediments and large masses of ice unique to Arctic coastline structures. The presence of first-year sea ice along the coast is critical for protecting coastal sediments from the impact of waves and storm surges. Near Tuktoyaktuk, a single storm can erode inland, over 10 m, although the historical retreat rate of coastlines in the Beaufort Sea is about 1-2 m/y (Solomon *et al.* 1993). Climate change may increase rates of erosion, beach migration and extreme flooding events by impacting storm frequency, sea-level rise, permafrost properties, and sea-ice characteristics (Mason and Solomon 2007). The greatest potential for coastal erosion and shoreline sensitivity to sea level rise is in the BSME, where it generally increases from east to west (Figure 20, Manson *et al.* 2005). The percentage of open water in the neashore Beaufort Sea is also increasing, lengthening the season during which storms can influence shorelines (Figure 20). Coastal erosion in the BSME continues to be of concern to communities such as Tuktoyaktuk, where it has destroyed a curling rink and led to the abandonment of an elementary school. Community members from Tuktoyaktuk and Sachs Harbour have noticed an increase in coastal erosion due to more wave action in longer ice-free seasons (Jolly *et al.* 2002).

HABITAT

In 1994 the identification of hot spots and areas of special interest were identified during a Parks Canada workshop (Figure 21). Since that time, habitat in the Marine Arctic Ecozones has been further assessed to determine Ecologically and Biologically Sensitive Areas (EBSAs) in support of Oceans Management Planning and initiatives such as Marine Protected Areas (MPAs) and environmentally vulnerable habitats in Large Management Ecosystems (LMEs). Bowhead and Beluga habitat in the eastern Arctic has also been assessed in support of critical habitat designations under the Species at Risk Act (SARA).

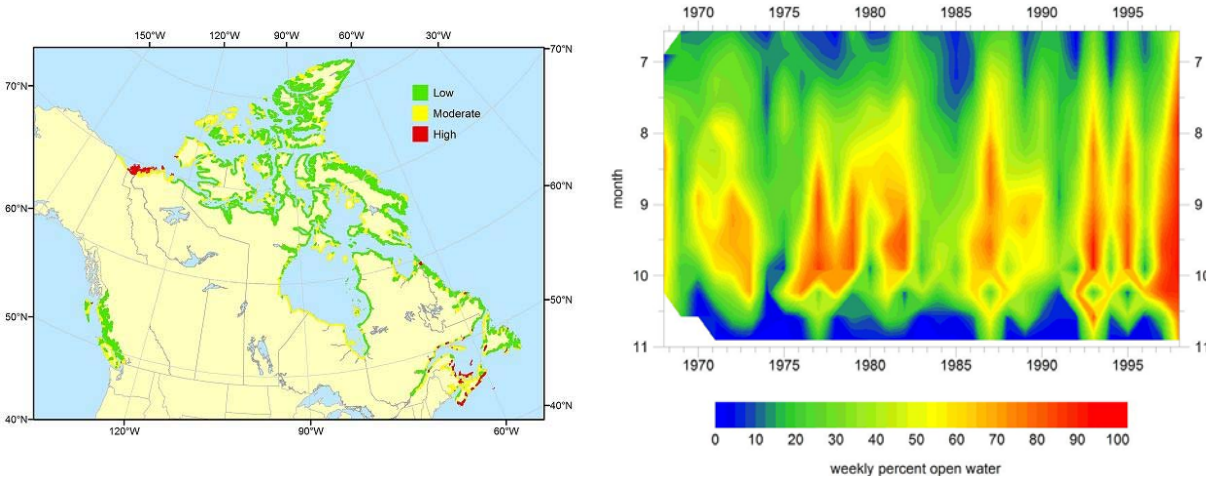


Figure 20. Coastline sensitivity to sea-level rise and percent open water trends in the coastal Beaufort Sea. (Figures complements of G. Manson)

Figure 22 shows EBSAs identified in the BSME and the location of the first proposed MPA for the Canadian Arctic. The Tarium Niryutait MPA has been proposed based on the importance of the habitat for the Beaufort Sea Beluga population. This MPA contains three areas, Niaqunnaq, Okeevik, and Kittigaryuit (Figure 22), which have been traditionally used by the Inuvialuit, and are important from cultural, subsistence and economic perspectives. A new area of interest that is undergoing an assessment as an MPA is located in Darnley Bay near Paulatuk, in the Beaufort Sea Large Ocean Management Area (LOMA).

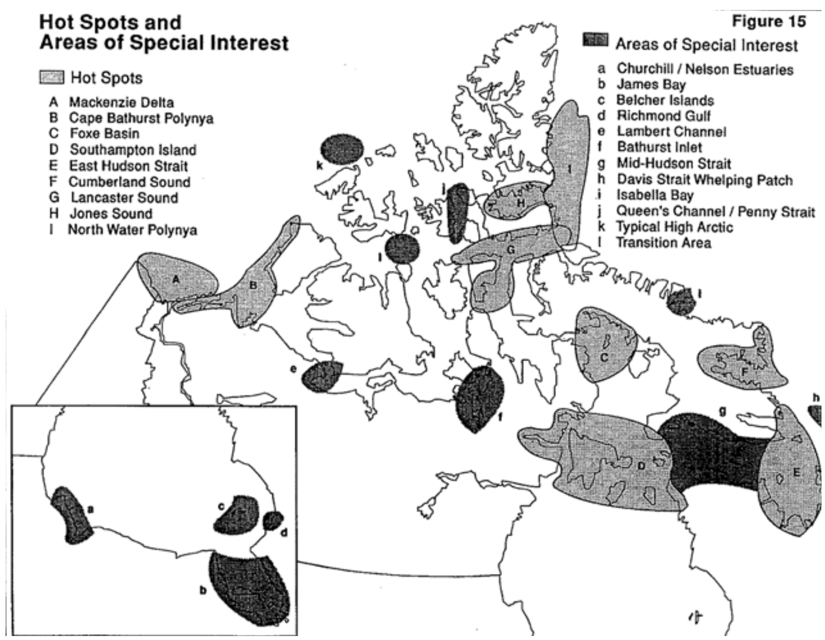


Figure 21. Hot spots and areas of special interest identified by Parks Canada in 1994

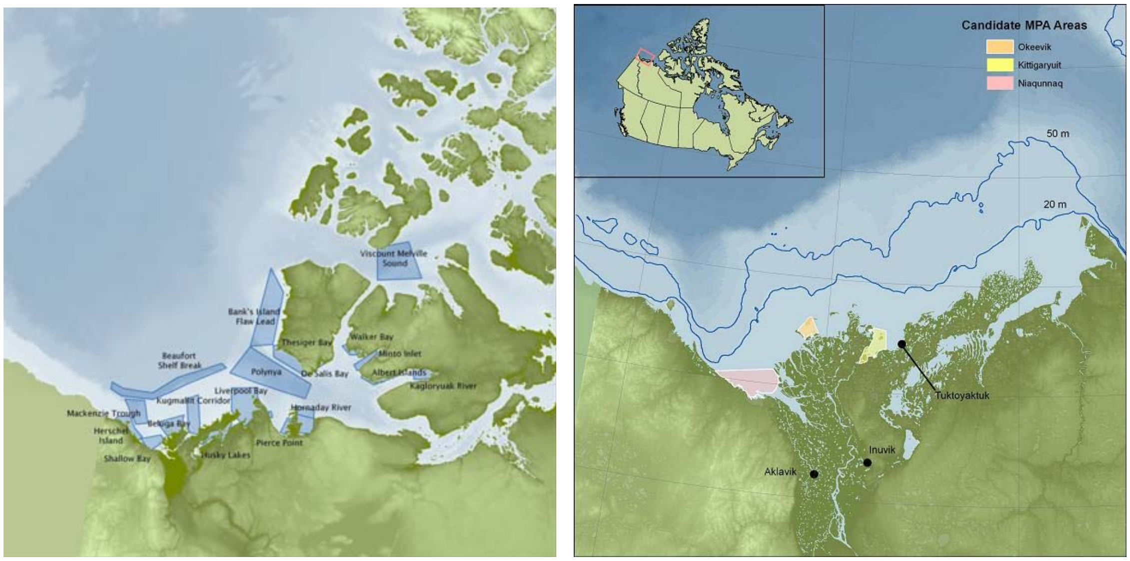


Figure 22. Ecologically and Biologically Sensitive Areas and the proposed Marine Protected Area in the BSME

DFO and the Nunavut Government have started the processes to establish another MPA in Foxe Basin. Areas around Rowley Island, Igloolik and Fury and Hecla Strait on the western side of northern Foxe Basin have been identified as important areas for Bowhead whales and Walrus that will be proposed as a MPA (DFO in prep.). Two of these areas are associated with polynyas and ice edges.

Despite having important habitat for Belugas and many other marine species, there has been no official designation of EBSAs or MPAs inside Hudson Bay. Figure 23 shows that a large portion of the HJBFB has important habitat areas that could be vulnerable to hydrocarbon development. Important bird habitat has been recognized in Hudson Bay with the establishment of eight migratory bird sanctuaries in the HJBFB Ecozone.

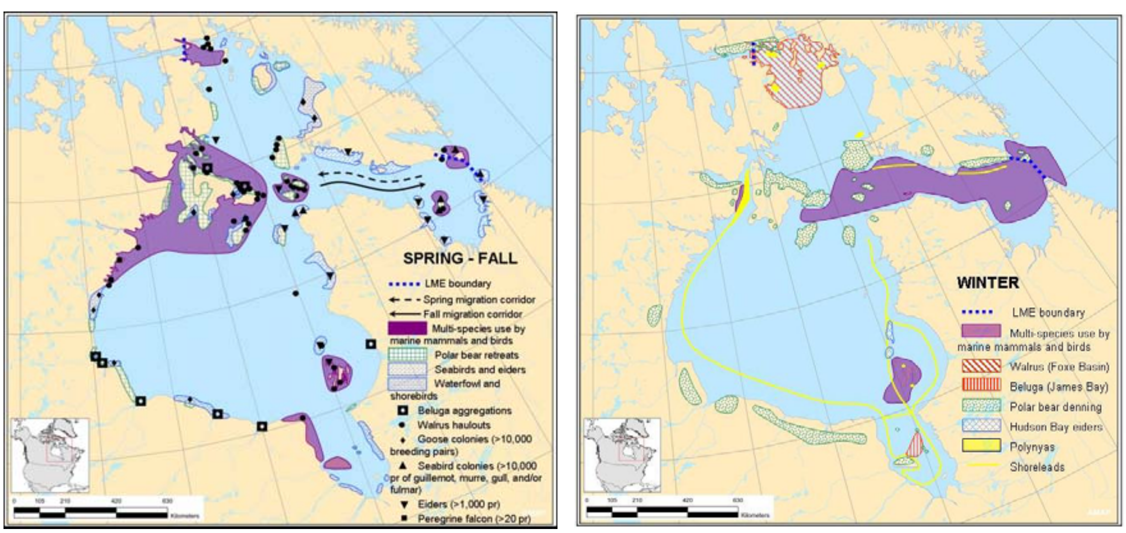


Figure 23. Particularly environmentally vulnerable areas for marine mammals and birds within the Hudson Bay during spring-fall and in winter (Source: AMAP)

To date, EBSAs have not been assessed in the CAA. However, areas such as Resolute Passage and Lancaster Sound are key areas of productivity and diversity. Lancaster Sound, for example, is the breeding site for approximately three million seabirds. Another region of great importance is the North Water Polynya which may be the most productive ecosystem north of the Arctic Circle, and has been an important resource for the Inuit for at least 5000 years. The ice-free waters of the North Water are a major part of the feeding, reproductive and migratory cycles of large populations of seabirds and mammals, many of which overwinter there. The enhanced activity of the lower foodweb within this polynya is also crucial for the transfer of energy from phytoplankton to fish and ultimately to human populations within the Archipelago. Parks Canada is working with the Nunavut government on a potential National Marine Park in the Lancaster Sound region. These initiatives typically take several years to complete. Recently habitat use has been assessed for the identification of Critical Habitats under SARA for Bowhead whales in the eastern Arctic (Hudson Strait and Davis Strait, northern Foxe Basin, Gulf of Boothia-Prince Regent Inlet, mid-eastern coastline waters off Baffin Island (Dueck and Ferguson 2008) and Beluga in Cumberland Sound (Richard and Stewart 2008).

There has likely been changes in marine habitat characteristics or shifts in habitat use by different species (e.g. shifts in migration, spawning) although the lack of baseline data precludes comparisons and the identification of trends. One exception is sea-ice habitat which, as previously discussed, is changing in extent, thickness and distribution. These changes have influenced predator-prey interactions (e.g., polar bears and seals) and the dependability of sea ice as a predictable platform for marine mammals. Continued monitoring is required to determine how ice-obligate or ice-associated species will adapt to this habitat change.

Increased hydrocarbon development and transportation have also been recognized as potential threats to habitat and biodiversity in the Arctic. In response, the Arctic Council has prepared reports that focus on species and habitat vulnerability to hydrocarbon development and shipping and includes regions of the Marine Arctic Ecozones. The AMAP Arctic Oil and Gas Assessment and Arctic Marine Shipping Assessment will both be available at the AMAP website (www.amap.no).

COMPOSITION

Species composition of the three Marine Arctic Ecozones is briefly summarized below. Further details for the BSME and HJBFB can be found in recent detailed reports (Stewart and Lockhart 2005; Cobb *et al.* 2008). Trends in individual species are generally unknown. However, known trends for indicator/keystone as well as SARA/COSEWIC species are provided when available.

BEAUFORT SEA

The BSME has a diverse community of bacteria, phytoplankton and ice algae. Bacterial diversity includes Archaea which is likely of river origin in the BSME (Wells *et al.* 2006). Diatoms are the major taxonomic group of primary producers. In the sea ice alone there are about 100 different species of diatoms (Rozanska *et al.* 2009). Species composition varies seasonally and spatially. For example, the greatest contribution to total phytoplankton cell numbers shifts from diatoms to flagellates when moving from near to offshore sites (Hsiao 1976).

Zooplankton species in the BSME represent marine as well as freshwater species from the Mackenzie River (Darnis *et al.* 2008). Keystone marine species are copepods (e.g., *Calanus glacialis*), which, with euphausiids, are the main prey for Bowhead whales (Hazard and Lowry 1984). Other important taxa include hydromedusae, pteropods and amphipods (e.g., *Themisto*). There is also the potential for Pacific zooplankton to enter Beaufort waters and they have previously been detected but at very small amounts. It is not known if changes in sea ice and water masses will lead to an increased presence of Pacific zooplankton or any populations that will be reproductively successful (i.e. a true range expansion, Nelson *et al.* 2009). Over 900 taxa of macrobenthic species have been identified in the Beaufort Sea, with Arthropoda, Annelida and Mollusca being the major phyla (Chapman and Kostylev 2005). Compared to the HJBFB Ecozone, the BSME has higher taxonomic distinctness but lower species richness in the benthos (Cusson *et al.* 2007).

Fish species in the BSME vary depending on the aquatic habitat types, namely freshwater drainages, nearshore coastal waters and offshore waters as well as seasonal changes in water salinity (DFO 2007). Anadromous stocks utilize the streams, rivers and brackish waters of the nearshore whereas marine species are distributed in the offshore waters (Craig 1984). Approximately 71 species of fish have been collected in the Beaufort Sea (Coad and Reist 2004). Local communities have also reported the increased observations of Pacific Salmon and Least Cisco (*Coregonus sardinella)*, locally called herring (Huntington *et al.* 2005). However, these sightings may not be evidence of a significant range extension/shift for these species. In recent years there has been an increased frequency of salmon observations in the Arctic. In the Beaufort Sea, chum, pink, sockeye, coho and chinook salmon have been observed even though only chum salmon are considered natal to the Mackenzie River watershed (Irvine *et al.* 2009). Keystone anadromous species include the Dolly Varden (*Salvelinus malma*) and Arctic Char. Keystone marine fish include Arctic Cod which is an important trophic link in the transfer of energy to seabirds and marine mammals (Bradstreet and Cross 1982). Arctic Char is also a species of interest in the Arctic and is discussed below.

