

## **Arctic Sea Ice Ecosystem:**

**A summary of species that depend on and associate with  
sea ice and projected impacts from sea ice changes**

Prepared for CAFF

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## Executive Summary

The Arctic sea ice is the basis for a unique ecosystem that is comprised of ice algae and microorganisms, fish, seabirds and marine mammals. Some species depend on sea ice for essential life functions and other associate with sea ice for a specific reason, but also occur in other habitats. Each species depends and associates with sea ice for different reasons that are unique to their individual biological needs.

The base of the Arctic marine food web is ice algae; its productivity is influenced seasonally by light and nutrient availability (Bluhm and Gradinger 2008). An important bloom of ice algae in the lower horizons of sea ice occurs as light increases in the spring which is then grazed upon by abundant zooplankton (amphipods and copepods). As the ice melts in summer, organic material releases into the water column and falls to the ocean floor, where it contributes to both pelagic and benthic food webs (Bluhm and Gradinger, Thomas et al. 2008). Under-ice amphipods are an important food source for Arctic diving birds and Arctic cod (*Boreogadus saida*) (Bradstreet and Cross 1982) and thereby provide the connection from the food web within the sea ice to the more accessible open water below (Bluhm and Gradinger). In turn, Arctic cod acts as an important link to birds, seals and beluga whales. Seals are preyed upon by polar bears at the top of the food chain. The productivity of each link in the food chain is timed in accordance with natural cycles of the season, including temperature and light availability, along with the biological process for each species. The various cycles align to ensure food is available from the lowest to the highest trophic levels in the harsh Arctic marine environment.

Arctic sea ice has changed over the last thirty years when satellite records began (NSIDC 2009). It has decreased in extent, particularly in summer, and it has thinned overall (NSIDC 2009). Reductions in sea ice extent are occurring faster than climate models project (Stroeve et al. 2007) and an ice-free summer Arctic is predicted within this century and possibly by mid-century (Wang and Overland 2009). Sea ice has changed in composition with first year (FY) ice compromising the majority of the sea ice cover compared to multi-year (MY) ice that survives the summer melt period (NSIDC 2009). First year ice is different in structure and biotic composition than multi-year ice, with fewer species of ice algae found in FY ice (Melnikov 2008, 2009). It has been estimated that ice algae was responsible for over 50% of primary production in the central Arctic (Gosselin et al. 1997), but the contribution of ice algae to total primary production may have changed due to the reduction in sea-ice thickness and extent over the Arctic Ocean reported during the last 10 years (Comiso et al. 2008, Rozanska et al. 2009). However, pelagic phytoplankton is increasing as more open water occurs (Pabi et al. 2008, Arrigo et al. 2008). Some project that the Arctic sea ice ecosystem will become more like the Antarctic sea ice system where sea ice melts annually (Melnikov 2008, 2009). It is unclear what the effects of the restructuring of the lowest trophic levels will be on the higher trophic level and whether there will be timing differences and spatial separations between energy requirements and food availability for many higher trophic levels. These mismatches may lead to decreased reproductive success, lower abundances, and changes in distribution at the higher trophic levels (Moline et al. 2008).

Baseline information about many species' populations is incomplete due to the difficulty and expense of surveying and studying animals in remote Arctic environments. For most species, while past studies have recognized a species' relationship with sea ice, researchers do not understand completely the importance of the association. Few studies show overall that sea ice changes are directly responsible for alterations in a species demographics or life history. However, there are individual case studies and observations that point to very unusual responses by animals from sea ice reductions as well as changes in body condition. For the most part, it is conjecture exactly how sea ice changes will affect each species that is connected to sea ice in some way due to incomplete information about sea ice reliance and trophic interdependence.

Arctic cod associates with sea ice in its larval and juvenile stages. Arctic cod represents the most important trophic link in the Arctic marine food web from lower trophic levels (copepods and under-ice amphipods) to other fish, birds, seals and whales (Tyman and DeMaster 1997, Bradstreet 1982;

Bradstreet et al. 1986; Ainley and DeMaster 1990; Borkin 1990; Welch et al. 1992; Crawford and Jorgenson 1993). Despite its central role in the Arctic marine food web, very little information exists on its biology in the central Arctic Ocean or its abundance. Further, how reduced sea ice may affect Arctic cod is uncertain. Bouchard and Fortier (2008) suggest that, at least in the short term, Arctic cod larvae survival could be favored by more open water, leading to enhanced recruitment, and potentially larger populations (Fortier et al. 2006). They conclude that in the longer term as sea ice becomes seasonal, a circumpolar generalist species will likely replace Arctic cod as the main forage fish for the Arctic Ocean.

Ivory gulls, thick-billed murres, spectacled eiders and king eiders associate with sea ice. The relationship with these birds and sea ice is not completely understood. It appears that they forage at the ice edge in areas of high productivity and also in the case of eiders benefit energetically from roosting on ice as opposed to being immersed in very cold waters (Petersen et al. 1999, Mosbech et al. 2006). It is not certain how reduced sea ice will affect these birds. The fish-eating ivory gull and thick-billed murre likely use visual detection for foraging. Thus, if sea ice retreats further north, where days are shorter, the birds will have less time available for foraging. It is possible that these birds may experience range contraction with a northward displacement of more southern populations that move with the sea ice (e.g., Gaston et al. 2005). Irons et al. (2008) suggests that not only the direction but the magnitude of change may be important in determining outcomes for murre populations.

Very few species of marine mammals have been studied anywhere in the Arctic for long enough to allow an assessment of the possible effects of long-term environmental fluctuations, including climate warming, on population size and demographic parameters (Laidre et al. 2008). Impacts of reduced sea ice on Arctic marine mammals vary depending on the unique ecological relationship between each species and sea ice. Species that have relatively fixed life history traits and that are highly dependent on seasonal sea ice will likely be the most affected by sea ice reductions (Moore and Huntington 2008). The ringed seal, for example, requires certain ice and snow conditions to build lairs where the females give birth to and nurse their pups (Kelly 1988). Polar bears depend on ice as a hunting platform and are already being stressed by the increasingly ice-free summer and seasonal changes in the accessibility of hunting and denning areas; in some regions there is reduced body condition, reproduction and cub survival, altered behaviors and population declines (Stirling and Derocher 1993, Amstrup and Gardner 1994, Stirling et al. 1999, Regehr et al. 2005, Fischbach et al. 2007). Walrus are able to access continental shelf foraging areas only if they can haul out on ice near those areas. The loss of sea ice is thereby reducing their access to prey (Moore and Huntington 2008). In recent years, very large groups of walrus have congregated on shore in Russia and Alaska when the summer ice receded far off the continental shelf. This resulted in stampeding and trampling mortality (Kochnev 2004, Kavry et al. 2008, Jay and Fischbach 2008, Fischbach et al. 2009, USFWS 2009c, 2010c).

In addition, Moore and Huntington (2008) anticipate decreases in sea ice to have a negative effect on ice-associated species due to their adaption to existing trophic regimes such as beluga and narwhals, and reliance on sea ice for an important life function such as pupping for harp, hooded, ribbon and spotted seals (Reeves et al. 1992, Johnston et al. 2005). Not all changes, however, are predicted to have negative impacts. Bowhead whales might benefit from any increased productivity that might be associated with more open water in their current summer foraging habitats (Moore and Laidre 2006). Milder winters can result in less ice entrapments for narwhals and belugas. Finally, seasonally migrant cetacean species are likely to benefit from net loss in sea ice, due to greater access to a pelagic-dominated ecosystem which has been observed for gray whales that are staying later, with a few overwintering in the Beaufort Sea (Moore and Huntington 2008). However, it is unclear whether sub-Arctic species will compete with Arctic residents when they are sharing space and prey items.

It is important to recognize that species by species analysis is only one part of the story. The reduction in sea ice has significant impacts on the basic Arctic marine food web, which is built on ice algae, amphipods, and Arctic cod. Loss of marine mammal habitat may therefore be accompanied by a loss of prey, although there is much uncertainty about the trajectories of food webs (Moore and Huntington 2008).

# Concept Paper – Sea Ice Ecosystem

## Introduction

Sea ice<sup>1</sup> is the basis of a unique ecosystem in the Arctic, providing habitat to specialized ice-dependent and ice-associated species that include microorganisms, fish, birds and marine mammals. Individual species live within the ice, below it, on top and along the ice edge and use sea ice in different ways depending on their biological needs and life history. The annual formation and recession of sea ice exerts broad-scale control on energy flux and primary and secondary production,<sup>2</sup> ultimately reaching the top of the food chain (Sakshaug and Skjoldal 1989; Heide-Jørgensen and Laidre 2004; Heide-Jørgensen et al. 2007a). Arctic sea ice has changed rapidly during the last thirty years, decreasing substantially in extent (NSIDC 2009) and thickness with thin first-year ice replacing thicker multi-year ice<sup>3</sup> (NSIDC 2009, Kwok et al. 2009, Haas et al. 2008). These changes are happening faster than models project (Stroeve et al. 2007) and a nearly ice-free Arctic Ocean in late summer is likely within this century and possibly before mid-century (Wang and Overland 2009).<sup>4</sup>

This transformation is likely to impact the Arctic sea ice food web which is driven by the complex interactions between ice, light penetration, nutrient supply, and productivity (Bluhm and Gradinger 2008). The response of an individual ice dependent species to sea ice changes depends on its adaptability, its natural history, and the scale of environmental changes (e.g., Laidre et al. 2008). Many species are already experiencing a variety of impacts as the sea ice diminishes. It is not clear exactly what will happen as summer sea ice continues to disappear and whether species will be able to adapt to the rate of ice loss that is occurring.

This paper describes several species which depend on sea ice for essential life functions including foraging, reproduction, protection from predators and cold water immersion, a platform for traveling, resting, and nursing, as well as some species that associate with sea ice for parts of the year. This paper specifically discusses ice algae and protists, Arctic cod, ivory gulls, thick-billed murres, spectacled and king eiders, polar bears, ringed seals, bearded seals, walruses, narwhals, beluga whales and bowhead whales. It identifies the different species' relationship with sea ice and the known and projected effects of a changing climate on them and their trophic relationships.