Key seabird species in the BSME include the Black Guillemot (*Cepphus grille*), Glaucous Gull (*Larus hyperboreus Gunnerus*), Thayer's Gull (*Larus thayeri*) and Arctic Tern (*Sterna parasisaea Pontoppidan*). Long-term trend data are not available for seabirds in this Ecozone. However, Black Guillemots on the Alaskan side of Beaufort Sea coast have shown decreased population and reproductive success since 2000 in response to changes in ice conditions (G. Divoky, http://cooperisland.org/importantfindings.htm).

The abundance and status of Arctic marine mammal populations are summarized in Table 4. The BSME is a year-round habitat for Beluga and Bowhead whales as well as Ringed and Bearded seals. Killer (*Orchinus orca*) and Gray (*Eschrichtius robustus*) whales, Narwhal, Harbour seals (*Phoca vitulina*) and Walrus (*Obodenus rosmarus*) are also observed on occasion. There are seven genetically different stocks of Beluga in the Canadian Arctic and the BSME Beluga population is identified as the Eastern Beaufort Sea stock. The Eastern Beaufort Sea stock is one of the largest Beluga stocks in Canada estimated at just under 40 000. The western arctic Bowhead whale population, which summer in the BSME, was depleted by commercial whaling between 1840 and 1907. The historic population for Bowhead is estimated between 10 400 and 23 000 and was reduced down to ca. 3000 individuals. As of 2001, the population was estimated to be between 7700 and 13 500 individuals (Zeh and Punt 2005; COSEWIC 2009), increasing at a rate of 3.4% per year between 1978 and 2001 (Figure 24). Ringed seals are much more abundant than Bearded seals (Table 4) and Ringed seal populations are consequently better known. Sharp declines in Ring seal populations in 1975 and 1985 were linked to heavy ice conditions which reduced productivity and ultimately food availability for the seals (Smith 1987). Local communities (e.g., Sachs Harbour) have also noticed an increasing occurrence of skinny seal pups, which has been linked to a reduction in sea ice (Jolly *et al.* 2002; Nichols *et al.* 2004).

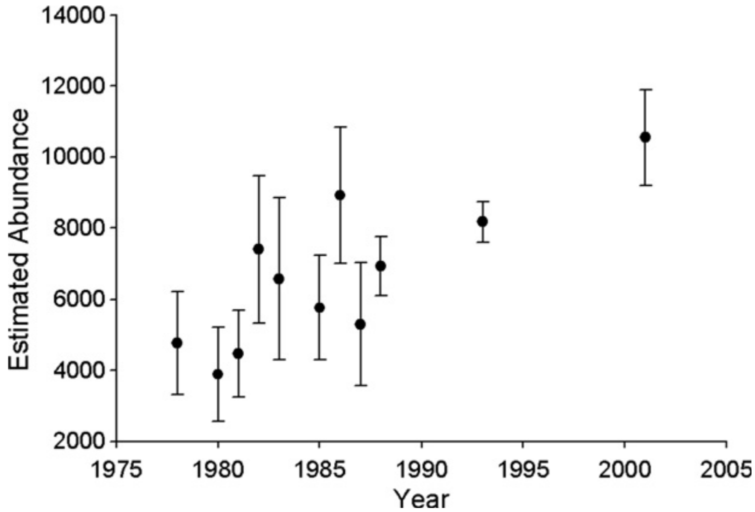


Figure 24. Abundance estimates and standard deviation for the western Arctic Bowhead whale stock (Zeh and Punt 2005)

CANADIAN ARCTIC ARCHIPELAGO

To date, the biodiversity of the Canadian Arctic Archipelago has not been assessed as a whole. However, similar to BSME and HJBFB, there is a diverse complement of primary and secondary producers. The composition of zooplankton assemblages is dominated by copepods and the relative contribution of different copepod species appears to be relatively stable. In studies between 1983 and 1995, the same seven species of copepods comprised numerically over 99% of the copepod assemblages (Fortier *et al.* 2002). Nine different benthic assemblages have been identified in the CAA with Lancaster Sound having among the highest benthic biomass in the Arctic (Thomson 1982). Many species of corals and sponges have also been discovered in the CAA including both Gorgonian and Antipatharian species of corals. Deep sea corals are located at depths greater than 500 m (DFO 2007) and there is a significant concentration of corals and sponges in the southeast corner of NAFO area 0A (Davis Strait, Campbell and Simms 2009). Important fish species in the CAA include Arctic Cod, Arctic Char, Capelin (*Mallotus villosus*), Pacific Herring and Fourhorn Sculpin (*Myoxocephalus quadricornis*). Arctic Cod, Sculpins and Capelin play a key role as prey for other fishes, birds and/or marine mammals. Char, herring and Greenland halibut (*Reinhardtius hippoglossoides*) are important locally for subsistence fishing. Complete lists of fish species in the CAA are available in Coad and Reist (2004).

Key seabird species for the CAA are the Northern Fulmar, Black-legged Kittiwake, Thick-billed Murre, Black Guillemot, Glaucous Gull, Iceland Gull, Thayer's Gull, Ivory Gull (*Pagophila eburnean*) and Arctic Tern. Data on diet and population trends have been collected from Thick-billed Murres, Northern Fulmars, Black-legged Kittiwakes and Glaucous Gulls at Prince Leopold Island since 1975. Population trend data are available for Northern Fulmars at Cape Vera, Devon Island. Additional data are available on Ivory Gulls (COSEWIC Endangered) and Black-legged Kittiwakes at several colonies.

At Prince Leopold Island several species have shown changes in timing of breeding, reproductive success and adult colony attendance in response to variations in ice conditions since 1975 (Gaston *et al.* 2005b). Figure 25 illustrates this relationship for breeding timing in Thick-billed Murres. Since the 1970s the overall population trends have been positive for both

Thick-billed Murres (+3.0%/y to 1988, no significant change subsequently) and Black-legged Kittiwakes (no significant change from 1975-1988, +1.7%/y from 1988-2008). Northern Fulmars

Table 4. Summary of marine mammal abundances and trends in the Marine Arctic Ecozones. (Updated from CAFF CBMP Report, Simpkins et al. 2009)

Species	Stock/Population	Abundance	Most recent data	Trend
Bowhead	Bering-Chukchi-Beaufort Seas	10500[1]	2001	Increasing
	E. Canada-W. Greenland	7309[2]	2002-2004	Increasing
Beluga	Eastern Beaufort Sea	39300	1999	Stable
	Foxe Basin	1000	1983	Unknown
	Western & Southern Hudson Bay	57300[3]	2004	Stable since 1987
	James Bay	9292[4]	2008	Unknown
	Eastern Hudson Bay	1265[4]	2008	Declining
	Ungava Bay	<50[4]	2008	Unknown
	Cumberland Sound	1500	2001	Declining prior to 1999
	Eastern High Arctic-Baffin Bay	21200	1996	Stable
Narwhal	Canadian High Arctic	70000	2002-2004	Unknown
	Northern Hudson Bay	610[5]	2008	Possibly declining
	Eastern Baffin Island	10073[6]	2002-2004	Unknown
Ringed seal	Arctic subspecies	~2.5 million	1970s	Unknown
Bearded seal	Canadian waters	190000	1958-1979	Unknown
Walrus (Atlantic subspecies)	South and East Hudson Bay Population	270[7]	1980s	Unknown
	Northern Hudson Bay–Davis Strait Population	1400[7]	1988-1990	Possible increase
	Foxe Basin Population	5500[7]	1988-1989	Unknown
	Baffin Bay (High Arctic) Population	350[7]	1998-2001	Unknown

[1]George *et al.* 2004, [2]Cosens *et al.* 2006, [3]Richard 2005, [4]Gosselin *et al.* 2009, [5]Richard 2010, [6]Richard 2008, [7]COSEWIC 2006

showed great inter-year variation in colony attendance. Numbers at Prince Leopold Island decreased at 1.0%/y from 1976 to 2008. Although evidence is sparse, several Northern Fulmar colonies in this Ecozone, the only one in Canada where Northern Fulmars are abundant, show signs of decline (Gaston *et al.* 2006). There is also evidence that Glaucous Gull numbers have declined by >50% since the 1970s, but monitoring samples are small (A.J. Gaston, Grant Gilchrist unpublished).

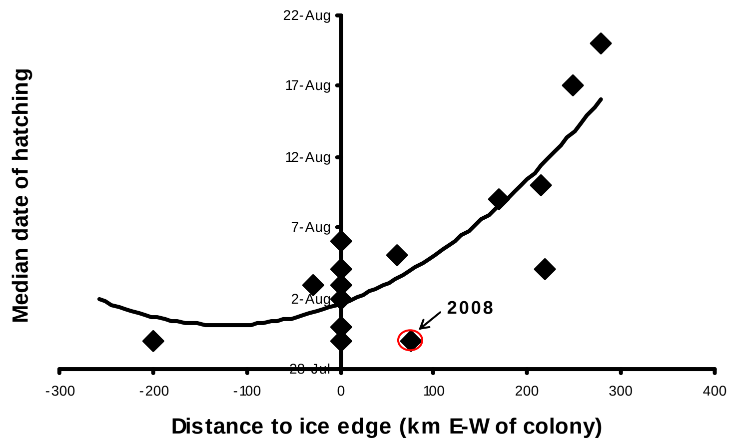


Figure 25. Median date of hatching for Thick-billed Murres at Prince Leopold Island, Nunavut, in 13 years between 1975 – 2008 (adapted FROM Gaston et al. 2005b).

The population of Ivory Gulls breeding on northern Baffin Island, Devon Island and southern Ellesmere Island, formerly about 2000 pairs, fell by >80% from the 1980s to 2005 (Gilchrist and Mallory 2005). The speed of this decline, the remoteness of their breeding sites, and their tendency to shift among breeding sites from year to year have made it difficult to study the problem. Consequently, it is not known whether it was due to changes on the breeding grounds, or on their marine feeding areas. The latter seems most likely, but the specific changes that have affected them are unknown.

Thick-billed Murres, Black-legged Kittiwakes and Northern Fulmars at Prince Leopold Island all feed similar food, principally Arctic Cod, to their nestlings. Therefore the divergence in population trends (Figure 26) strongly suggests that these trends are determined by events on the wintering grounds, or possibly differences/changes in the vertical distribution of their prey. For Thick-billed Murres, similarity between trends in the high and low Arctic suggests population control may be occurring during the non-breeding season (Gaston 2003).

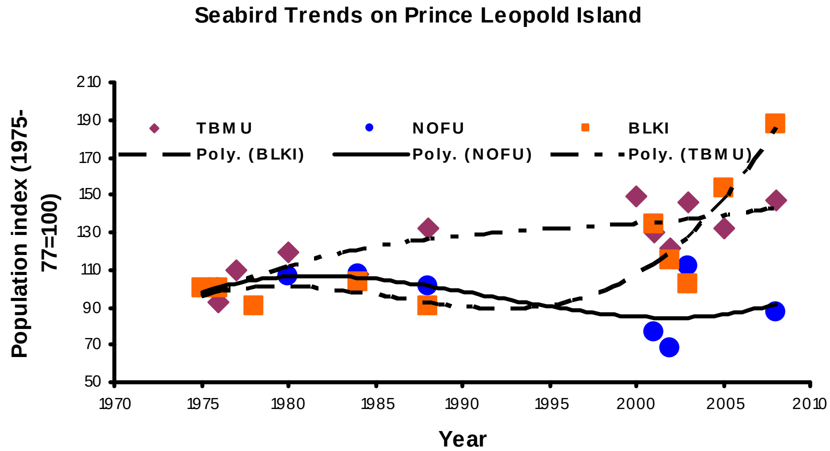


Figure 26. Trends in numbers of Thick-billed Murres (TBMU), Black-legged Kittiwakes(BLKI) and Northern Fulmars (NOFU) counted on population monitoring plots at Prince Leopold Island: baseline is mean of 1975-77 = 100.

Marine mammals in the CAA include Bowhead, Beluga and Narwhal; Bearded, Ringed and Harp seals; and the Atlantic walrus. Pods of Killer whales have also been observed during the summer. Marine mammal trends in the CAA are summarized in Table 4. Narwhal have very low genetic diversity (Palsbøll *et al.* 1997) suggesting that their diversity was previously reduced by a population bottleneck (Laidre and Heide-Jorgensen 2005). In addition, this species does not appear to adapt its behaviour to stressors such as hunting, indicating that it could be quite sensitive to changes in habitat (e.g., sea ice cover) or prey availability (Laidre and Heide-Jorgensen 2005).

HUDSON BAY, JAMES BAY AND FOXE BASIN

The HJBFB Ecozone has primary producers of marine and freshwater origin with about 500 identified taxa of phytoplankton (Roff and Legendre 1986; Harvey *et al.* 1997). Diatoms are most abundant in marine habitats whereas dinoflagellates and freshwater species dominate nearshore in river plumes (Stewart and Lockhart 2005). Unique to this Marine Arctic Ecozone are productive beds of eelgrass and other vascular plants in James Bay and sporadically along the south-western coast of Hudson Bay. These plant beds provide important food sources for seabirds, stabilize shorelines and provide habitat for invertebrates and juvenile fish (Stewart and Lockhart 2005). Benthic macrofauna in the HJBFB Ecozone varies spatially with mollusca and arthropoda phyla being dominant in James Bay and Ungava Bay, respectively (Cusson *et al.* 2007). Eighty taxa of zooplankton have been identified in Hudson Bay and Hudson Strait where their distributions are influenced by freshwater input, circulation patterns and phytoplankton concentrations (Harvey *et al.* 2001). The copepod *Calanus glacialis*, for example, is most abundant in samples from Hudson Strait where phytoplankton concentrations are highest.

There are about 60 species of fish in the HJBFB Ecozone, consisting of a mixture of marine, estuarine and freshwater species. Anadromous species such as salmonids (e.g. Arctic Char) are important for subsistence fisheries (Stewart and Lockhart 2005). Subsistence catches have declined from a peak of 897 tonnes in 1962 to about 290 tonnes in the early 2000s. This decline has been linked to use of snowmobiles instead of dog sleds, which reduces the need for fish as dog food (Booth and Watts 2007). Based on seabird diets between 1980 and 2002, the composition of fish in northern Hudson Bay has also appeared to change with a reduction in the relative abundance of Arctic Cod and an increase in Sandlance (*Ammodytes spp.*) and Capelin (*Mallotus villosus*) (Gaston *et al.* 2003). This shift may be the result of increased water temperatures. The Rainbow Smelt is an invasive species that has been spreading in the HJBFB Ecozone since the 1990s. Its impacts on the native fishes are unknown and merit study (Stewart and Lockhart 2005).

Key seabird species for the HJBFB Ecozone include the Thick-billed Murre, Black Guillemot, Glaucous Gull, Iceland Gull and Arctic Tern. Good data on diet and population trends for Thick-billed Murres and Glaucous Gulls are available for Digges and Coats islands from 1980 onwards. Information on population trends in gulls and terns is available from islands in eastern Hudson Bay. Information available on populations elsewhere derives from only two to three visits.

At Coats Island, where annual monitoring counts of Thick-billed Murres are available since 1985, the population has shown an overall increase of 1.7%/y (Gaston 2002, and unpublished; Figure 27). This has not been a consistent trend. A sharp decrease was observed in 1989-1991. It coincided with the crash of the groundfish industry off eastern Newfoundland, where these birds winter. This decline was followed by rapid increase in the 1990s, and a levelling off after 2000.

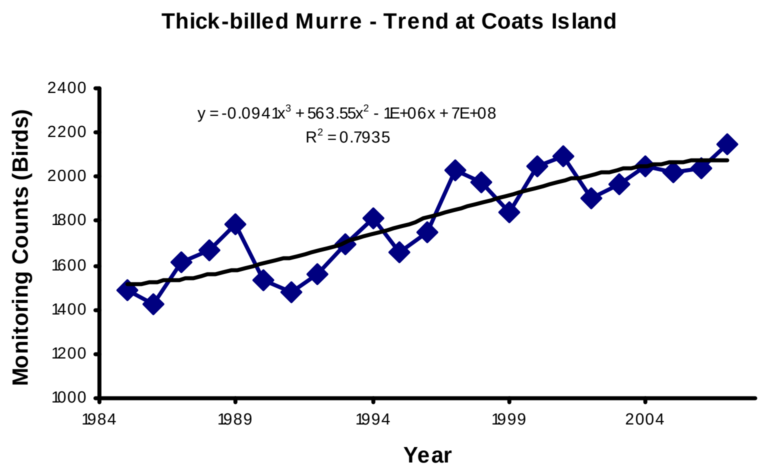


Figure 27. Trend in Thick-billed Murre population index (counts of fixed study plots) at Coats Island, Nunavut since 1985. (Source: Gaston 2002 and Unpublished)

Breeding of Thick-billed Murres at Coats Island has become earlier since the 1980s, with an average advance of five days in the mean date of hatching (Figure 28). This compares with a 17 day advance in the date of ice break-up in adjacent waters. Timing of breeding by Glaucous Gulls is closely tied to that of Thick-billed Murres (Gaston *et al.* 2009). These gulls breed in association with the murres, and young gulls are fed principally murre eggs and nestlings. Hence the date of laying of gulls has also advanced. These effects are probably linked to climate change.

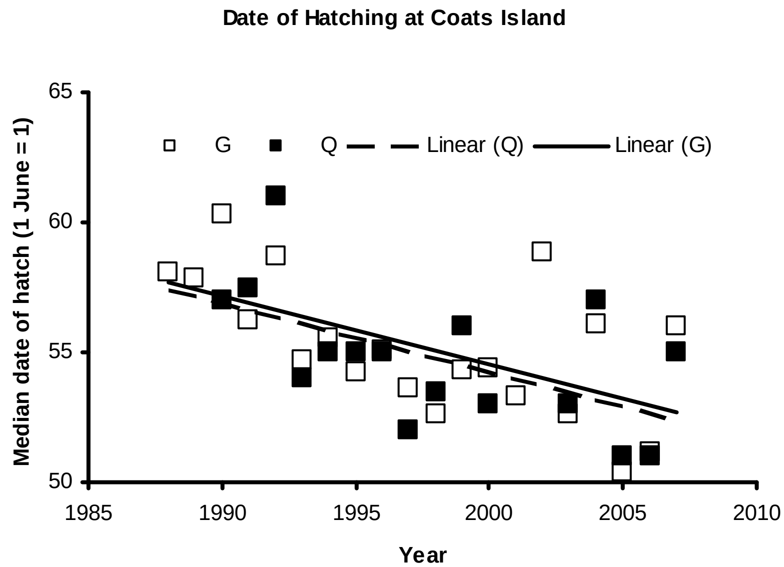


Figure 28. Change in median date of hatching at Coats Island since 1988, based on two study plots using different methods for determination: Q dates derived from observations without disturbance; G obtained by disturbing birds to observe eggs. Regression slopes suggest advance by about 1 day every three years (Source: A.J. Gaston, H.G. Gilchrist and M. Mallory unpublished)

Belugas, Narwhals and Bowhead whales frequent the HJBFB as ice conditions permit, with Killer and Minke whales sometimes visiting during the summer. Beluga are present in genetically distinct stocks (Caron and Smith 1990; de March and Postma 2003) with animals moving widely in this Ecozone during the summer. Belugas are the only whales to commonly enter James Bay and southeastern Hudson Bay. The largest summering concentration of Belugas in the world occurs around the Nelson River estuary in southwestern Hudson Bay (Richard *et al.* 1990; Richard 2005). Narwhals and Bowhead are found mostly in northwestern Hudson Bay and northern Foxe Basin. Inuit observations suggest that the Eastern Arctic Bowhead population is higher now than in the 1950s and they believe that the Bowheads are more common than previous scientific estimates (George 2008).

Four stocks of Atlantic walrus (*Obodenus rosmarus rosmarus*) have been identified based on their distribution, genetics and isotopic studies. Walrus stocks have been reduced by historical and recent harvesting, although levels of recovery are uncertain as historical numbers are not known (COSEWIC 2006). Currently population trends are mixed and often difficult to identify. For example, decreasing Walrus numbers may not necessarily indicate a declining population but rather a movement to better feeding grounds or haulout habitat (Stewart and Lockhart 2005). Community members have suggested that declines in Walrus populations in James Bay and southwestern Hudson Bay may be associated with poor or wasteful harvest techniques, changing shorelines and habitat alteration (e.g., overgrown with willow) (Fleming and Newton 2003). Ringed seal populations in Hudson Bay fluctuate and are presented along with trends in ice cover and break-up date anomalies in Figure 29. Marine mammal trends are summarized in Table 4.

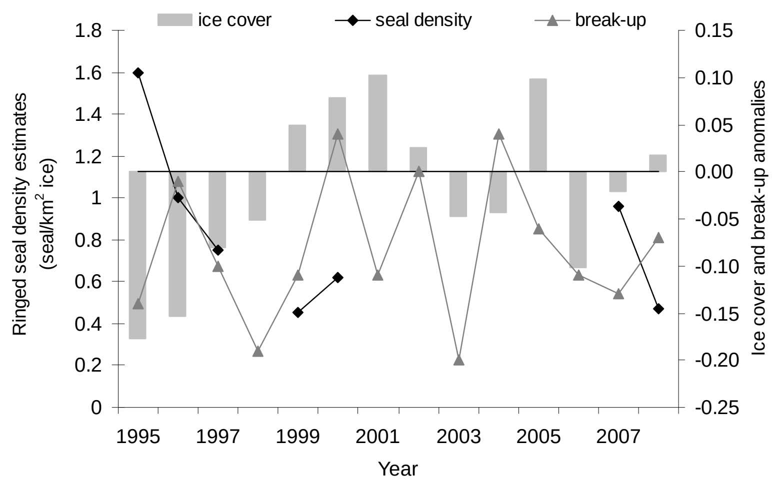


Figure 29. Ringed seal density, break-up date and mean ice cover anomalies for the end of May to beginning of June in western Hudson Bay over a 14-year period. The solid line denotes departures from the mean break-up and ice cover conditions calculated over the period 1971-2008 (Figure courtesy of S. Ferguson)

TRENDS IN SPECIES OF SPECIAL INTEREST

Species/populations of concern in the Marine Arctic Ecozones listed under COSEWIC (*Committee on the Status of Endangered Wildlife in Canada*) and/or SARA (*Species at Risk Ac*t) are summarized in Table 5. The status and trends of marine mammals is dependent on both its population dynamics and the key factors that drive those dynamics such as behaviour, health, trophic dynamics, habitat, and the effects of human activities. The majority of COSEWIC species in the Marine Arctic Ecozones are marine mammals. Obtaining status and trends for marine mammals are challenging and the majority of studies have focused primarily on population dynamics. Some of the information is outdated or only provides a snap-shot of a portion of the population. Monitoring of marine mammals is subject to changing priorities and requests. Consequently, robust assessments of long-term trends are not readily available. Continued monitoring is required to assess the impact of climate change on marine mammals.

Ivory Gulls

The ivory gull is an iconic seabird that inhabits Arctic oceans throughout the year, often in association with polar pack ice. It is rare, with <14 000 breeding pairs globally, and remains one of the most poorly known seabird species in the world. Canada supports breeding populations of international significance. Local Inuit reported that there were fewer ivory gulls in the early 2000s than in the 1980s (Mallory *et al.* 2003). No population trend data existed for this species in Canada prior to a 2002–2003 study that found an 80% decline in numbers of nesting ivory gulls (Gilchrist and Mallory 2005). Several of the largest known colonies were completely extirpated and those that remained supported significantly fewer nesting birds than previously observed. Results suggested a numerical decline in the population and not simply annual fluctuations in colony occupation. Declines have occurred in all habitat types and across the known Canadian breeding range. These dramatic declines led COSEWIC to raise the status of this species to endangered in 2006.

Colonies continued to decline from 2004 to 2006, with sites at the southern edge of the breeding range on Baffin Island almost completely extirpated; only one pair remained in 2005 and 2006. Ellesmere Island, where new colonies were discovered in 2006, may be the only Canadian site where breeding ivory gulls will persist in the future (Robertson *et al.* 2007).

Arctic Cod

The small Arctic Cod (*Boreogadus saida*) (<25 cm) is a keystone species that plays a central role in trophodynamics. Arctic Cod are a major food of seabirds and marine mammals, although they do not appear to be the sole food source of any one species. Lowry and Frost (1984) estimate that in the Alaskan Beaufort Sea, Ringed seals consume 21 203 tonnes, Beluga consume 5875 tonnes and marine birds consume 1552 tonnes of Arctic cod per year. There are no quantitative estimates of the size of the Arctic Cod population in the Marine Arctic Ecozones. In 1990, schools of Arctic Cod in the CAA were estimated to have about 900 million fish (Crawford and Jorgenson 1996). However, based on consumption estimates, the population must have been at least seven times greater to satisfy all the predators. In the search for the "missing" cod, acoustic instruments have recently been used to identify significant aggregations (ca. 11 kg cod/m^2) in Franklin Bay (BSME) that would certainly satisfy the requirements of predators in that area (Benoit *et al.* 2008). The significance of the Arctic Cod could be an important factor to consider when forecasting impacts of climate change and increased development on marine arctic ecosystems.

Table 5. Summary of species/populations in the Marine Arctic Ecozones listed under COSEWIC and/or SARA and the potential for human impact.

Species	Subspecies or population	COSEWIC Status	SARA Status	Human threats or potential threats
Ivory Gull		Endangered	Endangered	Illegal shooting, diamond exploration/drilling, contaminants, oil spills
Bowhead Whale	Bering-Chukchi-Beaufort population	Special Concern	Special Concern	Past commercial whaling, climate (e.g. Killer whale expansion), oil & gas exploration & development
	Eastern Canada-West Greenland population	Special concern	Under Consideration	Past commercial whaling, climate (Killer whale expansion)
Beluga Whale	Eastern Hudson Bay population	Endangered	Under Consideration	Hunting, shipping, contamination, habitat alteration
	Ungava Bay population	Endangered	Under Consideration	Hunting, shipping, contamination, habitat alteration
	Cumberland Sound population	Threatened	Under Consideration	Noise, increased vessel traffic & competition with commercial fisheries
	Eastern High Arctic-Baffin Bay population	Special Concern	Under Consideration	Human hunting & disturbance
	Western Hudson Bay population	Special Concern	Under Consideration	Human hunting (minimal)
Atlantic Walrus	Arctic population	Special Concern	Under Consideration	Hunting, noise, contaminants, industrial development
Atlantic Cod	Arctic population	Special Concern	Under Consideration	Overfishing
Narwhal		Special Concern	Under Consideration	Hunting, contaminants, industrial activities, turbot fishery
Atlantic wolffish		Special Concern	Special Concern	By-catch loss and disruption of spawning habitat by trawlers
Northern wolffish		Threatened	Threatened	By-catch loss and disruption of spawning habitat by trawlers
Spotted wolffish		Threatened	Threatened	By-catch loss and disruption of spawning habitat by trawlers

Chars

Chars (salmonids of the genus *Salvelinus*) are circumpolar in distribution and the most northerly freshwater fish species. In the Arctic there are two major taxonomic groups (species complexes) present, the Arctic char (Salvelinus alpinus (L.)) and Dolly Varden (Salvelinus malma (Walbaum)). Arctic char has a Holarctic distribution associated primarily with lacustrine-dominated river systems (Figure 30) whereas Dolly Varden has a north Pacific distribution associated primarily with arctic rivers (Johnson 1980; Savvaitova 1980; Dunham *et al.* 2008). Each of the two species complexes has a number of distinct forms that may be endemic to particular regions. Chars perform many ecological roles within and among ecosystems. Therefore, chars are considered to be keystone species critical to energy transfer and foodweb structure (Willson and Halupka 2002).

Chars utilize freshwater, estuarine and nearshore marine habitats. Arctic Char and other anadromous fish migrate from freshwater to coastal brackish waters in the summer where they actively feed on invertebrates and small fishes. Summer feeding in the brackish coastal waters account for as much as 80% of the yearly food intake of anadromous Arctic Char. Chars have been an important food resource for Inuit for centuries. In the eastern Arctic, for example, Arctic Char make up 45% by number of the top 15 species harvested as country food by the Inuit population (Nunavut Wildlife Harvest Study 2004) with recent annual harvest estimates ranging from 1200-1500 tonnes (Government of Nunavut and Nunavut Tuungavik Incorporated 2005). Commercial fisheries for wild Arctic Char also operate in many areas of the Arctic. Between 1985 and 2003 the commercial harvest from the Cambridge Bay area of the central Arctic ranged from 39 to 54 tonnes annually (DFO 2004).

Chars are susceptible to climate change effects that may act directly upon the fish or indirectly through ecosystem or habitat alterations (Reist *et al.* 2008a, b, c). Examples of local stressors include exploitation, industrial development (e.g., hydroelectric activities) and the introduction of non-natal species or foreign genetic types of chars. The response of chars to stressors will depend on the location and diversity of populations. The status and trends of chars in the Arctic are generally lacking. However, decreasing populations have been identified near some communities, for example, Dolly Varden in the Big Fish River (DFO 2002b) and Arctic Char in the Hornaday River (DFO 1999), where over-fishing perhaps combined with habitat changes has resulted in population collapse. Much effort is required to sustain the biodiversity of this keystone species in the Arctic.

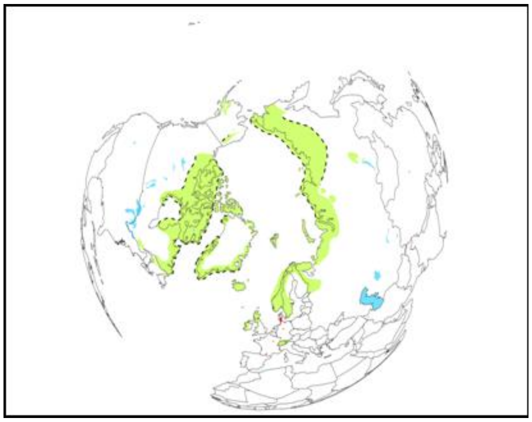


Figure 30. The distribution of the Arctic Char species complex (sensu stricto) and the location of introduced populations. Uncertain limits are indicated by dashed lines and the red areas indicate introduced populations (Figure compliments of C. Sawatzky)

Killer Whales

The number of Killer whale sightings has increased in recent years (Figure 31) and has been linked to reductions in sea-ice extent. The increase in Killer whale sightings is most pronounced in western Hudson Bay (Higdon and Ferguson 2009). The first occurrence of Killer whales in the HJBFB was about 50 years ago when ice conditions in Hudson Strait opened up and facilitated movement of the species into Hudson Bay. The Orcas in the Canadian Arctic (OCA) program is continuing to monitor movement of Killer whales into the Arctic, as this apex predator has the ability to influence marine ecosystems via top-down effects.