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<sup>1</sup> There are different kinds of sea ice. Land-fast ice is either frozen to land or to the bottom of the ocean and is relatively immobile throughout the winter. Shore-fast ice, a type of land-fast ice also known as "fast ice," is defined by the Arctic Climate Impact Assessment (2005) as ice that grows seaward from a coast and remains stationary throughout the winter and that is typically stabilized by grounded pressure ridges at its outer edge. Pack ice consists of annual and heavier multi-year ice that is in constant motion due to winds and currents. It is located in open ocean areas and, unlike land-fast ice, can be highly dynamic. The actions of winds, currents, and temperature result in the formation of leads or polynyas (linear openings or cracks in the sea ice), pressure ridges, and ice floes of various sizes. While the composition of land-fast ice is uniform, regions of pack ice can consist of various ages and thicknesses, from new ice only days old that may be several centimeters thick, to multiyear ice that has survived several years and may be more than 2 meters thick.

<sup>2</sup> Primary production is the production of organic compounds from inorganic molecules such as H<sub>2</sub>O and CO<sub>2</sub>, principally through the process of photosynthesis. In the oceans, algae perform almost all primary production. Secondary production is the generation of biomass of consumer organisms in a system. This is driven by the transfer of organic material between trophic levels.

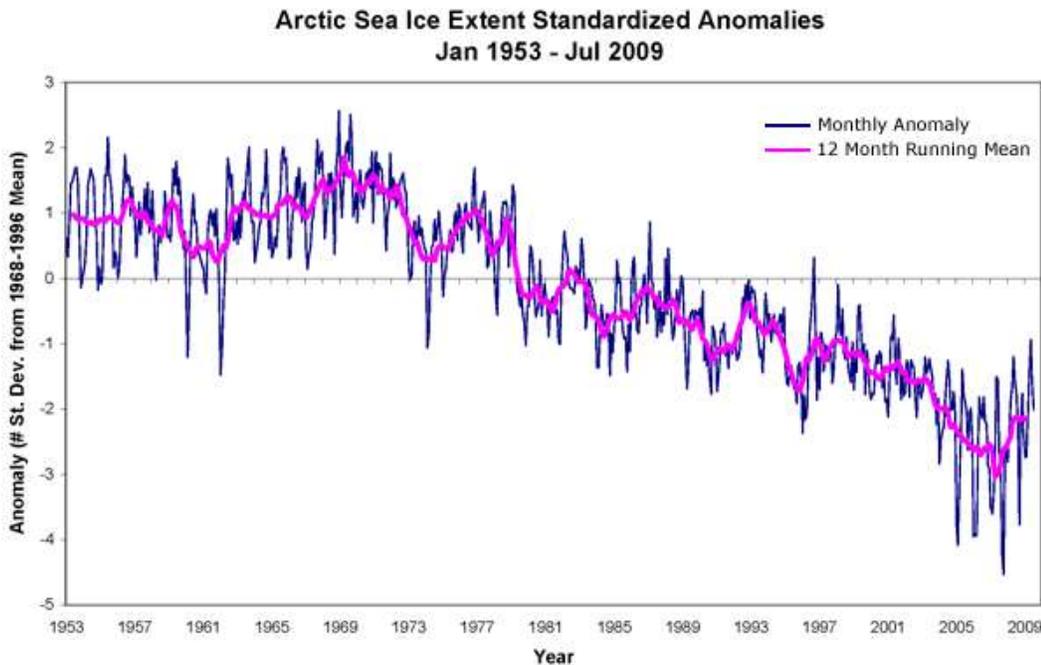
<sup>3</sup> Sea ice is classified as first year or multiyear ice. First-year is ice that has not yet survived a summer melt season, while multi-year ice has survived at least one summer and can be several years old.

<sup>4</sup> The information in this paper assumes that the climate is warming and ice reduction will continue in accordance with numerous climate models (e.g., Wang and Overland 2009, IPCC 2007, ACIA 2005). However, an alternative hypothesis (e.g. Frolov et al. 2009) asserts that climate and consequently ice cover will experience oscillatory rather than unidirectional changes. The second hypothesis projects that the current warm period will end by 2015-2020 and then air temperatures will decrease while ice cover will gradually increase by the 2030s until another warming period begins and causes a subsequent ice cover decrease by the 2060s (Frolov et al. 2009).

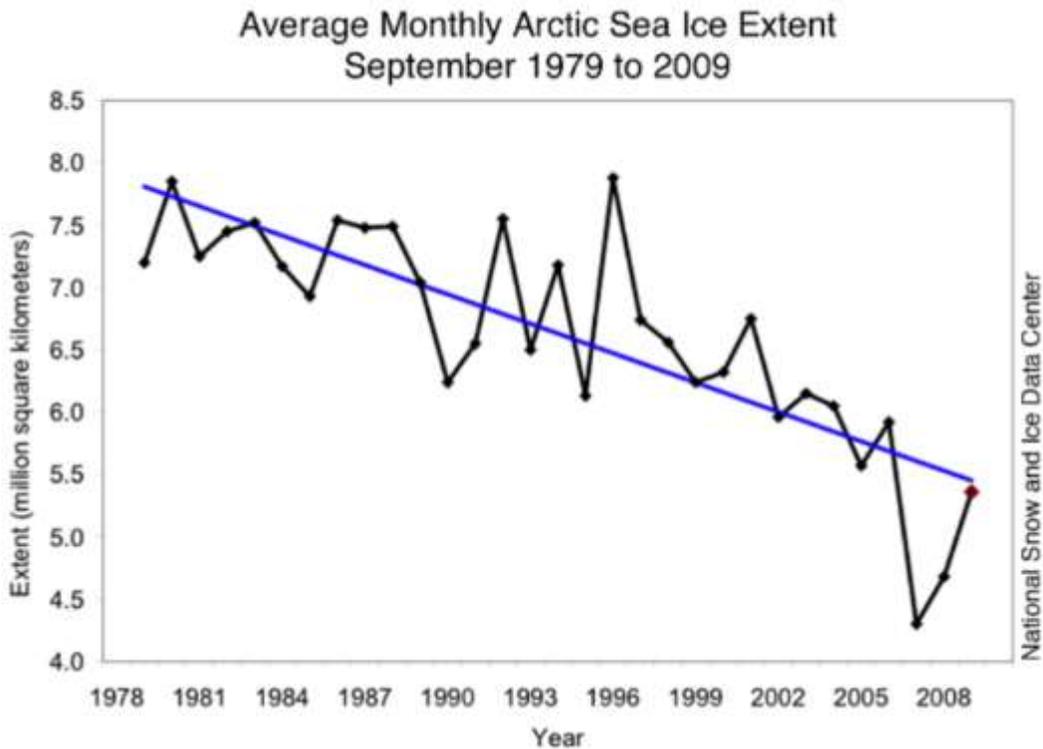
This paper is drafted specifically to inform discussion about the sea ice ecosystem for the CAFF meeting which will occur in March 2010 in Copenhagen. It summarizes information from many published sources. While it attempts to be comprehensive, there may be relevant information that has not been included or the exclusion of some species that associate with sea ice due to the time constraints in drafting this paper for the upcoming CAFF meeting.

## 1. Arctic sea ice changes

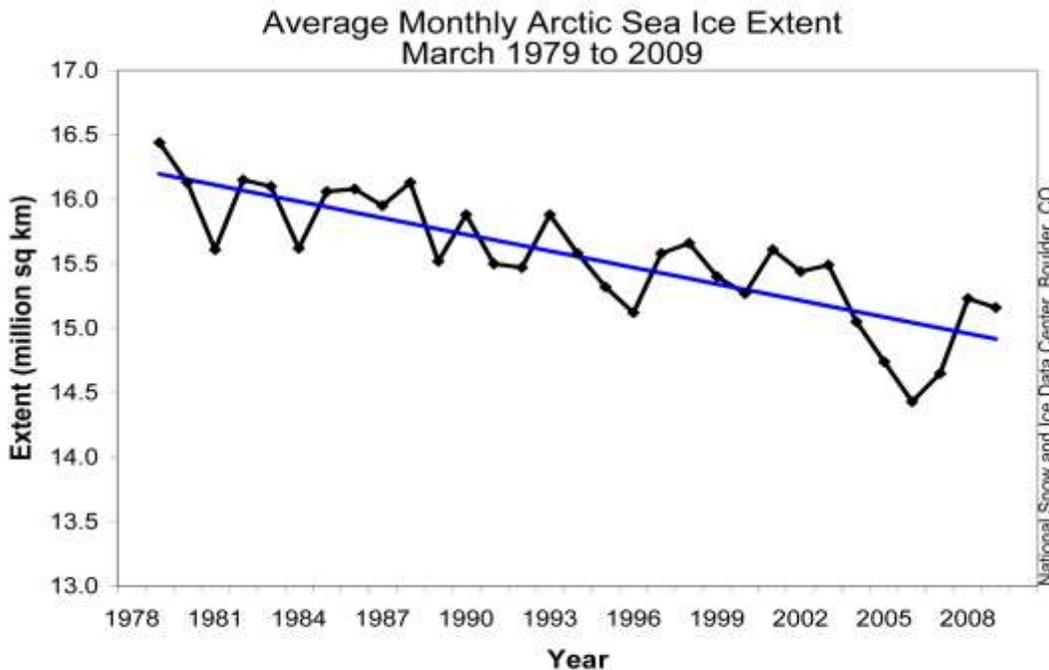
Satellite data combined with earlier observations from ice charts and other sources yields a time series of Arctic ice extent from the early 1900s onward (NSIDC 2010). While the pre-satellite records are not as reliable, their trends are in good general agreement with the satellite record and indicate that Arctic sea ice extent has been declining since at least the early 1950s as shown in Figure 1a (NSIDC 2010). At the end of the Arctic summer, more ice cover remained in 2009 than during the previous record-setting low years of 2007 and 2008, but sea ice has not recovered to previous levels (NSIDC 2010). September sea ice extent, the month of lowest ice extent during the year, was the third lowest since the start of satellite records in 1979, and the past five years have seen the five lowest ice extents in the satellite record as shown in Figure 1b (NSIDC 2010). The September rate of sea ice decline since 1979 has now increased to 11.2 % per decade (NSIDC 2010). Including March 2009, the month of maximum ice extent, the past six years have all had ice extent substantially lower than normal as shown in Figure 1c (NSIDC 2010). The linear trend indicates that for the month of March, ice extent is declining by 2.7% per decade (NSIDC 2010).