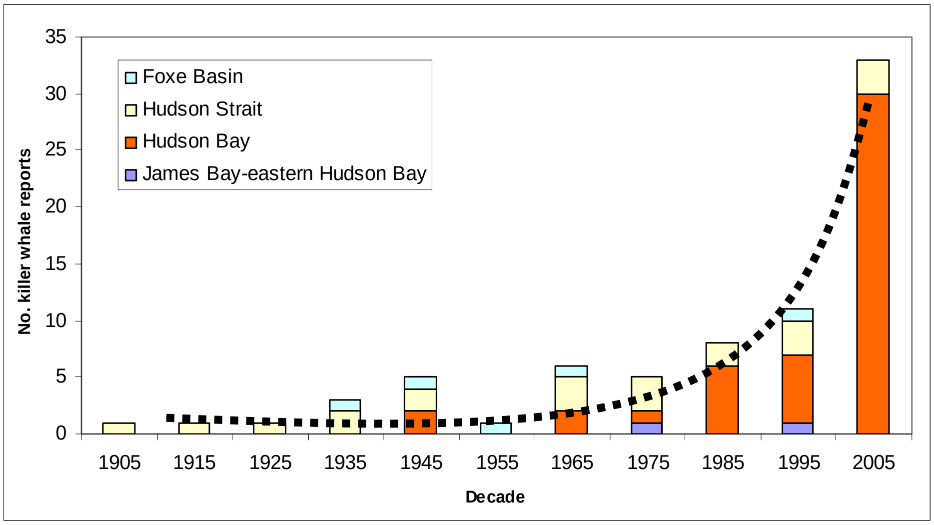


Figure 31. Trend in Killer whale reports in the HJBFB Ecozone (Figure provided by J. Higdon)

HUMAN INFLUENCES

STRESSORS/CUMULATIVE IMPACTS

As previously discussed, climate change is a key environmental and socio-economic issue facing the Marine Arctic Ecozones. Continued research is needed to assess trends in the rate and direction of climate related impacts. Other ongoing stressors within theses Ecozones include contaminants, shipping and harvesting. These anthropogenic stressors have global and local origins and act cumulatively to impact ecosystem structure and function.

Contaminants

The presence of contaminants and their pathways are impacted by changes that effect physical and biological interactions in Arctic ecosystems. Assessing how climate change will alter contaminant, transport and distribution within Arctic foodwebs is very challenging (see Macdonald *et al.* 2005 for a review). The Northern Contaminants Program (NCP) was established in 1991 in response to studies which showed the presence of contaminants in the Arctic ecosystem. Many of these pollutants have no Arctic sources. Contaminants of concern are those that fit the following criteria; 1) undergo long range transport, 2) persistent in the environment (do not readily break down), 3) bioaccumulate in organisms over time due to the inability to metabolize and eliminate the contaminant, resulting in foodweb magnification, and 4) cause toxic harm. These substances include persistent organic pollutants (POPs) such as

Polychlorinated Biphenyls (PCBs); current use organic contaminants such as flame retardants; and heavy metals such as mercury.

POPs that are of toxicological importance are primarily of industrial origin and have existed for only about. 50 years (Braune *et al.* 2005). They include legacy varieties that have resulted from past use (e.g., DDT, PCBs) as well as emerging or current use POPs such as; 1) Brominated Flame Retardants (BFRs, e.g., PBDEs, HCBD), 2) fluorinated compounds (e.g., PFOS, PFOA), 3) Polychlorinated Naphthalenes (PCNs) and 4) pesticides (e.g., endosulfan, HCH) (AMAP 2009).

Contaminants enter the Arctic via long-range transport by marine currents, air currents, freshwater runoff from land and migratory biota (Macdonald *et al.* 2005). Additional point sources may come from DEW line sites, local communities, shipping tracks and potential oil spills and natural gas leaks. Because of their low water solubility and high affinity for lipids and fatty tissues, they accumulate in organisms over time and biomagnify up Arctic foodwebs, making long lived, lipid rich top predators vulnerable. Within the BSME, some contaminants such as, mercury have increased significantly since the early 1980s, while others have stayed constant or declined in response to global action (i.e. Stockholm Convention on Persistent Organic Pollutants). Several new POPs have been detected in the Arctic food chain (e.g., BFRs). In particular, there has been a potential increase of BFRs in the blubber of Ringed seals sampled at Ulukhaktok, NWT (Ikonomou *et al.* 2002). In some Beluga, mercury and POPs are approaching levels which could lead to health effects (AMAP 2009).

In comparison to other circumpolar countries, Braune *et al.* (2005) report that many POPs in Canadian Arctic biota are generally lower than in the European Arctic and eastern Greenland, while mercury concentrations are substantially higher in Canada. The identification of temporal and spatial trends of legacy and new contaminants is ongoing under INACs Northern Contaminants Program within Canada as well as at an international level with the Arctic Monitoring Assessment Program (AMAP).

Detecting contaminant trends for marine mammal and seabirds can be complicated by confounding factors. Contaminant levels vary between tissues (e.g., liver, muscle, kidney, egg, blubber etc) as well as ages, gender and species. There is also considerable spatial and interannual variation in measured contaminant levels in the Arctic. Contaminant trends (e.g., mercury, HCH) in marine organisms also do not necessarily follow atmospheric emissions of the contaminants, nor Arctic air concentrations (Steffen *et al.* 2005; Macdonald *et al.* 2005). Figure 32, shows the long-term trend in atmospheric Gaseous Elemental Mercury (GEM) from Alert, NU, indicating strong seasonal variation and no discernable trend in atmospheric mercury levels despite changing trends in mammal and fish mercury concentrations (Stern 2009a). Changes in diet, foraging behaviour and the availability of the various contaminants (i.e., chemical structure) could contribute to observed tissue concentrations and trends (Loseto *et al.* 2008a, 2008b). For example, a recent study of mercury in Ringed seals found that higher concentrations could be associated with shorter ice-free seasons during which older, more highly contaminated Arctic Cod cohorts are present (Gaden *et al.* 2009).

Contaminant trends in various locations in the Marine Arctic Ecozones from the most recent assessment by the NCP are summarized in Table 6. Contaminants in seabirds have changed significantly since the 1970's (e.g., Figure 33). Mercury concentrations in the eggs of Thick-Billed Murres, Northern Fulmars and Black-Legged Kittiwakes have all increased. However, the rate of increase has been lower for the Kittiwakes possibly because they overwinter at temperate latitudes versus northern waters (Braune *et al.* 2005). In 2008, highest mercury concentrations for Prince Leopold Island seabirds were found in Glaucous Gull eggs whereas Kittiwake eggs had the lowest mercury concentration (Braune 2009).

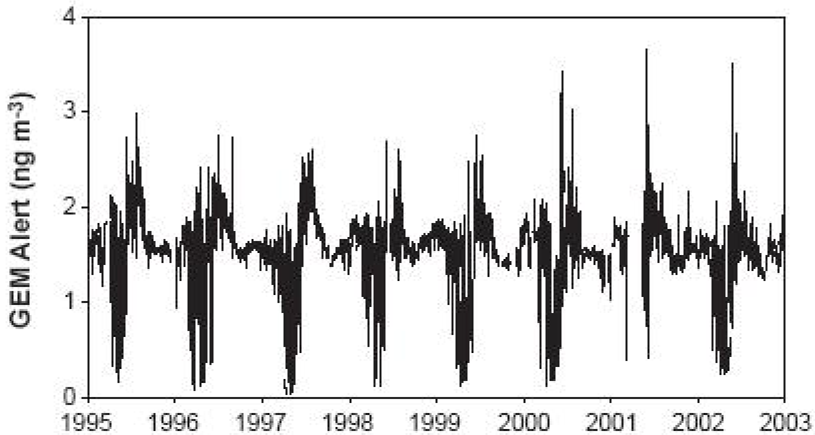


Figure 32. Atmospheric Gaseous Elemental Mercury (GEM) at Alert (Source: Steffen et al. 2005)

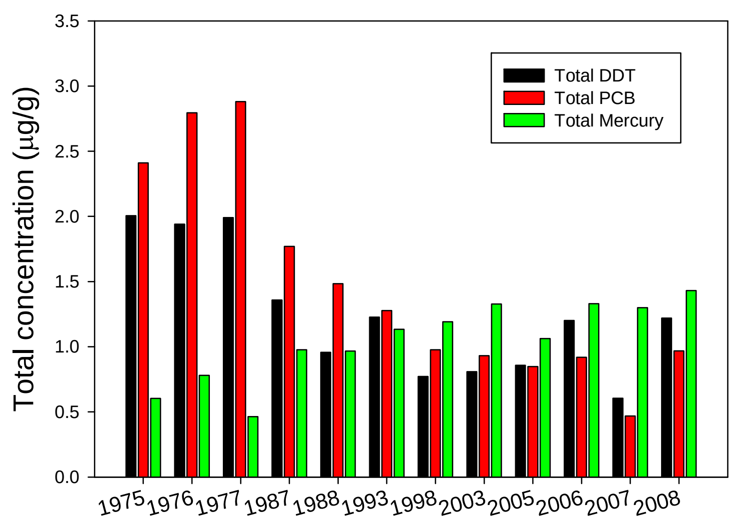


Figure 33. POPs and mercury trends for the eggs of Thick-billed Murres on Prince Leopold Island (Data compliments of B. Braune)

Beluga teeth provide a useful long-term (1450 to present) record of mercury accumulation (Figure 34). This record indicates that modern Beluga teeth contain higher concentrations of mercury than historical samples and indicate that Belugas do accumulate mercury as they age (Dietz *et al.* 2009). However, long-term mercury trends in Walrus do not show the same accumulation patters as for Beluga. In Foxe Basin, pre-industrial and modern Walrus teeth have similar mercury concentrations (Outridge *et al.* 2002).

Spatial and interspecies trends are also evident for different contaminants. Mercury in Beaufort Sea Beluga in the 1990's was three fold higher than in Beluga in the eastern Arctic, now levels are comparable (Lockart *et al.* 2005). However, great variability exists even within the same stock of Beluga (e.g., Mackenzie Bay versus Paulatuk) (Loseto *et al.* 2008b). For legacy POPs (e.g., DDT) in marine biota, the trend shows higher concentrations in the eastern than western Arctic (e.g., Hudson Bay, around Baffin Island), except for the pesticide HCH which shows the opposite spatial trend. Between species differences are also important. Analyses of organochlorine (PCBs and pesticides) and mercury concentrations between 1994 and 2003 in the Arctic found that Beluga tissues had reached levels that could cause effects in other species. However, contaminant levels in Bowhead tissues are significantly lower and likely do not pose a risk to the animals themselves or the Inuit who harvest them (Stern 2009a). These differences are linked to the trophic levels at which these species feed.

Biomagnification of contaminants does not stop at marine biota but also affects Northerners who harvest and consume these species. Human exposure to contaminants is dependent on a combination of the varying environmental concentrations of the contaminants, the local physical and biological pathways that make the contaminants available as well as the local diets of the communities (AMAP 2009).

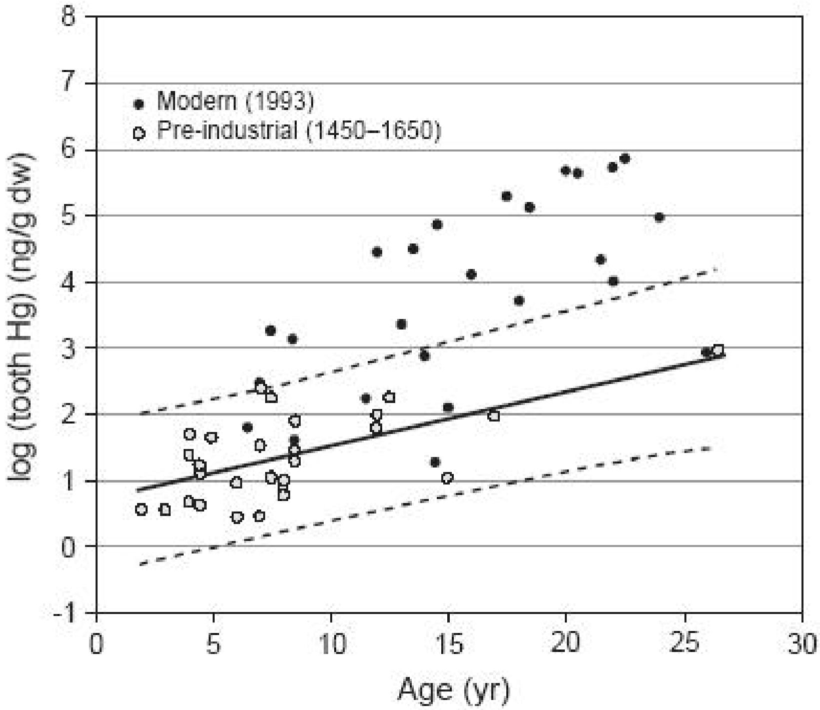


Figure 34. Mercury in modern and pre-industrial teeth of Beluga from the Beaufort Sea (Source: Outridge et al. 2002)

Table 6. Summary of contaminant trends from the Northern Contaminants Program (NCP) 2008-2009. Key at bottom.

Location	Trend	Measurement	Contaminant	Time Period	Reference	Notes
Mackenzie delta region of south Beaufort Sea	⇔	beluga blubber	Dichlorodiphenyltrichloroethane (DDTs), Chlordanes, Lindane (HCHs), dieldrin, Polychlorinated biphenyls (PCBs), toxaphene, chlorobenzenes	1989 to 2007	1	
	⇔ [red]	beluga liver	Mercury	1981 to 2007	1	Possibly increasing but need to look at age adjusted data.
	⇓ [green]	beluga liver	Perflurocarboxylic acids (PFCAs)	1984 to 2007	2	
	⇔	beluga liver	Perfluorooctane sulfonamide (PFOSA)	1984 to 2007	2	
	⇑ [red]	beluga liver	Perfluorooctane sulfonate (PFOS)	1984 to 2007	2	
	⇔	beluga blubber	Hexabromocyclododecanes (HBCDs)	1993 to 2007	2	
	⇔	beluga blubber	Polybrominated Diphenyl Ethers (PBDEs)	1993 to 2007	2	
	⇔	beluga blubber	Hydrophobic organic contaminants (HOCs)	1989-2008	3	
Sachs Harbour	⇓ [green]	rigned seal blubber	Polychlorinated biphenyls (PCBs), Lindane (HCHs), Dichlorodiphenyltrichloroethane (DDTs), chlorobenzenes, Chlordanes, Toxaphene	1972 to 2007	4	
	⇔ [red]	ringed seals liver	Mercury	1988 to 2007	4	Large year to year variation makes it difficult to discern trends
Resolute, Arviat, Gjoa Haven, Inukjuaq	⇓ [green]	ringed seal blubber	Polybrominated Diphenyl Ethers (PBDEs)	ca. 1970 to 2008	4	Females and juvenile males only

Table 6. Cont.

Location	Trend	Measurement	Contaminant	Time Period	Reference	Notes
Pangnirtung	⇑	beluga liver	Perflurocarboxylic acids (PFCAs)	1982 to 2008	2	Possibly increasing but need to look at age adjusted data for liver.
	⇑, ⇓	beluga liver	Perfluorooctane sulfonate (PFOS)	1982-2000 (increase), 2000-2008 (decrease)	2	
	⇓	beluga liver	Perfluorooctane sulfonamide (PFOSA)	1982-2008	2	
	⇑	beluga blubber	Brominated diphenyl ethers (BDEs)	1982-2008	2	
	⇑	beluga blubber	Hexabromocyclododecanes (HBCDs)	1982-2008	2	
	⇓	beluga blubber	Short-chain chlorinated paraffins (SCCPs)	1982-2008	2	
	⇔, ⇓	beluga blubber	Polychlorinated biphenyls (PCBs), Lindane (HCH), Dichlorodiphenyltrichloroethane (DDT), other halogenated organic compounds	1989-2008, decreasing HCH after 2000	3	Need age adjusted data.
	⇔	beluga liver and kidney	Mercury	1982-2008	1	Need age adjusted data.
Sanikiluaq	⇔	beluga liver and kidney	Mercury	1994-2008	1	Need age adjusted data.
Arviat	⇔	beluga liver and kidney	Mercury	1984-2008	1	

Table 6. Cont.

Location	Trend	Measurement	Contaminant	Time Period	Reference	Notes
Hall beach	⇔	walrus liver and kidney	Mercury	1988-2008 (liver), 1992-2008 (kidney)	1	Need age adjusted data and large year to year variation makes it difficult to discern trends.
Igloolik	⇔	walrus liver and kidney	Mercury	1982-2008	1	
Prince Leopold Island	⇑	Seabirds: Thick-billed Murre, Northern Fulmar, Black-legged Kittiwake eggs	Mercury	1975-2008	5	

⇔ no clear increase of decrease

⇔ (red) possible increase, year to year variability makes it difficult to discern at present

⇓ decreasing

⇑ increasing

References: [1]Stern 2009b, [2]Tomy 2009, [3]Stern 2009c, [4]Muir 2009, [5]Braune 2009.

Shipping
There is the potential for increased shipping in the Marine Arctic Ecozones. Increased shipping may be related to industrial and/or economic development, defense, scientific exploration, Northern population growth and/or tourism. There was an initial wave of tourism cruises beginning around 1994 in the high Canadian Arctic. However, the number of cruises was declining by 2004 (7 cruise ships in 2004) and it is expected that tourism cruises will remain at a low level (Brigham and Ellis 2004). Increased shipping related to community support (e.g., fuel barges) and industry is dependent on population growth and resource development. For example, the Port of Churchill in the HJBFB Ecozone may diversity to include nitrogen fertilizer. This expansion would result in increased shipping along the trade corridor between Churchill and Russia (Kusch 2007). The shipping season could potentially lengthen in conjunction with climate driven reductions in sea ice extent. However, transport through the Northwest Passage will remain difficult especially due to the presence of multiyear ice (Howell and Yackel 2004). Marine transportation in the Arctic is viewed as a key issue for Canadian sovereignty, as evidenced by the announcement of a new deepwater port for Nanisivik on Baffin Island. Currently there are only three deepwater ports in the Marine Arctic Ecozones; in Churchill, Kugluktuk and Cambridge Bay.

Increased shipping introduces threats to the Marine Arctic Ecozones and can also impact Northern communities that have been protected by the remote nature of the environment in which they live. Of particular concern are oil or gas spills and as previously mentioned, vulnerability assessments are currently taking place in response to this potential threat. Shipping also has the potential to influence ecosystems via the release of new species in ballast waters. To date, ballast water has not been identified as a source of new species in the Arctic. Noise from ships and direct contact (i.e., strikes) can also disturb and/or harm marine mammals and fish. Ringed seals and polar bears can be sensitive to noise and may abandon areas. Bowheads have also exhibited avoidance behaviours in response to seismic survey ships (Tynan and Demaster 1997). However, the long term effects of shipping disturbances are not known for fish or marine mammals.

Fisheries
The harvest of fish, birds and mammals has always been an important cultural aspect of Northern communities. Proper respect for and management of marine stocks is required to protect the integrity and biodiversity of the marine ecosystems. Management is complicated by migratory habits of harvested species and the lack of information on many populations. However, proper management of harvesting is essential to prevent overharvesting/exploitation especially in light of climate change and associated stressors. Subsistence, sport and commercial fisheries can all impact marine fisheries resources. Continuing and improving harvest studies will be important for monitoring trends and management of subsistence species. A number of sources of funding have helped maintain a formal BSME marine mammal harvest monitoring program from 1973 until the current program which has been conducted by FJMC along with Hunter and Trappers Committees. Each year, harvest data are collected at traditional Beluga hunting location in the Beaufort Sea and vital statistics are collect along with harvest numbers.

The Arctic Marine Ecozones have few commercial fisheries in comparison to other Marine Ecozones. There is currently no commercial fishery in the BSME. In 2006/07 there were six exploratory fisheries (stage I feasibility) that included different species of fish, shrimp and shellfish. In 2007/08 there were only two exploratory fisheries, both for Arctic Char and in 2009 there was only one exploratory char fishery. In the HJBFB Ecozone the Iceland scallop (*Chlamys islandica*) was harvested by exploratory commercial fisheries in Hudson and Strait and in Ungava Bay (Morin 1991; Lambert and Prefontaine 1995). However, no commercial fishery was developed for the scallop. The HJBFB Ecozone also has commercial fisheries for Arctic Char. The number of commercial fisheries in the Hudson Bay area decreased from 209 in 2005 to 42 in 2009.

The CAA area has a mixture of commercial and exploratory (stage I and II feasibility) fisheries. Between 2005 and 2008 the number of commercial and exploratory (stage I and II combined) fisheries averaged, 140 and 160, respectively. However, in 2009 the number of commercial and exploratory fisheries dropped to 9 and 21, respectively. An important commercial fishery, established in 1986, is the inshore winter turbot fishery in Cumberland Sound (DFO 2008). In addition, the offshore turbot fisheries in Northwest Atlantic Fisheries Organization (NAFO) areas 0A and 0B, including the Davis Strait/Baffin Bay area of this Ecozone, are economically important for Northern communities. In 2006 a portion of fishery area 0A, near southern Baffin Bay, was closed to protect southern Narwhal overwinter grounds and deep-sea coral habitat (DFO 2007). Commercial shrimp fisheries for Northern (*Pandalus borealis*) and striped (*Pandalus montagui*) shrimp began in the late 1970s off Baffin Island and expanded southward to the area of Resolution Island (Hudson Strait) in the mid-1990s, where the main fishery remains to date (DFO 2008b). The distribution of shrimp fishing effort in recent years remains unchanged. Offshore fishery licences for turbot and shrimp are summarized in Table 7.

Table 7. Summary of offshore fisheries in the Marine Arctic Ecozones between 2006 and 2009.

Year	Number of Licences	
	Turbot	Northern Shrimp
2009/10	13	2
2008/09	8	2
2007/08	6	4
2006/07	8	4

STEWARDSHIP/CONSERVATION

The development of EBSAs and MPAs indicate steps towards the conservation of biodiversity and ecosystems within the Marine Arctic Ecozones. Marine areas are also conserved through the International Union for Conservation of Nature (IUCN). In 2009, only 0.67% of the Marine Arctic Ecozones was protected through 46 protected areas of IUCN categories I-III (Figure 35). IUCN categories I-III include nature reserves, wilderness areas, and other parks and reserves managed for conservation of ecosystems and natural and cultural features. Four small category V protected areas were established to provide protection for an additional 17 km^2. Category V protected areas focus on sustainable use by established cultural tradition within the protected area. Protected areas new in 2009, including those at Isabelle Bay, Cape Searle and Reid Bay, all in the Canadian Arctic Archipelago, protected a further 4,029 km^2, but the total of all protected areas in the Ecozones remains less than one percent.

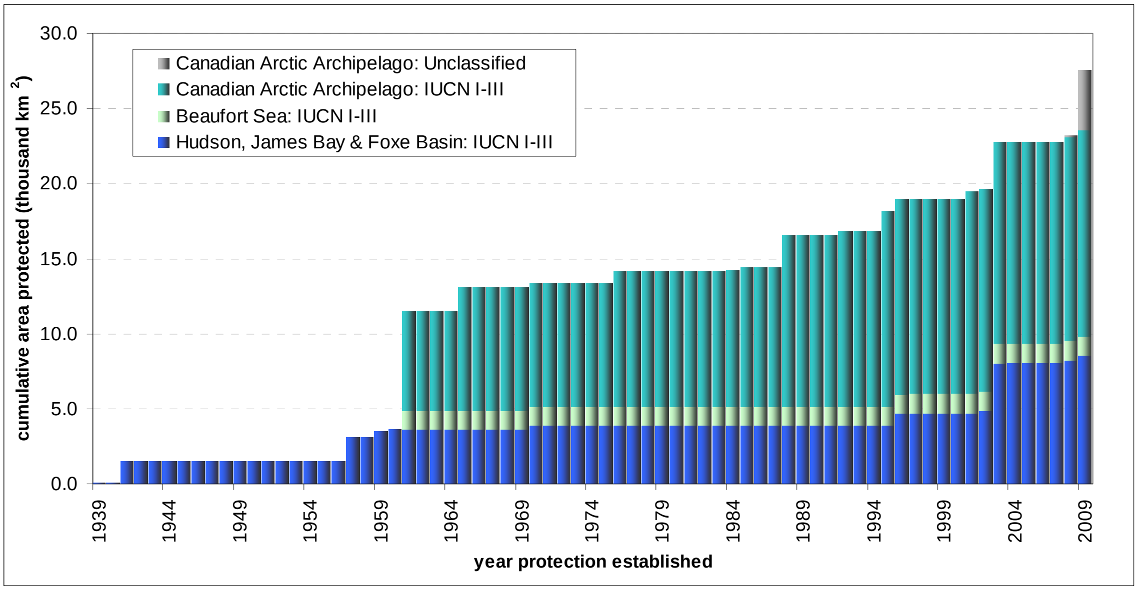


Figure 35: Growth of protected areas, Arctic Marine Ecozones, 1894-2009. Data provided by federal and provincial jurisdictions, updated to May 2009. Only legally protected areas are included. IUCN (International Union for Conservation of Nature) categories of protected areas are based on primary management objectives (see text for more information). The unclassified (grey) portion of the bar represents protected areas new in 2009 and not yet reported by IUCN category

Co-management partnerships within the Marine Arctic Ecozones are very important for stewardship and conservation. Within the Nunavut Settlement Area (NSA) the Nunavut Wildlife Management Board (NWMB) is central to wildlife management and the main regulator of access to wildlife. The NWMB was established in 1994 as an Institution of Public Government (IPG) under the Nunavut Land Claims Agreement, the treaty signed in 1993 that ultimately led to the creation of the new territory and public government of Nunavut. The mandate of the NWMB is to ensure the protection and wise use of wildlife and wildlife habitat for the long-term benefit of Inuit, as well as other residents of Nunavut and Canada. The NWMB is a decision-making body within the NSA, with advisory authority in the waters adjacent to the NSA. The governments of Nunavut and Canada carry out, but are not bound by, NWMB decisions regarding wildlife management.

The Joint Fisheries Management Committee (FJMC) is the co-management body between the Government of Canada Fisheries and Oceans Canada and the Inuvialuit. The FJMC was established by the Inuvialuit Final Agreement (IFA), the Inuvialuit Settlement Region (ISR) land claim. The mission of the FJMC is to ensure that the renewable marine, anadromous and freshwater resources of the ISR are managed and conserved for the wise use and benefit of present and future generations. The FJMC address their goals by providing effective management programs for fish and marine mammal stocks and their environments, by using sound scientific and traditional knowledge. This co-management supports Inuvialuit culture, beliefs, and practices with respect to fish and marine mammals and promotion of greater participation of Inuvialuit people in the management of the resources.

INTEGRATED ANALYSIS OF ECOZONES STATUS AND TRENDS

The Marine Arctic Ecozones remain a relatively pristine ecosystem relative to other Ecozones in Canada. However many stressors threaten the diversity and stability of the ecosystems. The availability of status trend data in these Ecozones remains limited by the challenges of assessing such an extensive area that is difficult to access. The extreme seasonality and diversity of ecosystems also present challenges to describing and predicting environmental status and potential future changes. Researchers in cooperation with Northern communities are working to fill the many knowledge gaps that remain. Long-term research and monitoring programs are vitally important for identifying trends of change, understanding why and how these trends are occurring, and assessing their ongoing and potential impacts. Without such programs and information, opportunities may be missed to avoid or mitigate adverse impacts.

Atmospheric-ice-ocean interactions are key drivers of change in these Ecozones. Changes are happening more quickly than anticipated yet the direction of ecosystem responses are difficult to predict. There is the potential for increased primary productivity but it is not yet known how or if this energy will transfer to higher trophic levels. Currently, the species at greatest risk is the Ivory Gull whereas Bowhead whales and other whales/walrus appear to be recovering from historical exploitation. Continued monitoring of trends is needed to determine how these and other species will respond to future cumulative effects of environmental change and development.

There is an encouraging trend towards the identification and protection of important marine habitats. Continued efforts are required to ensure that significant and vulnerable areas, and their associated ecosystems and communities, are protected. Local and international stewardship and conservations efforts need to continue to ensure ecosystem health. Contaminant inputs need to be reduced, and harvests must be set at sustainable levels. Interjurisdictional cooperation and co-management efforts are essential to this process.

Emerging issues to monitor include the multiple feedbacks from changing sea-ice conditions, which can impact all levels of the ecosystem. The spread and prevalence of diseases is also a critical issue for the health of marine mammals and Northern communities. Changing ice conditions and warming temperatures may also enable some species to increase in abundance and/or expand their range. Species invasions or introductions could seriously impact ecosystem structure and function. Oil and gas exploration and development and the potential for increased shipping bring both benefits and threats to the North. The potential for oil or gas spills is a major concern and much work and planning is required to protect and manage the Marine Arctic Ecozones.

ACKNOWLEDGEMENTS

We would like to acknowledge the following contributing authors who provided text for and/or reviewed sections on Hudson Bay; D. Hudd, J. Holm, seabirds; A.J. Gaston, D.F. Bertram, A. Boyne, J. Chardine, A.W. Diamond, H.G. Gilchrist, J.M. Hipfner, M.J.F. Lemon, M.L. Mallory, W.A. Montevecchi, J.-F. Rail, G.J. Robertson, disease; O. Nielsen, killer whales; S. Ferguson, J. Higdon, contaminants; G. Stern and Traditional Knowledge; Donna Hurlburt. We also appreciate the insightful comments of reviewers, D.B. Stewart, M. Papst, and L. Loseto whose comments improved the document.

REFERENCES

AMAP. 2009. AMAP assessment 2009: Human health in the Arctic. Arctic Monitoring and Assessment Programme (AMAP), Oslo, Norway. xiv + 254 p.

Agnew, T., Silis. A. 1995. Spring-season climate variability in the central Canadian Arctic islands. Ann. Glaciol. 21:330-336.

ACIA. 2004. Impacts of a Warming Arctic: Arctic Climate Impact Assessment. Cambridge University Press.

Arctic Report Card 2009. www.arctic.noaa.gov/reportcard.

Arrigo, K.R., van Dijken, G.L. 2004. Annual cycles of sea ice and phytoplankton in Cape Bathurst polynya, southeastern Beaufort Sea, Canadian Arctic. Geophys. Res. Lett. 31: L08304. doi:10.1029/2003GL018978.

Arrigo, K. R., van Dijken, G.L., Pabi, S. 2008. Impact of a shrinking Arctic ice cover on marine primary production. Geophys. Res. Lett. 35 :L19603. doi:10.1029/2008GL035028.

Atkinson, D.E., Brown, R., Alt, B., Agnew, T., Bourgeois, J., Burgess, M., Duguay, C,. Henry, G., Jeffers, S., Koerner, R., Lewkowicz, AG., McCourt, S., Melling, H., Sharp, M. 2006. Canadian cryospheric response to an anomalous warm summer. Atmos.-Ocean. 44:347-375.

Bates, N.R., Mathis, J.T. 2009. The Arctic Ocean marine carbon cycle: evaluation of air sea CO_2 exchanges, ocean acidification impacts and potential feedbacks. Biogeosciences Discuss. 6:6695-6747.

Barber, D.G., Massom, R.A. 2007. The role of sea ice in Arctic and Antarctic polynyas. *In:* Smith, W.O. Jr., Barber, D.G. (Eds.), Polynyas: windows to the world. Elsevier, Amsterdam. p. 1-54.