**Figure 1a. Mean sea ice anomalies, 1953-2009:** Sea ice extent departures from monthly means for the Northern Hemisphere. For January 1953 through December 1979, data have been obtained from the UK Hadley Centre and are based on operational ice charts and other sources. For January 1979 through July 2009, data are derived from passive microwave (SMMR / SSM/I) (NSIDC 2010).



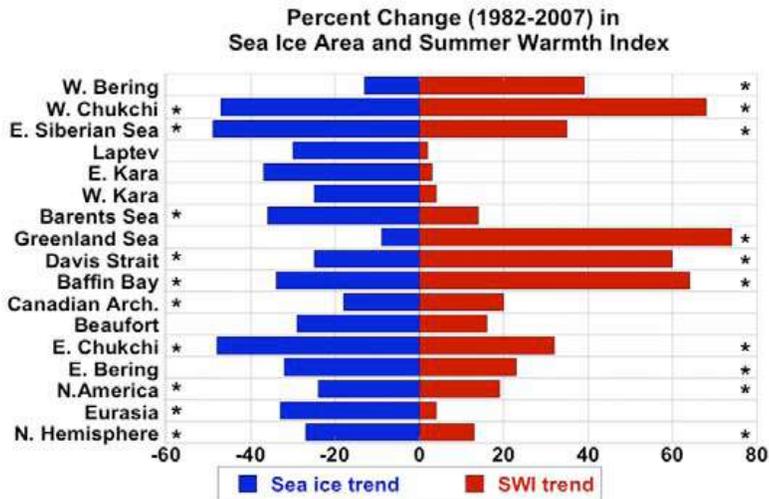
**Figure 1b.** Ice extent from 1979 to 2009 in September (the month of ice extent minimum) shows a continued decline. The September rate of sea ice decline since 1979 has increased to 11.2 % per decade (NSIDC 2010).



**Figure 1c.** Ice extent for 1979 to 2009 in March (the month of ice extent maximum) shows a decline of 2.7% per decade (NSIDC 2010).

The trend analysis in Figure 2 shows that summer sea ice within 50 km of the coast declined in all regions, with a decrease of 25% for the northern hemisphere as a whole (blue bars) (Walker et al.

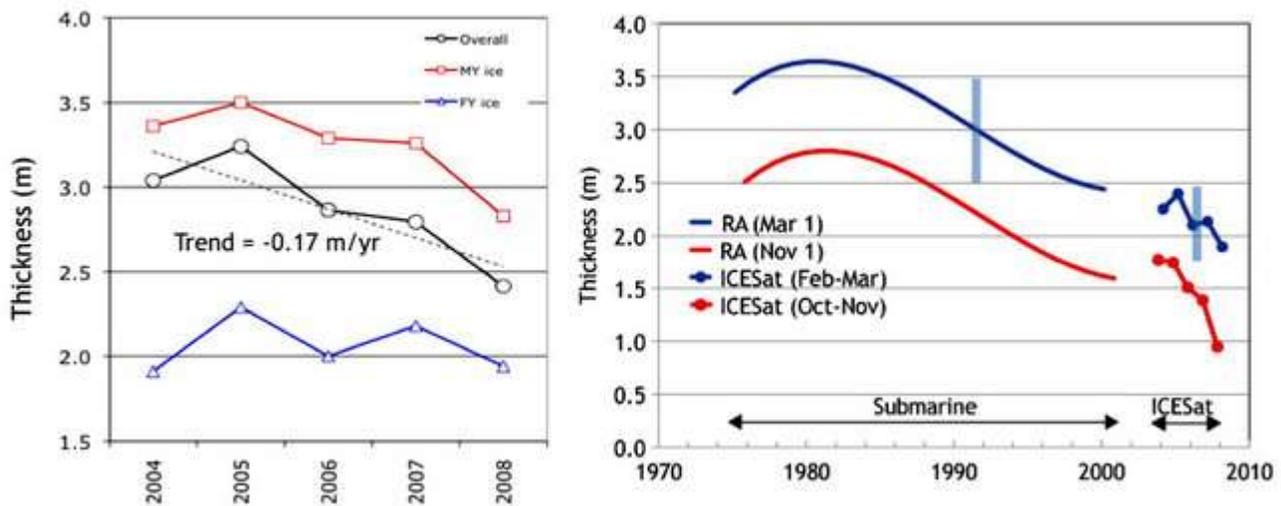
2009). The largest declines were along the northern Beringia region, including the E. Siberia (-47%), W. Chukchi (-46%), and E. Chukchi (-44%) seas (Walker et al. 2009). This portion of the Arctic saw large areas of summer ice retreat in 2005, 2007, and 2008 (Walker et al. 2009).



**Figure 2.** (Walker et al. 2009) Blue bars: Percentage change in sea-ice area in late spring (when the long-term mean 50% concentration is reached) during 1982–2008 along the 50-km-seaward coastal margin in each of the major seas of the Arctic using 25-km resolution SSIM passive microwave Bootstrap sea-ice concentration data (Comiso and Nishio 2008). Red bars: Percentage change in the summer land-surface temperature landward of each sea for the entire tundra domain as measured by the summer warmth index (SWI = sum of the monthly mean temperatures above freezing, °C mo) based on AVHRR surface-temperature data (Comiso 2003).

The 2009 Arctic Report Card provides recent estimates of Arctic Ocean sea ice thickness from satellite altimetry that show an overall thinning of approximately 0.6 meters (m) in multi-year ice thickness between 2004 and 2008 (Figure. 3a). In contrast, the average thickness of the thinner first-year ice in mid-winter (~2 m), did not exhibit a downward trend (Perovich et al. 2009). Seasonal ice covered more than two-thirds of the Arctic Ocean in 2008 (Perovich et al. 2009). The total multi-year ice volume in the winter experienced a net loss of more than 40% in the four years since 2005 while the first year ice cover gained volume due to increased overall coverage of the Arctic Ocean (Perovich et al. 2009). The declines in total volume and average thickness (black line in Figure 3) are explained almost entirely by thinning and loss of multi-year sea ice due to melting and ice export (Perovich et al. 2009). These changes have resulted in seasonal ice becoming the dominant Arctic sea ice type, both in terms of area coverage and of volume (Perovich et al. 2009).

The recent satellite estimates were compared with the longer historical record of declassified sonar measurements from U.S. Navy submarines (Figure 3b). Within the submarine data release area (covering ~38% of the Arctic Ocean), the overall mean winter thickness of 3.6 m in 1980 can be compared to a 1.9 m mean during the last winter of the ICESat record—a decrease of 1.7 m in thickness. This combined submarine and satellite record shows sea ice thinning that span three decades. The contribution of the increasing fraction of first year ice to the long term thickness trend remains to be determined (Perovich et al. 2009).



**Figure 3.** (Perovich et al. 2009). (a) Winter Arctic Ocean sea ice thickness from ICESat (2004–2008). The black line shows the average thickness of the ice cover while the red and blue lines show the average thickness in regions with predominantly multiyear and first-year ice, respectively. (b) Interannual changes in winter and summer ice thickness from the submarine and ICESat campaigns within the data release area spanning a period of more than 30 years. The data release area covers approximately 38% of the Arctic Ocean. Blue error bars show the uncertainties in the submarine and ICESat data sets. (after Kwok et al. 2009 and Kwok and Rothrock 2009)

### 1.1 Arctic Sea Ice Trends

Koc et al. (2009) provide the following trends regarding Arctic sea ice:

- Since reliable satellite observations began in 1979, there have been significant negative trends in annual Arctic sea ice extent. The maximum sea ice extent (March), has decreased by 2.7% per decade and the minimum (September) has decreased by 11.2% (NSIDC 2009).
- Ice extent reached a record minimum of only 4.2 million km<sup>2</sup> in September 2007 compared to 7.8 million km<sup>2</sup> in 1980. September 2008 saw the second lowest sea ice extent in the Arctic since September 1979, and the 2009 minimum was the third lowest on record. The three last minimum years reinforce 30-year downward trend in Arctic sea ice extent (NSIDC 2009).
- Sea ice extent is declining at an accelerating rate, especially in the summer. Data from 2007, 2008, and 2009 show that sea ice cover is shrinking faster than climate models projected.
- Arctic sea ice is thinning, with thin seasonal ice replacing thick older ice as the dominant type for the first time in the modern record. Between 2004 and 2008, the total area covered by the thicker, older, multi-year ice shrank by more than 40% (1.54 million km<sup>2</sup>). First-year ice made up more than 70% of the total cover in the 2008-09 winter, compared to 40–50% in the 1980s. Currently less than 10% of the Arctic sea ice is older than two years. As first-year ice is generally much thinner than multi-year ice, this implies that the volume of Arctic sea ice has greatly diminished (NSIDC 2009, Kwok et al. 2009, Haas et al. 2008).
- Low sea ice extent and large regions of thin first-year ice were observed in September 2008. This potentially represented the lowest volume of Arctic sea ice since 1979. However, few direct ice thickness measurements are available to support estimates of the ice volume loss (NSIDC 2009).
- Seasonal sea ice zones (including the Barents, Baltic, Bering, and Okhotsk seas) do not show the same rapid sea ice loss as in the central Arctic Ocean in recent years.

## 1.2 Climate Mechanisms

While the overall global temperature may be increasing and Arctic sea ice is melting, regional climate mechanisms may influence strongly the climate in specific areas. Thus, it is important to consider the role of different climate mechanisms that contribute to events occurring at high latitudes when projecting climate change impacts on the sea ice ecosystem.

The Arctic Oscillation (AO) appears to be the cause for much of the recent changes that have occurred in the Arctic (Bond et al. 2010). The AO has been described as "a seesaw pattern in which atmospheric pressure at polar and middle latitudes fluctuates between positive and negative phases. The negative phase brings higher-than-normal pressure over the polar region and lower-than-normal pressure at about 45 degrees north latitude. The positive phase brings the opposite conditions, steering ocean storms farther north and bringing wetter weather to Alaska, Scotland and Scandinavia and drier conditions to areas such as California, Spain and the Middle East" (Bond et al. 2010).