Barr, W. 2008. History of Arctic shipping up until 1945. Website: web.arcticportal.org.

Belkin, I.M. 2009. Rapid warming of large marine ecosystems. Prog. Oceanogr. 81:207-213.

Benoit, D., Simard, Y., Fortier, L. 2008. Hydroacoustic detection of large winter aggregations of Arctic cod (*Boreogadus saida*) at depth in ice-covered Franklin Bay (Beaufort Sea), J. Geophys. Res. 113:C06S90, doi:10.1029/2007JC004276.

Bergmann, M.A., Welch, H.E., Butler-Walker, J.E., Siferd, T.D. 1991. Ice algal photosynthesis at Resolute and Saqvaqjuac in the Canadian Arctic. J. Mar. Syst. 2:43-52.

Berkes, F., Jolly, D. 2001. Adapting to climate change: Social-ecological resilience in a Canadian Western Arctic community. Conserv. Ecol. 5:19.

Bluhm, B.A., Gradinger, R. 2008. Regional variability in food availability for arctic marine mammals. Ecol. Applic. 18:S77-S96.

Booth, S., Watts, P. (2007) Canada's arctic marine fish catches. *In:* Zeller, D., Pauly, D. (Eds.)

Reconstruction of marine fisheries catches for key countries and regions (1950-2005). Fisheries Centre Research Report 15(2). Fisheries Centre, University of British Columbia, Vancouver, British Columbia. p. 3-15.

Bradstreet, M.S.W., Cross, W.E. 1982. Trophic relationships at high arctic ice edges. Arctic 35:1-12.

Braune, B.M., Outridge, P.M., Fisk, A.T., Muir, D.C.G., Helm, P.A., Hobbs, K., Hoekstra, P.F., Kuzyk, Z.Z., Kwan, M., Letcher, R.J., Lockhart, W.L., Norstrom, R.J., Stern, G.A., Stirling, I. 2005. Persistent organic pollutants and mercury in marine biota of the Canadian Arctic: An overview of spatial and temporal trends. Sci. Tot. Envi. 351-352:4-56.

Braune, B. 2009. Temporal trends of contaminants in Arctic seabird eggs: inter-year variability. *In:* Smith, S., Stow, J., Edwards, J. (Eds.), Synopsis of research conducted under the 2008-2009 Northern Contaminants Program. Minister of Indian Affairs and Northern Development, Ottawa. p.131-136.

Brigham, L., Ellis, B. 2004. Arctic Marine Transport Workshop. Northern Printing. Anchorage. 56p.

Campbell, J.S., Simms, J.M. 2009. Status report on coral and sponge conservation in Canada. Fisheries and Oceans Canada: vii + 87 p.

Carmack, E.C., Macdonald, R.W. 2002. Oceanography of the Canadian Shelf of the Beaufort Sea: a setting for marine Life. Arctic 55(suppl. 1):29-45.

Carmack, E.C., Macdonald, R.W., Jasper, S. 2004. Phytoplankton productivity on the Canadian Shelf of the Beaufort Sea. Mar Ecol Prog Ser. 277:37-50.

Caron, L.M.J., Smith, T.G. 1990. Philopatry and site tenacity of belugas, *Delphinapterus leucas*, hunted by the Inuit at the Nastapoka estuary, eastern Hudson Bay. *In:* Smith, T.G., St. Aubin, D.J., Geraci, J.R. (Eds.) Advances in research on the beluga whale, *Delphinapterus leucas*. Can. Bull. Fish. Aquat. Sci. 224:69-79.

Chapman, A.S., Kostylev, V.E. 2005. Distribution, abundance, diversity and biomass of benthic species from the Beaufort Sea shelf – a summary of data collected between 1951 and 2000. GSC Open File Report.

Coad, B.W., Reist, J.D. 2004. Annotated list of the Arctic marine fishes of Canada. Can. MS Rep. Fish. Aquat. Sci. 2674:iv+112 p.

Cobb, D., Fast, H., Papst, M.H., Rosenberg, D., Rutherford, R., Sareault, J.E. 2008. Beaufort Sea Large Ocean Management Area: Ecosystem Overview and Assessment Report. Can. Tech. Rep. Fish. Aquat. Sci. 2780:ii-ix + 188 p.

Comeau, S., Gorsky, G., Jeffree, R., Teyssié, J.-L., Gattuso, J.-P. 2009. Impact of ocean acidification on a key Arctic pelagic mollusk (*Limacina helicina*). Biogeosciences. 6:1877-1882.

Conlan, K.E., Kvitek, R.G. 2005. Recolonization of soft-sediment ice scours on an exposed Arctic coast. Mar. Ecol. Prog. Ser. 286:21-42.

Cosens, S.E., Cleator, H., Richard, P.R. 2006. Numbers of Bowhead Whales (*Balaena mysticetus*) in the Eastern Canadian Arctic, based on aerial surveys in August 2002, 2003 and 2004. Sci. Advis. Sec. Res. Doc. 2006/052. iv + 21 p.

COSEWIC 2006. COSEWIC assessment and update status report on the Atlantic walrus *Odobenus rosmarus rosmarus* in Canada. Committee on the Status of Endangered Wildlife in Canada. Ottawa. ix + 65 p.

COSEWIC 2009. COSEWIC assessment and update status report on the Bowhead Whale *Balaena mysticetus*, Bering-Chukchi-Beaufort population and Eastern Canada-West Greenland population, in Canada. Committee on the Status of Endangered Wildlife in Canada. Ottawa. vii + 49 p.

Cota, G.F., Prinsenberg, S.J., Bennet, E.B., Loder, J.W., Lewis, M.R., Anning, J.L., Watson, N.H.F., Harris, L.R. 1987. Nutrient fluxes during extended blooms of arctic ice algae. J. Geophys. Res. 92:1951-1962.

Craig, P.C. 1984. Fish use of coastal water of the Alaskan Beaufort Sea: a review. Trans. Am. Fish. Soc. 113:265-282.

Crawford, R.E., Jorgenson, J.K. 1996. Quantitative Studies of Arctic Cod (*Boreogadus saida*) Schools: Important Energy Stores in the Arctic Food Web. Arctic. 49:181-193.

Cusson, M., Archambault, P., Aitken, A. 2007. Biodiversity of benthic assemblages on the Arctic continental shelf: historical data from Canada. Mar. Ecol. Prog. Ser. 331:291-304.

Darnis, G., Barber, D.G., Fortier, L. 2008. Sea ice and the onshore-offshore gradient in pre-winter zooplankton assemblages in southeastern Beaufort Sea. J. Mar. Syst. 74: 994-1011.

de March, B.G.E., Postma, L.D. 2003. Molecular genetic stock discrimination of belugas (*Delphinapterus leucas*) hunted in eastern Hudson Bay, northern Quebec, Hudson Strait, and Sanikiluaq (Belcher Islands), Canada, and comparisons to adjacent populations. Arctic 56:111-124.

Déry, S.J., Wood, E.F. 2004. Teleconnection between the Arctic Oscillation and Hudson Bay river discharge. Geophys. Res. Lett. 31: L18205. doi:10.1029/2004GL020729.

Déry, S.J., Wood, E.F. 2005. Decreasing river discharge in northern Canada. Geophys. Res. Lett. 33: L10401. doi:10.1029/2005GL022845.

Déry, S.J., Stieglitz, M., McKenna, E.C., Wood, E.F. 2005. Characteristics and trends of river discharge into Hudson, James and Ungava Bays, 1964-2000. J. Clim. 18:2540-2557.

Deser, C., Walsh, J.E., Timlin, M.S. 2000. Arctic sea ice variability in the context of recent atmospheric circulation trends. J. Climate. 13:617-633.

Dickson, R.R., Osborn, T.J., Hurrell, J.W., Meincke, J., Blindheim, J., Adlandsvik, B., Vinje, T., Aleksev, G. Maslowski, W. 2000. The Arctic Ocean response to the North Atlantic Oscillation. J. Climate. 13:2671-2696.

Dionne, J.-C. 1980. An outline of the eastern James Bay coastal environments. Geol. Surv. Can. Pap. 80-10:311-338.

DFO, 1999. Hornaday River Arctic charr, DFO, Stock Status Rep. D5-68. 12p.

DFO, 2002. Atlantic walrus. DFO Science Stock Status Rep. E5-17, 18, 19, 20. 19p.

DFO, 2002b. Big Fish River Dolly Varden, DFO Science, Stock Status Rep. D5-60. 15p.

DFO, 2004. Cambridge Bay Arctic Char. DFO Can. Sci. Advis. Sec. Stock Status Rep. 2004/010. 15p.

DFO, 2007. Development of a closed area in NAFO 0A to protect Narwhal over-wintering grounds, including deep-sea corals. DFO Can. Sci. Advis. Sec. Sci. Resp. 2007/002. 16p.

DFO, 2008. Cumberland Sound Greenland Halibut (Turbot) Inshore Fishery. DFO Can. Sci. Advis. Sec. Sci. Advis. Rep. 2008/040. 20p.

DFO, 2008b. Assessment of northern shrimp (*Pandalus borealis*) and striped shrimp (*Pandalus montagui*) in shrimp fishing areas 0, 2 and 3. DFO Can. Sci. Advis. Sec. Sci. Advis. Rep. 2008/018. 19p.

DFO, in prep. Ecologically and biologically significant areas (EBSA) in northern Foxe Basin: identification and assessment. Science Advisory Report (in prep).

Dietz, R., Outridge, P.M., Hobson, K.A. 2009. Anthropogenic contributions to mercury levels in present-day Arctic animals-A review. Sci. Total Environ. 407:6120-6131.

Dohler, G.C. 1968. Tides and currents. *In:* Beals, C.S., Shenstone, D.A. (Eds.) Science, history and Hudson Bay, Vol 2. Department of Energy, Mines and Resources, Ottawa. p. 824-837.

Drinkwater, K.F. 1988. On the mean and tidal currents in Hudson Strait. Atmos.-Ocean. 26:252-266.

Dueck, L., Ferguson H. 2008. Habitat use by bowhead whales (*Balaena mysticetus*) of the eastern Canadian Arctic. DFO Can. Sci. Advis. Sec. Res. Doc. 2008/082. iv + 24 p.

Duignan, P.J., Nielsen, O., House, C., Kovacs, K.M., Duffy, N., Early, G., Sadove, S., St. Aubin, D.J., Rima, B.K., Geraci, J.R. 1997. Epizootiology of morbillivirus infection in harp, hooded, and ringed seals from the Canadian Arctic and western Atlantic. J. Wildl. Dis. 33:7-19.

Dunham, J., Baxter, C., Fausch, K., Fredenberg, W., Kitano, S., Koizumi, I., Morita, K., Nakamura, T., Rieman, B., Savvaitova, K., Stanford, J., Taylor, E., Yamamoto, S. 2008.

Evolution, ecology and conservation of Dolly Varden, white-spotted char, and bull trout. Fisheries 33:537-550.

Else, B.G.T., Yackel, J.J., Papakyriakou, T.N. 2008. Application of satellite remote sensing techniques for estimating air-sea CO_2 fluxes in Hudson Bay, Canada during the ice-free season. Remote Sens. Environ. 112:3550-3562.

Fetterer, F., K. Knowles, W. Meier, and M. Savoie. 2009. Sea Ice Index. Boulder, CO: National Snow and Ice Data Center. Digital media.

Fleming, M., Newton, S. 2003. Hudson Bay TEKMS Report on select Hudson Bay features. Prepared for consideration by Bruce Stewart for incorporation for incorporation into Hudson Bay Ecosystem Overview, 24 p. Available from the Eric Marshall Aquatic Research Library, Fisheries and Oceans Canada, 501 University Cres., Winnipeg MB R3T 2N6.

Fortier, M., Fortier, L., Michel, C., Legendre, L. 2002. Climate and biological forcing of the vertical flux of biogenic particles under seasonal Arctic sea ice. Mar. Ecol. Prog. Ser. 225:1-16.

Fox, S. 2003. When the weather is Uggianaqtuq: Inuit observations of environmental change. Boulder, CO: University of Colorado Geography Department Cartography Lab. Distributed by National Snow and Ice Data Center. CD-ROM.

Gaden, A., Ferguson, S.H., Harwood, L., Melling, H., Stern, G.A. 2009. Mercury trends

in ringed seals (*Phoca hispida*) from the western Canadian Arctic since 1973: associations with length of ice-free season. Environ. Sci. Technol. 43:3646-3651.

Gagnon, A. S., Gough, W.A. 2005. Trends in the dates of ice freeze-up and breakup over Hudson Bay, Canada. Arctic 58:370-382.

Gaston, A. J. 2002. Results of monitoring Thick-billed Murre populations in the Eastern Canadian Arctic, 1976-2000. Occ. Pap. Can. Wildl. Serv. 106:50p.

Gaston, A. J. 2003. Synchronous fluctuations of thick-billed murre (*Uria lomvia*) colonies in the Eastern Canadian Arctic suggest population regulation in winter. Auk. 120:362-370.

Gaston, A.J., Woo, K., Hipfner, J.M. 2003. Trends in forage fish populations in northern Hudson Bay since 1981, as determined from the diet of nestling thick-billed murres *Uria lomvia*. Arctic. 56:227-233.

Gaston, A.J., Gilchrist, H.G., Hipfner, J.M. 2005a. Climate change, ice conditions and reproduction in an Arctic nesting marine bird: Brunnich's guillemot (*Uria lomvia L*.). J. Animal Ecology. 74:832-841.

Gaston, A.J., Gilchrist, H.G., Mallory, M.L. 2005b. Variation in ice conditions has strong effects on the breeding of marine birds at Prince Leopold Island, Nunavut. Ecography. 28:331-344.

Gaston, A.J., Mallory, M.L., Gilchrist, H.G., O'Donovan, K. 2006. Status, trends and attendance patterns of the northern fulmar *Fulmarus glacialis* in Nunavut, Canada. Arctic, 59:165-178.

Gaston, A.J., Gilchrist, H.G., Descamps, S. 2009. Reproduction and survival of Glaucous Gulls breeding in an Arctic seabird colony. J. Field Ornithology. 80:135-145.

George, J.C., Zeh, J., Suydam, R., Clark, C. 2004. Abundance and population trend (1978 2001) of western Arctic bowhead whales surveyed near Barrow, Alaska. Mar. Mammal Sci. 20:755-73.

George, J. 2008. New Bowhead numbers show Inuit are right. Page 3 Nunatsiaq News. 14 March 2008.

Gilchrist, G.H., Mallory, M.L. 2005. Declines in abundance and distribution of the ivory gull (*Pagophila eburnea*) in Arctic Canada. Biol. Conserv. 121:303-309.

Godin, G. 1974. The tide in eastern and western James Bay. Arctic 27:104-110.

Gosselin, M., Legendre, L., Therriault, J.-C., Demers, S., Rochet, M. 1986. Physical control of the horizontal patchiness of sea-ice microalgae. Mar. Ecol. Prog. Ser. 29:289-298.

Gosselin, M., Levasseur, M., Wheeler, P.A., Horner, R.A., Booth, B.C. 1997. New measurements of phytoplankton and ice algal production in the Arctic Ocean. Deep-Sea Res. II. 44:1623-1644.

Government of Nunavut and Nunavut Tuungavik Incorporated. 2005. Nunavut Fisheries Strategy, 50 p.

Grebmeier, J.M., Overland, J.E., Moore, S.E., Farley, E.V., Carmack, E.C., Cooper, L.W., Frey, K.E., Helle, J.H., McLaughlin, F.A., McNutt, S.L. 2006. A major ecosystem shift in the northern Bering Sea. Science. 311:1461-1464.