The AO appears related to a well-known mode of variability for the North Atlantic called the North Atlantic Oscillation (NAO). The NAO has been recognized for decades and has been considered "the dominant mode of winter climate variability in the North Atlantic region ranging from central North America to Europe and much into Northern Asia. The NAO is a large scale see-saw in atmospheric mass between the subtropical high and the polar low. The corresponding index varies from year to year, but also exhibits a tendency to remain in one phase for intervals lasting several years." (Bond et al. 2010). The positive phase of the NAO is associated with more frequent and intense storms in the North Atlantic Ocean, warmer and wetter winters in Europe, and cooler, drier winters in Greenland and northern Canada.<sup>5</sup>

The Pacific side of the Arctic is also significantly influenced by an inter-related pair of modes, the Pacific Decadal Oscillation (PDO) and the North Pacific Index (NPI) (Bond et al. 2010). The PDO is based on the pattern of SST in the North Pacific while the NPI is based on sea level pressure. The positive phase of the PDO is associated with warm ocean temperature along western North America and with generally prosperous fisheries in Alaska and poor fisheries along the west coast of the continental US, especially with regards to salmon. The North Pacific Index provides a measure of the intensity of the mean wintertime Aleutian Low pressure cell. An alternative measure of the latter is provided by the Aleutian Low Pressure Index (ALPI).

While there may warming occurring on a global scale, the different oscillations may influence strongly the conditions in a particular region. For example, while most of the Arctic had unprecedented reductions of sea ice and record warm air temperature during summer through late fall in 2007, 2008 and 2009, the Bering Sea had near record cold temperatures and maximum ice extents during spring (Overland et al. 2010). The 2007 to 2009 cold period in the Bering Sea followed a major warm event from 2000 to 2005. Since 1916, ten similar, multi-year (MY) but less-than decade warm and cold events occur in the data record from St. Paul Island, Alaska. Little is known about these events compared to the longer Pacific Decadal Oscillation (PDO), but Overland et al. (2010) state that it is possible that the transitions that occur as interdecadal PDO shifts are also related to rapid shifts between extreme MY warm and cold year events as in the 1940s and 1970s. They consider that while Arctic change proper is driven by radiation and amplified by ice albedo feedback, the climate of the Bering Sea for the present and future will mainly be driven by natural variability due to the relative dominance between warm storms and cold air masses. They hypothesize that Bering Sea ocean

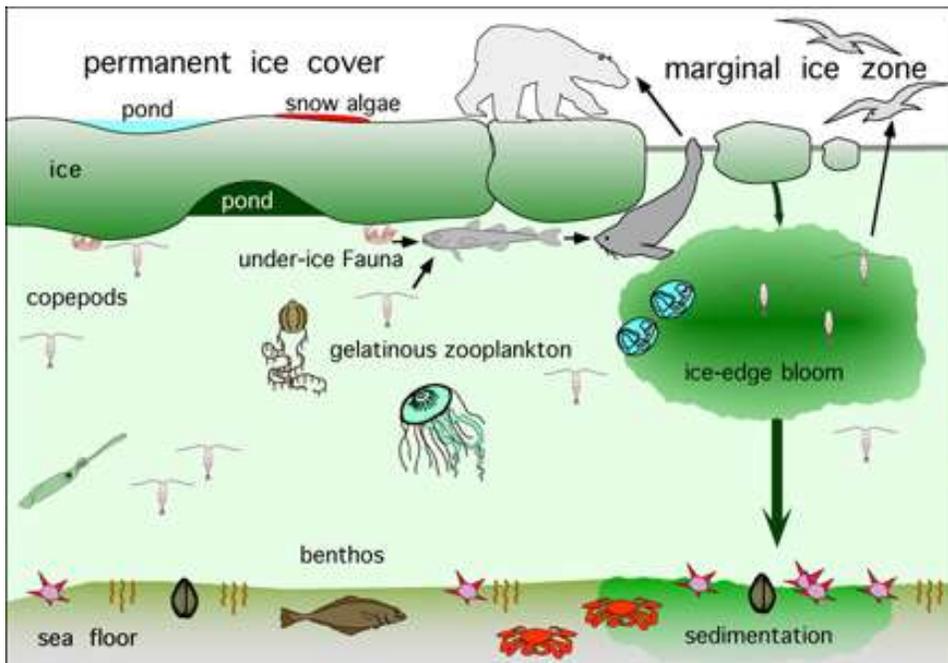
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<sup>5</sup> Some controversy exists concerning the relationship between the AO and the NAO, namely whether they represent fundamentally the same mode, or whether the distinctions between them are meaningful. At any rate, a systematically positive sense to both indices since the end of the 1980s has coincided with relatively warm conditions in the Arctic and net melting of the Arctic ice pack (Bond et al. 2010).

temperatures, modified by seasonal sea ice and other factors, have sufficient memory that only large hemispheric changes in the atmospheric general circulation, including those forced by El Niño Southern Oscillation (ENSO), can shift the MY events from cold to warm or the reverse. Overland et al. (2010) provide that while for 2010 the North Pacific is shifting to El Niño conditions which would imply a warmer Bering Sea, the potential weakness of northward teleconnections signals and the shortness of the present cold event compared to their more normal duration suggest that the Bering Sea may not shift back to warm conditions this year.

## 2. Sea ice ecosystem – general overview

The sea ice food chain begins with ice algae that cling to the underside of the dark ice pack all winter, resulting in a dense mat under the ice by the time spring arrives. About six weeks later, a phytoplankton bloom develops in the water beneath the ice, followed by zooplankton bloom timed to graze on the phytoplankton. As the ice begins to break-up, the bloom spreads into a wide 20-80 kilometer belt surrounding the ice edge. This highly productive ice-edge ecosystem is home to numerous crustaceans and other invertebrates. These in turn are eaten by fish species such as Arctic cod which are eaten by seals, birds and cetaceans. Polar bears prey almost exclusively on ice seals. Bowheads and birds prey upon the abundant zooplankton associated with ice algae. Organic material released from the ice algae mat and the phytoplankton bloom enriches the floor of the vast Arctic continental shelves, supporting a benthic community of shellfish and other invertebrates. Unique among the world's ecosystems, the ice-edge zone moves thousands of kilometers each year, north in spring as ice melts and south in fall as ice freezes. Walrus, numerous species of seals and cetaceans such as belugas and narwhals all follow the ice-edge, taking advantage of the ready access to food and with the pinnipeds using the ice to haul-out, rest, molt and nurse.



**Figure 4.** (from Gradinger et al. 2004). Schematic representation of the Arctic marine ecosystem and its interactions.

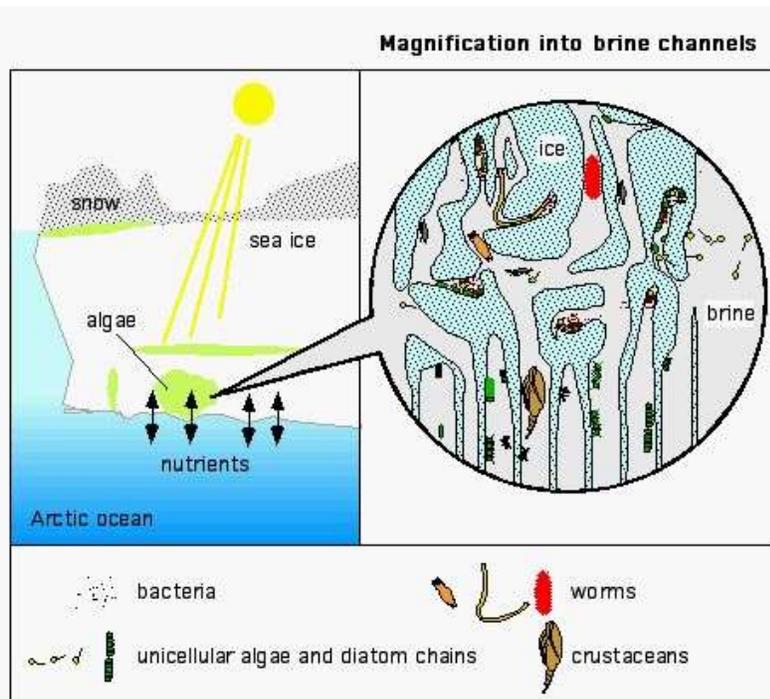
### 2.1 Sea ice algae

Sea ice plays a significant role in the biology and ecology of polar marine ecosystems, supporting a productive community of ice algae (e.g. Horner 1985, Gosselin et al. 1997) and a high diversity of

heterotrophic organisms<sup>6</sup> ranging from bacteria (Riedel et al. 2007a, 2008) to metazoans (reviewed by Schnack-Schiel 2003). The biology related to sea ice is largely controlled by its physical and chemical properties (e.g., Gradinger 2002), mainly light availability and nutrient supplies. Ice thickness and snow cover strongly influence the transmission of photosynthetically active radiation (PAR) through the sea ice, therefore affecting the growth, production, and biomass of the bottom ice algal communities (Arrigo 2003, Mundy et al. 2005).

In winter, sea ice constitutes a thermal barrier against the cold winter atmosphere which keeps the interface between the ice and the seawater near the temperature of the warmer seawater (Krembs and Deming 2006). Algae (diatoms) and protists are found inside the sea ice in brine pockets and a network of channels and capillaries mostly in the bottom horizon of annually-formed sea ice, which is in direct contact with the underlying waters. During spring, when light becomes available for photosynthesis, and throughout the summer, a large biomass of unicellular photosynthetic ice algae develops within the lowermost sections of the ice (Gradinger et al. 2004, Gradinger 1999, Weissenberger et al. 1992, Eicken 2003, Poulin et al. 1983, Horner 1985, Gradinger 2002, Carey 1992, Michel et al. 2002, Schnack-Schiel 2003, Rózańska et al. 2008, 2009). These algae occasionally form long filaments that can extend several meters into the water column (*Melosira arctica*).

The incorporation of protists into sea ice starts during fall at the time of ice formation (Gradinger and Ikävalko 1998, Riedel et al. 2007b, Rózańska et al. 2008). The development of these cells in the bottom ice is very slow in winter, but their numbers increase exponentially in early spring with increasing solar irradiance and air temperature and decreasing brine salinity to reach a maximum prior to the melt period, and then decline rapidly in late spring or early summer with ice melting (Hsiao 1980, Horner 1985, Lavoie et al. 2005, Rózańska et al. 2008).



**Figure 5** (from Krembs and Deming 2006). The flourishing life within the briny habitat of sea ice.

<sup>6</sup> Organisms that cannot synthesize their own food and depend on complex organic substances for nutrition. Heterotrophs are known as consumers in food chains and obtain organic carbon by eating other heterotrophs or autotrophs (organisms that can create their own food using photosynthesis for example).

Bluhm and Gradinger (2008) discuss the diversity of ice algae and the ice-associated food web:

So far, more than 200 diatom species (mainly pennate taxa) and more than 70 species of flagellates are described from Arctic sea ice (Horner 1985). Ice algae contribute 4–26% to total primary production in seasonally ice-covered waters and more than 50% in the permanently ice covered central Arctic (Gosselin et al. 1997, Sakshaug 2004; Fig. 1). Overall, absolute production rates of organic carbon were below 10 g C/yr. The organic matter produced within the sea ice serves as the base for the ice-associated food web including protozoans and metazoans, e.g., ciliates, rotifers, copepods, copepod nauplii, nematodes, turbellarians, and, in fast ice, larvae of benthic polychaetes and gastropods (Horner 1985). Meiofauna abundances decrease from the nearshore fast ice (up to 350 000 animals/m<sup>2</sup>) to the deep-sea basin by about three orders of magnitude (Gradinger and Bluhm 2005, Gradinger et al. 2005). Although a variety of ice meiofauna and meroplanktic larvae consume ice algae, only a minor fraction (,10%) of the ice algal production is consumed by sea ice metazoans (Gradinger et al. 2005).

Gammaridean amphipods, the dominant macrofaunal taxon in the Arctic under-ice habitat, are the best studied consumers of ice algal production in all parts of the Arctic (e.g., Gradinger and Bluhm 2004). Several species of amphipods (e.g., *Gammarus wilkitzkii*, *Apherusa glacialis*, *Onisimus* spp.) are endemic to the multiyear sea ice cover and exploit the ice cover year round, while benthic species such as *Onisimus litoralis* are common in nearshore seasonal ice regimes (Bradstreet and Cross 1982). Under-ice amphipods occur in abundances of 1–1000 individuals/m<sup>2</sup> in coastal areas and with, on average, 1–40 individuals/m<sup>2</sup> in offshore pack ice (Gradinger and Bluhm 2004). These under-ice amphipods are an important food source for Arctic diving birds and Arctic cod (*Boreogadus saida*) (Bradstreet and Cross 1982) and thereby provide the link from the food web within the sea ice to the more accessible open water below.

Previous studies have provided a glimpse of the seasonal and regional abundances of ice-associated biota. However, the biodiversity of these communities is virtually unknown for most groups, from bacteria to metazoans and many taxa are likely still undiscovered. Methodological problems in analyzing ice samples hamper the identification of sea-ice biota.<sup>7</sup>

As grazing pressure is small within the brine channels due to limited access (Krembs et al. 2000) significant quantities of organic material can accumulate within the ice crystals. Excretions of metabolic products and debris from dying cells contribute to an increasing pool of organic material (Krembs and Deming 2006). As the ice melts in summer, this material releases into the water column, where it contributes to both pelagic and benthic food webs (Krembs and Deming 2006, Bluhm and Gradinger 2008); also the diatom mats sink to the sea floor where they may provide a substantial input to the benthic system (Thomas et al. 2008).

Some components of this organic pool, however, have been shown to affect the properties of the ice itself long before it melts (Krembs et al. 2006). Sea ice is sculpted by micro-organisms and seawater, creating important habitat for ice algae which flourishes within this nutrient-rich skeletal layer or ice (Krembs and Deming 2006). Zooplankton grazers (such as *Gammarus wilkitzkii*) which eat algae, seek food in this algal-rich ice as well as protection from their own predators (Krembs and Deming 2006). Arctic cod (*Boreogadus saida*), an important food source for many marine mammals and birds, use the same habitat as nursery grounds (Krembs and Deming 2006).

Ice algal communities play an important role in polar ecosystems and have a major influence on various trophic levels of Arctic marine food webs (e.g. Runge and Ingram 1988, Vézina et al. 1997, Fortier et al.

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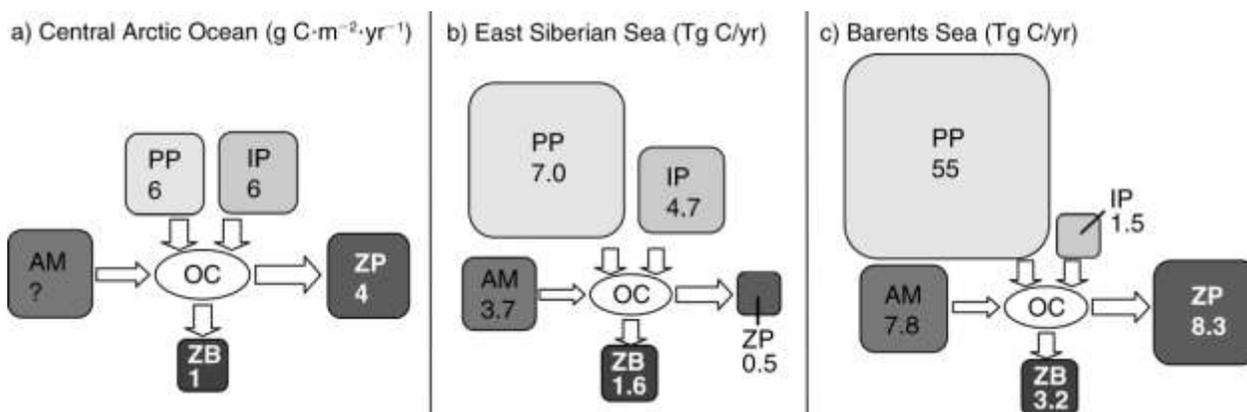
<sup>7</sup> The Arctic Ocean Diversity Census of Marine Life is an international collaborative effort that is inventorying biodiversity in the Arctic sea ice.

2002). They serve as a main food source for ice-associated and pelagic herbivorous protists (Sime-Ngando et al. 1997, Michel et al. 2002) and metazoans (Runge and Ingram 1988, Nozais et al. 2001), contributing significantly to carbon cycling in Arctic regions (Rozanska et al. 2009, Michel et al. 2006).

## 2.2 Primary Production Rates and Trends

Bluhm and Gradinger (2008) provide primary production rates in the Arctic:

Total primary production rates in the Arctic can exceed values of  $>100 \text{ g C m}^{-2} \text{ yr}^{-1}$  on the shelves of the Barents, Chukchi, and Bering Seas (Sakshaug 2004). The highest production values are encountered on the Bering Shelf, where values are close to  $5 \text{ g C m}^{-2} \text{ yr}^{-1}$  or  $>500 \text{ g C m}^{-2} \text{ yr}^{-1}$  and are among the highest in the world's oceans. These very high rates reflect the high nutrient concentrations that allow the buildup of substantial phytoplankton biomass while Arctic shelves with lower nutrient availability (e.g., northern Barents Sea, East Siberian Sea, Kara Sea) exhibit much lower production values ( $15\text{--}70 \text{ g C m}^{-2}$ ; Sakshaug 2004). Primary production rates in the central Arctic Basin are one order of magnitude ( $<20 \text{ g C m}^{-2} \text{ yr}^{-1}$ ) lower than on the shelves (Gosselin et al. 1997, Sakshaug 2004; Figure 6). Within the ice pack, enhanced primary production rates were found in polynyas around Greenland, where yearly primary production estimates range between  $20$  and  $50 \text{ g C m}^{-2}$ .



**Figure 6.** (from Bluhm and Gradinger 2008). Yearly production estimates for phytoplankton (PP), ice algae (IP), allochthonous material (AM), zooplankton (ZP), and zoobenthos (ZB) contributing to the organic-carbon pool (OC) for three different Arctic regions: (a) central Arctic Ocean (from Gosselin et al. 1997 [PP, IP], Klages et al. 2004 [ZB], and Mumm et al. 1998 [ZP]), (b) East Siberian Sea (Petrova et al. 2004), and (c) Barents Sea (Vetrov and Romankevich 2004). Units used correspond to those in the original data sources. This schematic depicts only rough estimates to emphasize the different sizes of the boxes in each region.

Studies carried out over the past decade revealed appreciable changes in the qualitative and quantitative composition of the biota in the Arctic sea ice compared to the composition in the mid-1970s (Melnikov 2008). The total list of ice algae identified for the period of 1975–1982 comprises 172 taxa and about 30 species identified in 1997–2008 (Melnikov 2008). The prevalence of sea diatoms was a significant feature of sea ice photosynthesis in the 1970s, and their domination greatly decreased in the past decade, while other groups are growing in importance (Melnikov 2008, 2009). The ice fauna composition has changed as well. In the 1970s, protozoans and invertebrates as foraminifers, tintinninids, mites, nematodes, turbellarians, rotifers, copepods, and amphipods inhabited the ice mass in the 1970s, but were rarely encountered in the past decade (Melnikov 2008, 2009).

## 2.3 Area of future concerns

Melnikov (2009) provides that the biotic composition of first year (FY) and multi-year (MY) sea ice is different in structure and function. Under conditions of a stable climate, MY sea ice represents an

integral ecological system that is stable in time with a constant species composition of the flora and fauna (Melnikov 1989, Melnikov 2009). The system stability persists due to average equilibrium thickness supported by summer ice thawing from above and winter compensation ice growth from below (Melnikov 2008). In contrast, FY ice is a dependent ecosystem that is unstable with time, affected by complex environmental factors, most significantly by temperature (Melnikov 2009). The thickness and salinity are main physical factors accentuating differences between MY and FY ice (Melnikov 2008). MY ice is thicker and fresher than FY ice (Melnikov 2008). In MY ice, the constant species composition of algae and the invertebrate fauna exist, with benthic-type algae dominating (Melnikov 2009). In FY ice, the species composition of the ice flora was formed directly from water and mainly represented by typical planktonic forms making up long chains from cells and mainly evolving in the lower layer of ice or on its lower surface (Melnikov 1989).