Hamilton, J., Collins, K., Prinsenberg, S. 2009. Temporal variability in Arctic zooplankton and phytoplankton populations from moored ADCP and icycler profiler measurements. Bedford Institute of Oceanography, Fisheries and Oceans Canada. ICES CM. I:14

Harvey, M., Therriault, J.-C., Simard, N. 1997. Late-summer distribution of phytoplankton in relation to water mass characteristics in Hudson Bay and Hudson Strait (Canada). Can. J. Fish. Aquat. Sci. 54:1937-1952.

Harvey, M., Therriault, J.-C., Simard, N. 2001. Hydrodynamic control of late summer species composition and abundance of zooplankton in Hudson Bay and Hudson Strait (Canada). J. Plankton Res. 23:481-496.

Harvey, M., Starr, M., Therriault, J.-C., Saucier, F., Gosselin, M. 2006. MERICA-Nord program: Monitoring and research in the Hudson Bay complex. AZMP bulletin PMZA. 5:27-32

Harwood, L.A., Norton, P., Day, B. Hall, P.A. 2002. The harvest of beluga whales in Canada’s western arctic: Hunter-based monitoring of the size and composition of the catch. Arctic 55:10-20.

Hazard, K.W., Lowry, L.F. 1984. Benthic prey in a bowhead whale from the northern Bering Sea. Arctic.37:166–168.

Henderson, P.J. 1989. Provenance and depositional facies of surficial sediments in Hudson Bay, a glaciated epeiric sea. PhD Thesis, Department of Geology, University of Ottawa, Ottawa, ON. xvii+287 p.

Higdon, J.W., Ferguson, S.H. (2009) Loss of Arctic sea ice causing punctuated change in sightings of killer whales (Orcinus orca) over the past century. Ecol. Applic. 19:1365-1375.

Horner, R., Schrader, G.C. 1982. Relative contributions of ice algae, phytoplankton, and benthic microalgae to primary production in nearshore regions of the Beaufort Sea. Arctic. 35:485-503.

Howell, S.E.L., Yackel, J.J. 2004. A vessel transit assessment of sea ice variability in the western Arctic, 1969-2002: implications for ship navigation. Can. J. Remote Sensing. 30:205-215.

Howell, S.E.L., Tivy, A., Yackel, J.J., Else, B.G.T., Duguay, C.R. 2008. Changing sea ice melt parameters in the Canadian Arctic Archipelago: Implications for the future presence of multiyear ice. J. Geophys. Res. 113:C09030. doi:10.1029/2008JC004730.

Howell, S.E.L., Duguay, C.R., Markus, T. 2009. Sea ice conditions and melt season duration variability within the Canadian Arctic Archipelago: 1979-2008. Geophys. Res. Lett. 36: L10502. doi:10.1029/2009GL037681.

Hsiao, S.I.C. 1976. Biological productivity of the southern Beaufort Sea: phytoplankton and seaweed studies. Beaufort Sea Project Technical Report No. 12C. Environment Canada, Victoria, B.C. 99 p.

Huntington, H. P., S. Fox, F. Berkes, I. Krupnik, and *et al.* 2005. The changing Arctic: Indigenous perspectives. Arctic Climate Impact Assessment (ACIA). Cambridge University Press, Cambridge. p. 61-98.

Ikonomou, M.G., Rayne, S., Addison, R.F. 2002. Exponential increases of the brominated flame retardants, polybrominated diphenyl ethers, in the Canadian Arctic from 1981 to 2000. Environ. Sci. Technol. 36:1886–1892.

Ingram, R.G., Prinsenberg, S. 1998. Coastal oceanography of Hudson Bay and surrounding eastern Canadian Arctic waters, coastal segment. *In:* Robinson, A.R., Brink, K.H. (Eds.) The Sea, Volume 11. John Wiley and Sons, New York. p. 835-861.

Ingram, R.G., Carmack, E.C. 2006. Arctic Ocean sea ice status: subject to change without notice. Vulnerability of cryospheric and socio-economic systems (workshop).

Irvine, J.R., Macdonald, R.W., Brown, R.J., Godbout, L., Reist, J.D., Carmack, E.C. 2009. Salmon in the Arctic and how they avoid lethal low temperatures. N. Pac. Anadr. Fish Comm. Bull. 5:39–50.

Jakobsson, M., Grantz, A., Kristoffersen, Y., Macnab, R. 2004. Bathymetry and physiography of the Arctic Ocean and its constituent seas. *In:* Stein, R., Macdonald, R.W. (Eds.) The organic carbon cycle in the Arctic Ocean. Springer-Verlag Berlin Heidelberg. p. 1-5.

Johnson, L. 1980. The arctic charr, *Salvelinus alpinus*. *In:* Balon E.K. (Ed.) Charrs: salmonid fishes of the genus Salvelinus. Dr. W. Junk Publishers, The Hague, Netherlands. p. 15-98

Jolly, D., Berkes, F., Castledon, J., Nichols, T., the community of Sachs Harbour. 2002. We can't predict the weather like we used to: Inuvialuit observations of climate change, Sachs Harbour, Western Canadian Arctic. *In:* Krupnik, I., Jolly, D. (Eds.) The earth is faster now: Indigenous observations of Arctic climate change. Arctic Research Consortium of the United States in cooperation with the Arctic Resource Studies Center, Smithsonian Institution, Fairbanks, Alaska. p. 93-125.

Jones, P.E., Anderson, L.G. 1994. Northern Hudson Bay and Foxe Basin: water masses, circulation and productivity. Atmos.-Ocean. 32:361-374.

Jones, E.P., Swift, J.H., Anderson, L.G., Lipizer, M., Civitarese, G., Falkner, K.K., Kattner, G., McLaughlin, F. 2003. Tracing Pacific water in the North Atlantic Ocean. J. Geophys. Res. 108:3116, doi: 10.1029/2001JC001141.

Josenhans, H.W., Zevenhuizen, J. 1990. Dynamics of the Laurentide ice sheet in Hudson Bay, Canada. Mar. Geol. 92:1-26.

Juul-Pedersen, T., Michel, C., Gosselin, M. 2008. Seasonal changes in the sinking export of particulate material, under first-year sea ice on the Mackenzie shelf (western Canadian Arctic). Mar. Ecol. Prog. Ser. 353:13-25.

Kapoor, A., Victoria, J., Simmonds, P., Wang, C., Shafer, R.W., Nims, R., Nielsen, O., Delwart, E. 2008. A highly divergent picornavirus in a marine mammal. J. Virology. 82:311-320.

Kleim, N., Greenberg, D. 2003. Diagnostic simulations of the summer circulation in the Canadian Arctic Archipelago. Atmos.-Ocean. 41:273-289.

Köberle, C., Gerdes, R. 2003. Mechanisms determining the variability of Arctic sea ice conditions and export. J. Climate. 16:2843-2858.

Kusch, L. 2007. New day dawns on Churchill. Russia sends first ocean shipment to northern port. Winnipeg Free Press October 18, 2007.

Kuzyk, Z.A., Macdonald, R.W., Granskog, M.A., Scharien, R.K., Galley, R.J., Michel, C., Barber, D., Stern, G. 2008. Sea ice, hydrological, and biological processes in the Churchill River estuary region, Hudson Bay. Estuar. Coast. Shelf Sci. 77:369-384.

Laidre, K.L., Heide-Jørgensen, M.P. 2005. Arctic sea ice trends and narwhal vulnerability. Biol. Conserv. 121:209-517.

Lambert, J., Préfontaine, G. 1995. The Iceland scallop (Chlamys islandica) in Nunavik. Can. Tech. Rep. Fish. Aquat. Sci. 2071:vii + 40 p.

Lapoussiere, A., Michel, C., Gosselin, M., Poulin, M., Martin, J., Tremblay, J.-E. Coupling between primary production and sinking export in Hudson Bay and Hudson strait, Canada. Submitted.

Lavoie, D., Macdonald, R.W., Denman, K.L. 2009. Primary productivity and export fluxes on the Canadian shelf of the Beaufort Sea: a modelling study. J. Mar. Syst. 75:17-32.

Lindsay, R.W., Zhang, J., Schweiger, A., Steele, M., Stern, H. 2009. Arctic sea ice retreat in 2007 follows thinning trend. J. Climate. 22:165-176.

Lockhart, L., Stern, G. A., Wagemann, R., Hunt, R. V., Metner, D. A., DeLaronde, J., Dunn, B., Stewart, R. E.A., Hyatt, C. K., Harwood, L.A., Mount, K. 2005. Concentrations of mercury in tissues of beluga whales (*Delphinapterus leucas*) from several communities in the Canadian Arctic from 1981-2002. Sci. Total Environ. 351-352:391-412.

Loseto, L.L., Stern, G.A., Deibel, D., Connelly, T.L., Prokopowicz, A., Fortier, L., Ferguson, S.H. 2008a. Linking mercury exposure to habitat and feeding behaviour in Beaufort Sea beluga whales. J. Mar. Syst. 74:1012.

Loseto, L.L., Stern, G.A., Ferguson, S.H. 2008b. Size and biomagnification: how habitat selection explains beluga mercury levels. Environ. Sci. Technol. 11:3982-3988.

Lowry, L.F., Frost, K.J. 1984. Foods and feeding of bowhead whales in western and northern Alaska. Scientific Reports of the Whales Research Institute 35:1–16.

Macdonald, R.W., Wong, C.S., Erickson, P.E. 1987. The distribution of nutrients in the southeaster Beaufort Sea: Implication for water circulation and primary production. J. Geophys. Res. C. Oceans. 92:2939-2952.

Macdonald, R.W., Carmack, E.C., McLaughlin, F.A., Iseki, K., MacDonald, D.M., and O'Brien, M.C. 1989. Composition and modification of water masses in the Mackenzie shelf estuary. J. Geophysical Res. C. Oceans 94:18057-18070.

Macdonald, R.W., Paton, D.W., Carmack, E.C., Omsted, T.A. 1995. The freshwater budget and under-ice spreading of Mackenzie River water in the Canadian Beaufort Sea based on salinity and 18O/16O measurements in water and ice. J. Geophys. Res. 100:895-919.

Macdonald, R.W., Solomon, S.M., Cranston, R.E., Welch, H.E., Yunker, M.B., Gobeil, C. 1998. A sediment and organic carbon budget for the Canadian Beaufort Shelf. Marine Geology 144:255-273.

Macdonald, R.W., Sakshaug, E., Stein, R. 2004. The Arctic Ocean: modern status and recent climate change. *In:* Stein, R., Macdonald, R.W. (Eds.), The Arctic Ocean organic carbon cycle present and past. Springer, New York, NY. p. 6-21

Macdonald, R.W., Harner, T., Fyfe, J. 2005. Recent climate change in the Arctic and its impact on contaminant pathways and interpretation of temporal trend data. Sci. Tot. Envi. 342:5-86.

Mallory, M.L., Gilchrist,H.G., Fontaine, A.J., Akerok, J.A. 2003. Local ecological knowledge of Ivory Gull declines in Arctic Canada. Arctic. 56:293-298.

Manson, G.K., Solomon, S.M., Forbes, D.L., Atkinson, D.E., Craymer, M. 2005. Spatial variability of factors influencing coastal change in the western Canadian Arctic. Geo-Mar. Lett. 25:138-145.

Manson, G.K., Solomon, S.M. 2007. Past and future forcing of Beaufort Sea coastal change. Atmos.-Ocean. 45:107-122.

Martini, I.P. (Ed.) 1986. Canadian inland seas. Elsevier Oceanography Series 44. Elsevier Science Publishers, Amsterdam.

Maxwell, J.B. 1981. Climatic regions of the Canadian Arctic Islands. Arctic 34:225-240.

McDonald, M., Arragutainaq, L., Novalinga, Z. (Eds.) 1997. Voices from the Bay: Traditional Ecological Knowledge of Inuit and Cree in the James Bay Bioregion. Ottawa, Ontario.

McLaughlin, F.A., Carmack, E.C., Macdonald, R.W., Bishop, J.K. 1996. Physical and geochemical properties across the Atlantic/Pacific water mass front in the southern Canadian Basin. J. Geophys. Res. 101:1183-1197.

McLaughlin, F., Carmack, E.C., Macdonald, R., Weaver, A., Smith, J. 2002. The Canada Basin 1989-1995: upstream events and far-field effects of the Barents Sea Branch. J. Geophys. Res. 107: 101029-101049.

McPhee, M.G., Proshutinsky, A., Morison, J.H., Steele, M., Alkire, M.B. 2009. Rapid change in freshwater content of the Arctic Ocean. Geophys. Res. Lett. 36: L10602. doi:10.1029/2009GL037525.

Michel, C., Legendre, L., Ingram, R.G., Gosselin, M., Levasseur, M.. 1996. Carbon budget of sea-ice algae in spring: evidence of a significant transfer to the zooplankton grazers. J. Geophys. Res. 101:18345-18360

Michel, C., Ingram, R.G., Harris, L.R. 2006. Variability in oceanographic and ecological processes in the Canadian Arctic Archipelago. Prog. Oceanogr. 71:379-401.

Morin, R. 1991. A report on the exploratory cruise for Iceland scallops in eastern Hudson Bay during 1990. Unpublished report prepared by Department of Fisheries and Oceans, Ste-Anne de Bellevue, Quebec, for Kativik Regional Government, Kuujjuak, QC. 29 p. (preliminary draft).

Muir, D. 2009. Temporal trends of persistent organic pollutants and metals in ringed seals from the Canadian Arctic. *In:* Smith, S., Stow, J., Edwards, J. (Eds.), Synopsis of research conducted under the 2008-2009 Northern Contaminants Program. Minister of Indian Affairs and Northern Development, Ottawa. p.76-84.

Mundy, C.J., D.G. Barber, and C. Michel. 2005. Variability of snow and ice thermal, physical, and optical properties pertinent to sea ice algae biomass during spring. J. Mar. Syst. 58:107-120.

Mundy, C. J., Gosselin, M., Ehn, J., Gratton, Y., Rossnagel, A., Barber, D.G., Martin, J., Termblay, J.-E., Palmer, M., *et al.* (2009), Contribution of under-ice primary production to an ice-edge upwelling phytoplankton bloom in the Canadian Beaufort Sea. Geophys. Res. Lett. 36:L17601, doi:10.1029/2009GL038837

Murata, A., Takizawa, T. 2003. Summertime CO_2 sinks in shelf and slope waters of the western Arctic Ocean. Cont. Shelf Res. 23:753-776.

Nelson, R.J., Carmack, E.C., McLaughlin, F.A., Cooper, G.A. 2009. Penetration of Pacific zooplankton into the western Arctic Ocean tracked with molecular population genetics. Mar. Ecol. Prog. Ser. 381:129-138.

Nemoto, T., Harrison, G. 1981. High latitude ecosystems. *In:* Longhurst, A.R. (Ed.). Analysis of marine ecosystems. Academic Press, New York, p.95-126.

Nichols, T., Berkes, F., Jolly, D., Snow, N.B. 2004. Climate change and sea ice: local observations from the Canadian western Arctic. Arctic 57:68-79.

Nielsen, O., Nielsen, K., Stewart, R.E.A. 1996. Serologic evidence of Brucella spp. exposure in Atlantic walruses (*Odobenus rosmarus rosmarus*) and ringed seals (*Phoca hispida*) of arctic Canada. Arctic. 49:383-386.

Nielsen, O., Clavijo, A., Boughen, J.A. 2001. Serologic evidence of influenza A infection in marine mammals of Arctic Canada. J. Wildlife Diseases. 37:820-825.

Norris, A.W. 1986. Review of Hudson Platform Paleozoic stratigraphy and biostratigraphy. *In:* Martini, I.P. (Ed.) Canadian inland seas. Elsevier Oceanography Series 44. Elsevier Science Publishers, Amsterdam. p.17-42.

Nunavut Wildlife Harvest Study. 2004. The Nunavut Wildlife Harvest Study: final report. Nunavut Wildlife Management Board, Iqaluit, Nunavut, Canada. 822 p.

Outridge, P.M., Hobson, K.A., McNeely, R., Dyke, A. 2002. A comparison of modern and preindustrial levels of mercury in the teeth of beluga in the Mackenzie Delta, Northwest Territories, and walrus at Igloolik, Nunavut, Canada. Arctic. 55:123-32.

Pabi, S., van Dijken, G.L., Arrigo, K.R. 2008. Primary production in the Arctic Ocean, 1998–2006, J. Geophys. Res. 113:C08005, doi:10.1029/2007JC004578.

Palsbøll, P.J., Heide-Jørgensen, M.P., Dietz, R. 1997. Population structure and seasonal movements of narwhals, *Monodon monoceros*, determined from mtDNA analysis. Heredity. 78:284-292.

Parkinson, C.L., Cavalieri, D.J. 2008. Arctic sea ice variability and trends, 1979-2006. J. Geophys. Res. 113:C07003. doi:10.1029/2007JC004558.

Philippa, J.D.W., Leighton, A., Daoust, P.Y., Nielsen, O., Pagliarulo, M., Schwantje, H., Shury, T., van Herwijnen, R., Martina, B.E.E., Kuiken, T., Van de Bildt, M.W.G., Osterhaus, A.D.M.E. 2004. Antibodies to selected pathogens in free-ranging terrestrial carnivores and marine mammals in Canada. Veterinary Record. 155:135-140.

Piepenburg, D. 2005. Recent research on Arctic benthos: common notions need to be revised. Polar Biol. 28:733-755.

Polyakov, I.V., Alexeev, V.A., Belchansky, G.I., Dmitrenko, I.A., Ivanov, V.V., Kirillov, S.A., Korablev, A.A., Steele, M., Timokhov, L.A., Yashayaev, I. 2008. Arctic Ocean freshwater changes over the past 100 years and their causes. J. Climate. 21:364-384.

Prinsenberg, S.J. 1984. Freshwater contents and heat budgets of James Bay and Hudson Bay. Cont. Shelf Res. 3:191-200.

Prinsenberg, S.J. 1986. The circulation pattern and current structure of Hudson Bay. *In:* Martini, I.P. (Ed.) Canadian inland seas. Elsevier Oceanography Series 44. Elsevier Science Publishers, Amsterdam. p.187-204.

Prinsenberg, S.J., Bennet, E.B. 1987. Mixing and transports in Barrow Strait, the central part of the Northwest Passage. Cont. Shelf Res. 7:913-935.

Prinsenberg, S.J., Hamiltion, J. 2005. Monitoring the volume, freshwater and heat fluxes passing through Lancaster Sound in the Canadian Arctic Archipelago. Atmos.-Ocean. 43:1-22.

Proshutinsky, A., Krishfield, R., Timmermans, M.-L., Toole, J., Carmack, E., McLaughlin, F., Zimmerman, S., Itoh, M., Shimada, K. 2009. The Beaufort Gyre freshwater reservoir: state and variability from observations. J. Geophys. Res. 114:C00A10. doi:10.1029/2008JC005104.

Rampal, P., Weiss, J., Marsan, D. 2009. Positive trend in the mean speed and deformation rate of Arctic sea ice, 1979-2007. J. Geophys. Res. 114:C05013. doi:10.1029/2008JC005066.

Reist, J.D., Wrona, F.J., Prowse, T.D., Power, M., Dempson, J.B., Beamish, R.J., King, J.R., Carmichael, T.J., Sawatzky, C.D. 2008a. General effects of climate change on arctic fishes and fish populations. Ambio 35:370-380.

Reist, J.D., Wrona, F.J., Prowse, T.D., Power, M., Dempson, J.B., King, J.R., Beamish, R.J. 2008b. An overview of effects of climate change on selected arctic freshwater and anadromous fishes. Ambio 35:381-387.

Reist, J.D., Wrona, F.J., Prowse, T.D., Dempson, J.B., Power, M., Koeck, G., Carmichael, T.J., Sawatzky, C.D., Lehtonen, H., Tallman, R.F. 2008c. Effects of climate change and UV radiation on fisheries for arctic freshwater and anadromous species. Ambio 35:402-410.

Renaud, P.E., Riedel, A., Michel, C., Moratea, N., Gosselin, M., Juul-Pedersen, T. Chiuchiolo, A. 2007. Seasonal variation in benthic community oxygen demand: a response to an ice algal bloom in the Beaufort Sea, Canadian Arctic? J. Mar. Syst. 67:1-12.

Richard, P.R. 2005. An estimate of the Western Hudson Bay beluga population size in 2004. DFO Can. Sci. Advis. Sec. Res. Doc. 2005/017. ii + 29 p.

Richard, P.R. 2010. Stock definition of belugas and narwhals in Nunavut. DFO Can. Sci. Advis. Sec. Res. Doc. 2010/022. iv + 14 p.

Richard, P., Stewart, D.B. 2008. Information relevant to the identification of critical habitat for Cumberland Sound belugas (*Delphinapterus leucas*). DFO Can. Sci. Advis. Sec. Res. Doc. 2008/085. iv + 24 p.

Richard, P. R., Orr, J.R., Barber, D.G. 1990. The distribution and abundance of belugas, *Delphinapterus leucas*, in eastern Canadian subarctic waters: a review and update. Can. Bull. Fish. Aquat. Sci. 224:23-38.

Riedel A., Michel, C., Poulin, M., Lessard, S. 2003. Taxonomy and abundances of microalgae and protists at a first-year sea ice station near Resolute Bay, Nunavut, spring to early summer 2001. Can. Dat. Rep. Hydrol. Ocean Sci. 159: 54p.

Riedel, A., Michel, C., Gosselin, M., LeBlanc, B. 2008. Winter-spring dynamics in sea-ice carbon cycling in the coastal Arctic Ocean. J. Mar. Syst. 74:918-932.

Robertson,G.J., Gilchrist, H.G., Mallory, M.L. 2007 Colony dynamics and persistence of ivory gull breeding in Canada. Avian Conservation and Ecology. 2:8.

Roff, J.C., Legendre, L. 1986. Physio-chemical and biological oceanography of Hudson Bay, *In:* Martini, I.P. (Ed.) Canadian inland seas. Elsevier Oceanography Series 44. Elsevier Science Publishers, Amsterdam. p.265-291.

Rozanska, M., Gosselin, M., Poulin, M., Wiktor, J.M., Michel, C. 2009. Influence of environmental factors on the development of bottom ice protist communities during the winter–spring transition. Mar. Ecol. Prog. Ser. 386:43-59.

Rung, J.A., Ingram, R.G. 1991. Under-ice feeding and diel migration by the planktonic copepods Calanus glacialis and Pseudocalanus minutus in relation to the ice algal production cycle in southeastern Hudson Bay, Canada. Mar. Biol. 108:217-225.

Rysgaard, S., Bendtsen, J., Pedersen, L.T., Ramlov, H., Glue, R.N. 2009. Increased CO_2 uptake due to sea ice growth and decay in the Nordic Seas. J. Geophys. Res. 114: C09011. doi:10.1029/2008JC005088.

Savvaitova, K.A. 1980. Taxonomy and biogeography of charrs in the Palearctic. *In:* Balon, E.K. (Ed.) Charrs: salmonid fishes of the genus Salvelinus. Dr. W. Junk Publishers, The Hague, Netherlands. p.281-294.

Schauer, U., Fahrbach, E., Osterhus, S., Rohardt, G. 2004 Arctic warming through the Fram Strait - Oceanic heat transport from three years of measurements. J. Geophys. Res. 109:C06026, doi:10.1029/2003JC001823.

Simpkins, M. Kovacs, K.M., Laidre, K., Lowry, L. 2009. A Framework for Monitoring Arctic Marine Mammals - workshop Findings, Valencia 2007. CAFF International Secretariat, CAFF CBMP Report No. 16. 17 p.

Smith, R.E.H., Anning, J.A., Clement, P., Cota G.F. 1988. Abundance and production of ice algae in Resolute Passage, Canadian Arctic. Mar. Ecol. Prog. Ser. 48:251-163.

Smith, R.E.H., Herman, A.W. 1991. Productivity of ice algae: In situ vs. incubator methods. J. Mar. Syst. 2:97-110.

Smith, R.E.H., Gosselin, M., Taguchi, S. 1997. The influence of major inorganic nutrients on the growth and physiology of high arctic ice algae. J. Mar. Syst. 11:63-70.

Smith, T.G. 1987. The ringed seal, *Phoca hispida*, of the Canadian Western Arctic. Can. Bull. Fish. Aquat. Sci. 216. 81 p.

Smith, T.G., Hammill, M.O., Burrage, D.J., Sleno, G.A. 1985. Distribution and abundance of belugas, *Delphinapterus leucas*, and narwhals, *Monodon monoceros*, in the Canadian High Arctic. Can. J. Fish. Aquat. Sci. 42:676-684.

Smith, W.O., Barber, D.G. 2007. Polynyas and climate change: a view to the future. *In:* Smith, W.O. Jr., Barber, D.G. (Eds.), Polynyas: Windows to the World. Elsevier, Amsterdam. p. 411-419.

Solomon, S.M., Forbes, D.L., Kierstead, B. 1993 Coastal impacts of climate change: Beaufort Sea erosion study. Geol. Surv. Can. Open File Rep. 2890:35.

Steele, M., Ermold, W., Zhang, J. 2008. Arctic Ocean surface warming trends over the past 100 years. Geophys. Res. Lett. 35:L02614. doi:10.1029/2007GL031651.

Steffen, A., Schroeder, W., Macdonald, R. Poissant, L., Konoplev, A. 2005. Mercury in the Arctic atmosphere: An analysis of eight years of measurements of GEM at Alert (Canada) and a comparison with observations at Amderma (Russia) and Kuujjuarapik (Canada). Sci. Tot. Envi. 432:185-198.

Steinacher, M., Joos, F., Frölicher, T. L., Plattner, G.-K., Doney, S. C. 2009. Imminent ocean acidification in the Arctic projected with the NCAR global coupled carbon cycle-climate model, Biogeosciences. 6:515–533.

Stern, G.A. 2009a. Contaminants in Canadian arctic bowhead whales. DFO Can. Sci. Advis. Sec. Res. Doc. 2009/028. iv + 7 p.

Stern, G.A. 2009b. Mercury in beluga, narwhal and walrus from the Canadian Arctic: status in 2009. *In:* Smith, S., Stow, J., Edwards, J. (eds.), Synopsis of research conducted under the 2008-2009 Northern Contaminants Program. Minister of Indian Affairs and Northern Development, Ottawa. p.108-122.

Stern, G.A. 2009c. Temporal trends of halogenated organic compounds in Canadian Arctic Beluga. *In:* Smith, S., Stow, J., Edwards, J. (Eds.), Synopsis of research conducted under the 2008-2009 Northern Contaminants Program. Minister of Indian Affairs and Northern Development, Ottawa. p.123-130.

Stewart, D.B., Lockhart, W.L. 2005. An overview of the Hudson Bay marine ecosystem. Can. Tech. Rep. Fish. Aquat. Sci. 2586: vi + 487p.

Stewart, D.B., Howland, KL. 2009. An ecological and oceanographical assessment of the alternate ballast water exchange zone in the Hudson Strait Region. DFO Can. Sci. Advis. Sec. Res. Doc. 2009/008. vi + 96 p.

Stirling, I. 1997. The importance of polynyas, ice edges and leads to marine mammals and birds. J. Mar. Syst. 10:9-21.

Stirling, I., Lunn, N.J., Iacozza, J. 1999. Long-term trends in the population ecology of polar bears in western Hudson Bay in relation to climatic change. Arctic. 57:59-67.

Straneo, F., Saucier, F.J. 2008. The arctic–subarctic exchange through Hudson Strait. *In:* Fiammetta R.R., Dickson *et al.* (Eds.), Arctic-Subarctic Ocean Fluxes: 249 Defining the Role of the Northern Seas in Climate. p. 249-262.

Stroeve, J., Markus, T., Meier, W.N., Miller, J. 2006. Recent changes in the Arctic melt season. Annals Glaciol. 44:367-374.

Subba Rao, D.V., Platt, T. 1984. Primary production of Arctic waters. Polar Biol. 3:191-201.

Thomson, D.H., 1982. Marine benthos in the Eastern Canadian High Arctic: multivariate analyses of standing crop and community structure. Arctic. 35:61-74.

Thomson, D.H. 1982. Marine benthos in the Eastern Canadian High Arctic: multivariate analyses of standing crop and community structure. Arctic 31:61–74.

Tomy, G. 2009. Temporal trends of halogenated chemicals of emerging concern in beluga whales (*Delphinapterus leucas*) from Hendrickson Island and Pangnirtung. *In:* Smith, S., Stow, J., Edwards, J. (Eds.), Synopsis of research conducted under the 2008-2009 Northern Contaminants Program. Minister of Indian Affairs and Northern Development, Ottawa. p.99-107.

Tremblay, J.E., Smith, W.O. Jr. 2007. Primary Production and Nutrient Dynamics in Polynyas. *In:* Smith, W.O. Jr., Barber, D.G. (Eds.), Polynyas: Windows to the World. Elsevier, Amsterdam. p. 239-269.

Tynan, C.T., DeMaster, D.P. 1997. Observations and predictions of Arctic climatic change: Potential effects on marine mammals. Arctic. 50:308-322.

Wang, J., Zhang, J., Watanabe, E., Ikeda, M., Mizobata, K., Walsh, J.E., Bai, X., Wu, B. 2009. Is the dipole anomaly a major driver to record lows in Arctic summer sea ice extent? Geophys. Res. Lett. 36:L05706, doi:10.1029/2008GL036706.

Welch, H.E., Bergmann, M.A. 1989. Seasonal development of ice algae and its prediction from environmental factors near Resolute N.W.T. Can. J. Fish. Aquat. Sci. 46:1793-1804.

Welch, H.E., Bergman, M.A., Siferd, T.D., Martin, K.A., Curtis, M.F., Crawford, R.E., Conover, R.J., Hop, H. 1992. Energy flow through the marine ecosystem of the Lancaster Sound Region, Arctic Canada. Arctic. 45:343-357.

Webber, R.J., Richardson, J.W., Andrews, J.T. 1970. Post-glacial uplift and substrate age at Cape Henrietta Maria, southeastern Hudson Bay, Canada. Can. J. Earth Sci. 7:317-325.

Wells, L.E., Cordray, M., Bowerman, S., Miller, L.A., Vincent, W.F., Deming, J.D. 2006. Archaea in particle-rich waters of the Beaufort Shelf and Franklin Bay, Canadian Arctic: Clues to an allochthonous origin? Limnol. Oceanogr. 51:47–59.

Williams, W.J., Carmack, E.C., Ingram, R.G. 2007. Physical oceanography of polynyas. *In:* Smith, W.O. Jr., Barber, D.G. (Eds.), Polynyas: Windows to the World. Elsevier, Amsterdam. p. 55-85.

Willson, M.F., Halupka, K.C. 2002. Anadromous fish as keystone species in vertebrate communities. Cons. Biol. 9:489-4.

Yamamoto-Kawai, M., McLaughlin, F.A., Carmack, E.C., Nishino, S., Shimada, K. 2009. Aragonite undersaturation in the Arctic Ocean: effects of ocean acidification and sea ice melt. Science 326:1098-1100.

Zeh, J.E., Punt, A.E. 2005. Updated 1978-2001 abundance estimates and their correlations for the Bering-Chukchi-Beaufort Seas stock of bowhead whales. J. Cetacean Res. Manage. 7:169-175.