As the proportion of MY ice is decreasing and the share of the FY ice is simultaneously increasing, a gradual reorganization in the ecosystem of the Arctic Ocean pelagic region is occurring - organic production by phytoplankton should be growing and the contribution of the sea ice flora should be decreasing (Melnikov 2009). This is consistent with the findings of Pabi et al. (2008) and Arrigo et al. (2008) that found annual primary production of phytoplankton increased between 1998 and 2007, with interannual differences most tightly linked to changes in summer sea ice extent, more open water and a longer phytoplankton growing season. In addition, Rozanska et al. (2009) state that the contribution of ice algae to total primary production may have changed due to the reduction in sea-ice thickness and extent over the Arctic Ocean reported during the last 10 years (Comiso et al. 2008). If such a dynamic continues, over time the marine Arctic regions will gain features of the marine Antarctic regions where the sea ice cover in the Southern Ocean disappears in summer and reappears in winter (Melnikov 2009). This may result in reorganization of the whole lower trophic structure of the Arctic Ocean and may affect all higher chains of the trophic structure, including fish, birds and marine mammals (Melnikov 2009).

The ongoing trends of declining sea ice, earlier ice melt, and increased water temperatures in the Arctic (ACIA 2004) are highly likely to lead to changes in the sea ice ecosystem, shifting toward a pelagic, subarctic ecosystem over a geographically larger area (Moline 2008, Bluhm and Gradinger 2008). Phytoplankton productivity is predicted to increase as light allows utilization of available nutrients (Moline et al. 2008, Smetacek and Nicol 2005). As a result, mesozooplankton productivity should also increase, with existing Arctic species meeting increasing competition from subarctic species that are expanding their range (Moline 2008, Gradinger 1995). According to Bluhm and Gradinger's (2008) conceptual model, the increased consumption of pelagic primary production by pelagic herbivores enhancing planktivorous fish abundance would increase the prey concentrations for pelagic-feeding marine mammals such as bowhead whales. Their model proposed that reduced carbon input to the benthic environment could have the reverse effect for benthic-feeding marine mammals such as walrus (Bluhm and Gradinger 2008). Also, Arctic marine mammal species currently flexible in their feeding mode and capable of utilizing both pelagic and benthic prey, such as beluga whales, may be less affected by the proposed alterations of the food web structure (Bluhm and Gradinger 2008). In the extreme case of all capable benthic-feeding marine mammal species switching to pelagic feeding, resource competition might be intensified (Bluhm and Gradinger 2008).

Temporal shifts in the expansion and reduction of sea ice may lead to mismatches with the life histories of key sea ice organisms (Moline 2008). These links include the timing of increased activity and reproduction of primary and secondary consumers in anticipation of increased productivity of ice algae (Moline 2008). If one or more of the links between increased light penetration, higher production by ice algae, increased activity and breeding of crustacean grazers and predators, and production and feeding of larval and juvenile Arctic cod fail, then effects may flow through the ice ecosystem assemblage and on to top predators, such as ringed seals, various bird species and possibly polar bears (Moline 2008).

### 3. Arctic cod (*Boreogadus saida*)

Arctic cod (sometimes referred to as “polar cod”) is the most northerly distributed *Gadidae* species, occurring north of 60°N from the coast to off-shore waters, in Arctic seas off northern Russia, Alaska, Canada and Greenland. Arctic cod are most common at the water's surface, but they also occur at depths below 900 meters, forming very large schools when in ice-free waters. Arctic cod are frequently observed in close association with fast ice and pack ice year-round, from their larval stage through their juvenile stages, and they can be found sheltering in brine channels and wedges in the ice (Gradinger and Bluhm 2004). Resting in the wedges may be a strategy to reduce energetic requirements and avoid predators (Gradinger and Bluhm 2004). They use the ice as a feeding habitat (Gradinger and Bluhm 2004) where they consume crustaceans associated with the ice undersurface and the adjacent water column, primarily amphipods and copepods (Lønne and Gulliksen 1989, Crawford and Jorgenson 1993). Arctic cod spawn under the ice in winter and their buoyant eggs rise to the ice–water interface (Bouchard and Fortier 2008, Graham and Hop 1995, Ponomarenko 2000). The egg hatch coincides with the early-summer production of copepod eggs and larval crustaceans, the main prey source for larvae Arctic cod (Bouchard and Fortier 2008, Graham and Hop 1995, Fortier et al. 1995). In Admiralty Inlet in the Northwest Territories, Canada, hydroacoustic surveys recorded the highest fish densities immediately below landfast sea ice (Crawford and Jorgenson 1990). The distributions of fish, presumably Arctic cod, were associated with layers of zooplankton (Tynan and DeMaster 1997).

Arctic cod is a pivotal species in the Arctic marine food web as it represents the most important trophic link from lower trophic levels (copepods and under-ice amphipods) to other fish, birds, seals and whales (Tynan and DeMaster 1997, Bradstreet 1982; Bradstreet et al. 1986; Ainley and DeMaster 1990; Borkin 1990; Welch et al. 1992; Crawford and Jorgenson 1993). In Arctic regions, no other prey items compare with Arctic cod in abundance and energetic value (Tynan and DeMaster 1997, Finley et al. 1990). In Lancaster Sound, Canada, alone, marine mammals and birds consume ~148,000 metric tons per year of Arctic cod (Welch et al. 1992). In the Beaufort Sea, many species' diets (beluga whales, ringed seals, ribbon seals, spotted seals, black-legged kittiwakes, glaucous gulls, ivory gulls, black guillemots, thick-billed murre, northern fulmars, and loons) are comprised of over 50 percent Arctic cod, and over 90 percent in certain seasons and areas, especially during winter for foraging seals (Bluhm and Gradinger 2008).

#### 3.1 Abundance and trend

Despite its central role in the Arctic marine food web, there is very little information on its biology in the central Arctic Ocean or its abundance. In the Alaskan Chukchi and Beaufort Seas, August-September 2008 surveys estimate Arctic cod biomass at 27,122 metric tons (mt) and 15,217 mt respectively, totaling 42,339 mt (NPFMC 2009).

Decreases in Arctic cod abundance have been recorded and correlated with shrinking ice cover. Gaston et al. (2003) inferred changes in Arctic cod abundance in northern Hudson Bay by analyzing the composition of the diet fed to thick-billed murre chicks in northern Hudson Bay since 1981, and compared those trends to ice cover in Hudson Bay over the same period. Between 1980-82 and 1999, the percentage of Arctic cod in the diet of thick-billed murre chicks fell from 51.5% to 18.9%, while the percentage of capelin increased from 6.7% to 41% over the same time period (Gaston et al. 2003). Ice cover, defined as the extent of ice cover greater than 10% on July 15th of each year, also declined significantly between 1981 and 1999 (Gaston et al. 2003). Gaston et al. (2003) stated:

We conclude that the trends we observed related to real changes in fish populations, rather than simply reflecting changes in the accessibility of the fish to murre...Given the relative ecology of Arctic cod and capelin, the trends that we have identified seem best explained by changes in the oceanography of northern Hudson Bay, perhaps driven by temperature increases over recent decades. Our evidence from the diet of

nestling thick-billed murres suggests that a switch from an Arctic to a Subarctic fish community occurred from 1997 onwards.

### **3.2 Area of future concerns**

Bouchard and Fortier (2008) suggest that, at least in the short term, the survival of Arctic cod larvae in the Laptev Sea could be favored by more frequent winter and spring polynyas, leading to enhanced recruitment, and potentially larger populations (Fortier et al. 2006). They note, however, that different stages in the life cycle of the species are closely adapted to (and strongly dependent on) sea ice (e.g. Lønne and Gulliksen 1989, Gradinger and Bluhm 2004). Bouchard and Fortier (2008) conclude that in the longer term, as sea ice becomes seasonal, a circumpolar generalist species is likely to replace Arctic cod as the main forage fish of the Arctic Ocean. According to modeling, with warming temperatures and a retreat of the ice edge of 5 km per year, Arctic cod will be extirpated from most of its range in 30 years (Cheung et al. 2008).

## **4. Sea birds**

While many bird species seasonally use the Arctic in the summer, relatively few species associate with sea ice. The ivory gull, thick-billed murre, spectacled eider and king eider are found in and near sea ice. Their relationship with sea ice is not entirely understood, nor is how sea ice changes will affect these birds. Each seabird is discussed below.

### **4.1 Ivory Gull (*Pagophila eburnea*)**

The ivory gull is a seabird which spends the entire year in the High Arctic where it rarely ranges far from sea ice (Haney and MacDonald 1995). Small, scattered colonies occur in Arctic Canada, Greenland, Svalbard (Norway), and the northern islands of Russia in the Barents and Kara seas (Blomquist and Elander 1981). It breeds at high latitudes in the Atlantic sector of the Arctic on coastal or inland cliffs, up to 300 m high, on nunataks, on broken ice-fields or on bare, level shorelines with low rocks (del Hoyo et al. 1996, Snow and Perrins 1998). Outside of the breeding season, the ivory gull generally winters along the southern edge of pack ice in the waters of the North Atlantic Ocean (Davis Strait and Labrador, Greenland and Barents seas), and the North Pacific Ocean (Bering Sea, Sea of Okhotsk, and perhaps the Beaufort and Chukchi seas), or at persistent areas of polynyas (Haney and MacDonald 1995), showing a preference for areas with 70-90% ice cover (del Hoyo et al. 1996). It is often associated with the edge of ice floes and leads in pack ice, where it feeds on small fish including juvenile Arctic cod, lanternfish, walleye pollock, squid, mollusks and other invertebrates, and macro-zooplankton, such as amphipods and euphausiids (Divoky 1976, Haney and MacDonald 1995, Gjertz et al. 1985). Ivory gulls also scavenge carrion on the ice and are reported to forage on marine mammal feces and placenta (Haney and MacDonald 1995). As a fish-eating bird, the ivory gull is believed to be a visual forager.

#### **4.1.1 Population and trends**

The historical estimate of the global breeding population was 14,000 pairs in 1996 (Volkov and de Korte 1996). The current estimate is 8,900-13,500 pairs (Gilchrist et al. 2008, Gilg et al. 2009) (Table 1).

The most recent information on population trend of ivory gulls exists for Canada, Svalbard and Russia. In Canada, the ivory gull has a highly restricted range, breeding exclusively in Nunavut Territory. Until recently, the Canadian Arctic was thought to support 20-30% of the entire global breeding population, and colonies of continental and global importance. However, aerial surveys conducted in 2002-2006 suggest that the Canadian breeding population has declined by 80-85% since the early 1980s, a decline from 2450 breeding pairs down to 500 breeding pairs. There are fewer ivory gull colonies in the

Canadian Arctic when compared to the 1980s, and of those colonies that still exist, they support fewer birds (Gilchrist and Mallory 2005; Robertson et al. 2007).

In Svalbard, the breeding population has been thought to be in decline during the last century (Birkenmajer 1969, Bakken and Tertitski 2000). Previously occupied large colonies in the north-eastern part of the archipelago have not been used for decades, and few new colonies have been discovered. Surveys conducted in 2006-2007 show a population numbering between 350 to 500 breeding pairs and confirm that few of the known colonies are still being used, and those colonies that still exist, support fewer birds (Strøm et al. 2008). While the total population is smaller than previously estimated, the full extent of the population decline is difficult to assess because of the lack of historical data.

Surveys conducted in the Russian Arctic in 2006 and 2007 indicate stable populations in some key colonies and no signs of a general decline, but rather considerable annual fluctuations in the numbers of breeding birds.

Gilg et al. (2009) estimated the ivory gull population size in Greenland as 1,800 adult birds ( $\pm 25\%$ ), based on a review of published sources, an extensive recent survey from 2003 to 2008, and coupled satellite monitoring and aerial surveys. This estimate is twice what Gilchrist et al. (2008) reported in the table below. However, Gilg et al.'s estimate is considered a minimum and the actual figure is probably  $>4,000$  adult birds (i.e.  $>2,000$  pairs) since all colonies have not yet been discovered and since only 50% or less of the breeding birds are usually present in the colonies at the time the surveys occur (Gilg et al. 2009). Although the new estimate is four to eight times higher than the previous estimate, ivory gulls seem to be declining in the south of its Greenland breeding range, while in North Greenland the trends are unclear and unpredictable (Gilg et al. 2009).

**Table 1.** Ivory Gull population estimates and trends from International Ivory Gull Conservation Strategy and Action Plan (Gilchrist et al. 2008).

Country	Region	Historical estimate	Historical survey period	Current estimate	Recent survey period	No. of occupied colonies	Population Trend
Canada	Seymour Island	170 pairs	1970-early 1980s	60-71 pairs	2004-2006	Stable	Decline
	Baffin Island	280-290 pairs	1970-early 1980s	0-26 pairs	2004-2006	Decline	Decline
	Ellesemere/ Devon Islands	450 pairs	1970-early 1980s	225 pairs	2004-2006	Decline	Decline
Greenland	East and North coasts	Unknown		400-500 pairs  *Gilg et al. 2009 now estimates at least 900 pairs (and up to 2000 pairs)	1978-2004  *2003-2008 (Gilg et al. 2009)	Uncertain  *35? (Gilg et al. 2009)	Uncertain  *Declining in southern breeding range *Uncertain in northern breeding range (Gilg et al. 2009)
Norway	Svalbard	Unknown		350- 500 pairs	2006, 2007	Decline	Declined since 1900. After 1970 trend uncertain
Russia	Victoria Island	100-750 pairs	1960s-1995	0 pairs	2001, 2004, 2006	Decline	Decline

	Franz Josef Land	Few 1000 Birds	1980s	> 1000 pairs	2006-2007	Stable	Fluctuating, no trend
	Severnaya Zemlya	Unknown		min 2000	2007	Stable	Fluctuating, no trend
	Sedov Archipelago	Ca. 100 – 1100 pairs	1931-1996	1890–2000 pairs	2006–2007	Stable	Fluctuating, no trend
	Vize Island, Kara Sea	180 pairs	1996	200–1000 pairs	2005 – 2007	Stable	Fluctuating, no trend
	Troinoy Island, Kara Sea	100–800 pairs	1992–1995	> 200 pairs	2006	Stable	Fluctuating, no trend
	Other islands of the Kara Sea	Unknown		Unknown		Unknown	Unknown
<b>Global estimate</b>		<b>14000 pairs</b>	<b>1996</b>	<b>8000 - 11500 pairs *8900-13500 pairs (Gilg et al. 2009)</b>	<b>2008</b>		

#### 4.1.2 Area of future concerns

Ivory gulls are thought to be declining due to changes in conditions on its staging or wintering grounds such as more severe winters and changing sea-ice distribution and thickness (Birdlife International 2009, Gilchrist and Mallory 2005, Haney and Macdonald 2003). Some studies have found that reproduction in polar marine birds varies in response to annual ice conditions (e.g., Gaston and Hipfner 1998, Barbraud and Weimerskirch 2001, Jenouvrier et al. 2003, Gaston et al. 2005). Conditions on North Atlantic wintering grounds of thick-billed murre (*Uria lomvia*), which may be similar with that of the ivory gull, can influence the numbers of birds returning to breeding colonies synchronously, even though breeding colonies may be distant from each other and experience different climatic conditions during the murre breeding season (Gilchrist et al. 2008).

Given the ivory gull's strong and year-round association with pack ice, it is possible that some large-scale ecological perturbation, such as a change in the extent or thickness of ice cover, has caused a serious degradation of their foraging and wintering habitat in Baffin Bay and Davis Strait (Gilchrist et al. 2008). Moline et al. (2008) suggest that the changing ice may be making ivory gulls vulnerable to being preyed upon. The ivory gull nests on nunataks, islands of bedrock surrounded by rough pack ice. As the ice around the nunataks smooths, or disappears altogether, nunataks no longer afford protection from predators, such as the Arctic fox (Krajick 2003, Moline et al. 2008). Their wintering grounds, thought to be between Greenland and Canada, may also be undergoing major change; the sea ice in this area has actually increased since the 1950s, and may be depriving the gull of crucial ice edges needed to get at its prey (Krajick 2003, Moline et al. 2008).

Ivory gulls forage in the sea ice year round, relying on visual prey detection. Thus, if winter sea ice retreats to the north where the days are shorter, the ivory gull will have less time available to forage each day. However, no data exists to establish a causative relationship between sea ice changes and ivory gull declines and further studies on the potential effect of decreasing sea ice on ivory gulls are required (Gilchrist et al. 2008).

## 4.2 Thick-billed murre (*Uria lomvia*)

The thick-billed murre, also known as the Brünnich's Guillemot, is an Arctic seabird that is associated with areas of seasonal and sometimes extensive sea-ice cover (Irons et al. 2008) and occurs mostly in Arctic waters in the winter (Gaston and Gilchrist 2009). The world population of the thick-billed murre breeds totally within the Arctic region – in the United States, Canada, Greenland, Iceland, Jan Mayen, Svalbard, mainland Norway, and Russia (CAFF 2004). They breed in very large colonies of up to 1 million birds on mainland cliffs or offshore islands, returning annually to the same breeding sites (Gaston and Gilchrist 2009). Murres dive regularly to depths >100 m, reaching a maximum depth of ~150 m. Their diving capacity, when combined with their typical foraging radius of up to 100 km from the colony, means that murres sample a relatively large volume of the marine environment around their colonies (Falk et al. 2000, Elliott et al. 2008). In the north Atlantic, Arctic cod (*Boreogadus saida*) and sculpins (*Cottidae*) are important prey items of thick-billed murres in the high Arctic areas, while capelin (*Mallotus villosus*) and gadoid species such as Atlantic cod (*Gadus morhua*) dominate their diet in the low Arctic (Irons et al. 2008).

Laidre et al. (2008a) examined the relationship between population size of thick-billed murre breeding colonies and year-to-year variation in sea ice break-up to understand how large-scale latitudinal gradients influence Arctic sea bird colony size. They quantified spring-time trends in sea ice recession around each of 46 current and historical thick-billed murre colonies in west Greenland across a 20° latitudinal gradient and investigated the magnitude and timing of the associated spring-time primary production. The arrival at the breeding colonies was strongly correlated with latitude in all areas, suggesting that the timing of ice break-up is an important determining factor in when birds begin to breed (Laidre et al. 2008a). Their results show that thick-billed murres at high latitudes depend on the strict development of primary production and the predictable peak of this event offers reliable and abundant ice-related foraging opportunities, ultimately supporting large colonies. Birds at lower latitudes, where little to no sea ice is present or where ice recession is more variable, experience a greater variability in the timing of the primary production bloom and greater dispersal of prey resources. Laidre et al. (2008a) suggest that larger colonies can be supported at high Arctic latitudes, where the overall fraction of open water may be lower than subarctic latitudes yet the predictability of primary production bloom is high. Abundant and reliable food concentrations near the colonies in the entire breeding season are necessary for the large colonies located in the high Arctic where the adults forage to feed chicks (Falk et al. 2002). Furthermore, as thick-billed murres produce a single egg, the quality and quantity of food delivered to the chick by the parents has a large effect on reproductive success (Durant et al. 2006).

### 4.2.1 Population and trends

The world population of thick-billed murres is estimated at ca. 6.8 million breeding pairs (Nettleship and Evans 1985), of which ca. 75% are in the Atlantic region (Gaston and Jones 1998) (CAFF 2004). Thick-billed murres have shown substantial variation in regional population trends since the 1970s (Gaston and Gilchrist 2009). Trends in the North Pacific and Northwest Atlantic have been generally positive when trends in the European Arctic were negative and vice versa (Irons et al. 2008). Studies by the Seabird Working Group of CAFF demonstrate the sensitivity of murre populations on a hemispheric scale to changes in environmental conditions. By combining population trend data from around the Arctic with information on surface sea temperature (SST) and decadal-scale oscillations, Irons et al. (2008) showed that thick-billed murres, along with the more sub-Arctic common murres, tended to show negative population trends where there was a large change in SST. A comparison of the period from 1977-1989, when SST in the North Pacific were generally above normal and those in the Northeast Atlantic generally below normal, with the period from 1989-1999 when the situation reversed, showed that populations in the North Pacific were generally decreasing during the earlier decade and increasing subsequently (Irons et al. 2008). Conversely, those in the eastern Atlantic showed more variable trends. However, several European colonies were affected by widespread collapse of fish stocks in the 1980s (Vader et al. 1990). Those European colonies not affected by fish-

stock collapses mostly increased up to 1989, but increases were less general between 1989-1999. Only a few colonies, principally those in the eastern Canadian Arctic, have shown consistent increases in population and no colonies have shown persistent downward trends (C-bird unpubl. data, Gaston and Gilchrist 2009). Subsequent to 1999, regional trends have been less clear (Gaston and Gilchrist 2009). Populations of both species in the Barents Sea have begun to recover from earlier declines related to fish stock collapse (Barrett et al. 2006). Those in Alaska and in the Canadian Arctic have been stable overall since the 1990s (Dragoo et al. 2008, Gaston et al. in press).

Irons et al. (2008) found that colony growth was most often positive where conditions remained relatively stable. More specifically, thick-billed murres exhibited highest population growth where conditions warmed moderately (Irons et al. 2008). This result suggests that not only the direction but the magnitude of change may be important in determining outcomes for murre populations (Irons et al. 2008).

#### **4.2.2 Concerns for the Future**

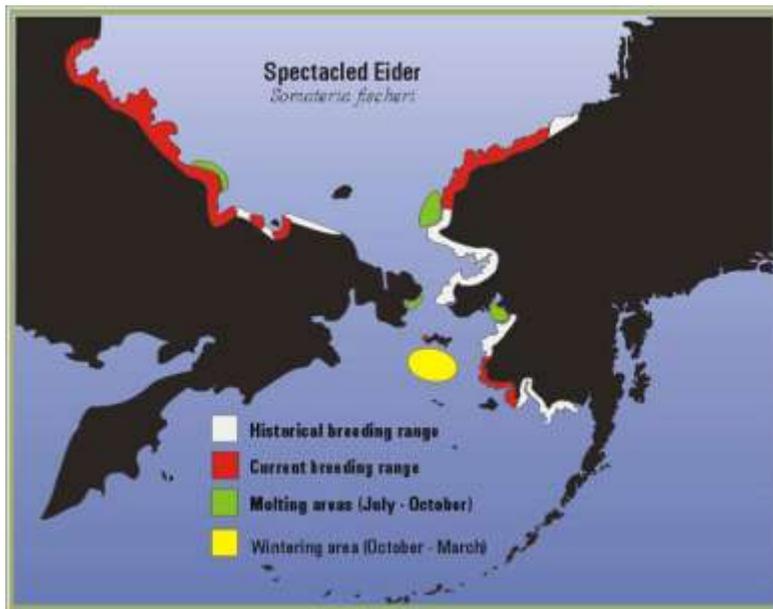
Although thick-billed murres are currently abundant, with few populations showing cause for alarm, some suggest that climate change will pose a future problem and range contraction appears likely in the longer-term (Gaston and Gilchrist 2009, Gaston et al. 2005). Dates for egg-laying advanced with the earlier disappearance of ice (Gaston et al. 2005). In northern Hudson Bay in low Arctic waters, the growth of chicks is slower in years when ice break-up is early relative to egg-laying by the murres, suggesting that reduction in summer ice extent is having a negative effect on reproduction (Gaston et al. 2005). Conversely, at Prince Leopold Island in the High Arctic, there has been no trend in summer ice cover and no detectable change in timing of breeding (Gaston et al. 2005). Reproduction there is less successful in years of late ice than in years of early ice break-up. According to Gaston et al. (2005), current trends suggest that continued warming should benefit birds breeding on the northern limit of the species range, while adversely affecting reproduction for those on the southern margin. The probable result will be an eventual northward displacement of the population. However, the species may be adaptable as populations at the southern edge of their range switched from feeding on ice-associated Arctic cod to warmer-water capelin (Gaston et al. 2003) as ice break-up became earlier.

In 1997-99, mosquitoes and heat from high maximum daily temperatures killed some breeding thick-billed murres at Coats Island in Canada (Gaston et al. 2002). Gaston et al. (2002) note that the dates of first appearance and peak abundance of mosquitoes at Coats Island have advanced since the mid-1980s, perhaps in response to ongoing climate change. They suggest that thick-billed murres have not had time to adjust their behavior to the resulting changes in the timing of peak mosquito parasitism which has resulted in adult mortality and egg loss.

#### **4.3. Eiders - Spectacled Eider (*Somateria fischeri*) and King Eider (*Somateria spectabilis*)**

Spectacled eiders and king eiders are large sea ducks that occur and breed in the Arctic. Both species of eiders associate with offshore dense pack ice in the winter, although in different parts of the Arctic.

The spectacled eider breeds primarily in three locations: the Yukon-Kuskokwim Delta (Y-K Delta), the North Slope, and Arctic Russia (USFWS 1996) and are present on breeding grounds from mid-May through mid-September (USFWS 2001). Their winter habitat was discovered in 1999 with the primary wintering area in the central Bering Sea south and southwest of St. Lawrence Island (Petersen et al. 1999). Once ice forms, spectacled eiders from all three main breeding populations concentrate within a 50-km (27.0 nm) diameter circle in small openings in the sea ice (Figure 7) (USFWS 2001). Their late winter location appears to move with annual ice coverage as the birds search for open water; when ice cover is extensive, dense flocks of many thousands of eiders gather in small ice-free openings (Petersen et al. 1999). While at sea, they appear to be primarily bottom feeders, eating clams, mollusks and crustaceans at depths of up to 70 meters in the wintering area (USFWS 2001, Lavvorn et al. 2003).



**Figure 7.** USFWS Spectacled Eider Range Map ([http://alaska.fws.gov/media/SpecEider\\_FactSheet.htm](http://alaska.fws.gov/media/SpecEider_FactSheet.htm))

King eiders are migratory sea ducks that breed in the circumpolar Arctic northeast of North America, northeast Europe and Asia in summer in Arctic tundra and winter at sea. There are two major molting and wintering areas for king eiders (CAFF 1997). In western North America, the king eider winters in the Bering Sea after staging in the Chukchi Sea and breeding in Siberia and western North America (Oppel et al. 2009, Phillips et al. 2006). In eastern North America, king eiders from Canada and Greenland winter primarily at sea along the coasts of Labrador and Newfoundland with large numbers molting, staging and wintering in West Greenland (Salomonsen 1968, Frimer 1995, Lyngs 2003, Mosbech and Boertmann 1999, Mosbech et al. 2006). An estimated 300,000 king eiders winter in West Greenland (Mosbech and Johnson 1999). Along the southwest coast of Greenland in the eastern Davis Strait (62-67°N), there are large areas with open water and open drift ice all year round. The area is called the South-west Greenland Open Water Area, and is a very important wintering area for eiders (Boertmann et al. 2004). King eiders are found in large flock sizes of up to 25,000 individuals (Mosbech et al. 2006). They dive in deep offshore waters to feed on polychaetes, echinoderms, crustaceans and molluscs (Merkel et al. 2007).

The presence and dynamic nature of ice in the core wintering area may decrease total energy costs of both eider species (Petersen et al. 1999, Mosbech et al. 2006). The eiders may lower daily maintenance costs by roosting on the ice in winter because the energetic cost is great from complete contact with the water such as when diving (Petersen et al. 1999, Mosbech et al. 2006). In addition, the ice pack may dampen the effects of winter storms as wave height in the ice pack is lower than in open waters (Divoky 1981), allowing birds to feed in conditions that otherwise might be considered severe (Petersen et al. 1999, Mosbech et al. 2006).

#### 4.3.1 Population and trends

The entire spectacled eider wintering population, and perhaps the worldwide population is estimated conservatively at 374,792 birds (USFWS 2001). Less than 10% breed in North America with the remainder of the world population breeding in Arctic Russia. The status of spectacled eider populations in Arctic Russia is unknown. The breeding distribution of the Arctic Russia population (uncorrected for visibility) was estimated to be in excess of 140,000 birds (Hodges and Eldridge 1995). In North America, about 4,744 ± 907 pairs nest on the North Slope of Alaska (Larned et al. 1999) and about 3,500–4,000 breeding pairs nest on the Y-K Delta. The population trend for the Y-K Delta nesting population can be characterized as stable to slightly increasing from 1991 – 2001, the year when U.S.

Fish and Wildlife Service designated critical habitat for the species. Based on USFWS survey data, the North Slope breeding population does not show a significant decline throughout most of the 1990s, but a downward trend of 2.6 percent per year (USFWS 2001). USFWS does not know the size of the non-breeding segment of any population (USFWS 2001).

Over the past 30 years, king eider numbers surveyed on breeding (Dickson et al. 1997, Gratto-Trevor et al. 1998, Raven and Dickson 2006), molting, and wintering grounds (Frimer 1995, Mosbech and Boertmann 1999), and during migration have declined substantially (Suydam et al. 2000, Dickson and Gilchrist 2001). From surveys done off Point Barrow in the Beaufort Sea, king eider population appeared to remain stable between 1953 and 1976 but declined by 56% from approximately 802,556 birds in 1976 to about 350,835 in 1996 (Suydam et al. 2000). Reasons for the declines are unknown. Surveys of molting areas in West Greenland show 50% declines over the last 40 years (Mehl et al. 2005, Mosbech and Boertmann 1999) and the Rasmussen Lowlands breeding area in Canada (Gratto-Trevor et al. 1998) indicate a decreasing population size (Mosbech et al. 2006).

#### **4.3.2 Area of future concerns**

It is difficult to project how spectacled eiders will respond to changing Arctic conditions because little is known about spectacled eider habitat use and survival away from breeding areas. Scientists are studying whether migratory timing, molting and wintering locations have changed compared to a previous satellite telemetry study conducted from 1993-1996 (Sexson et al. 2010). Between 2008 and 2009, USGS researchers marked 66 birds with implantable satellite transmitters at breeding sites in the Yukon-Kuskokwim Delta in western Alaska, and in the Colville River Delta and at Peard Bay in northern Alaska (Sexson et al. 2010). To date, their data suggest that adults are molting in the same areas as identified previously as well as using these areas for spring staging (Sexson et al. 2010). In addition, adults used the same wintering area in the northern Bering Sea, with males arriving and departing within the same time periods as identified in the previous study (Sexson et al. 2010). However, in western and northern Alaska, females that had failed nesting attempts departed breeding areas 11 days later and 5 days earlier, respectively, than median departure dates in the mid-1990s (Sexson et al. 2010). Transmitters that will be deployed in 2010 will provide additional data to future analysis.

Based on analyses of two indices spanning 1957–2002 and 1988–2002, Petersen and Douglas (2004) did not identify the single environmental parameter that explained the precipitous decline in nesting spectacled eider populations in western Alaska. In general, researchers found that the number of days with extreme sea ice in winter, extreme winds, and winds in spring explained the greatest variability in annual indices. These analyses support the conclusion that annual population estimates on the breeding grounds can be negatively impacted by extended periods of dense sea-ice concentration and weather during the previous winter (Petersen and Douglas 2004). Thus it is possible that heavy ice years in the Bering Sea negatively correlate with reduced abundance estimates of spectacled eiders.

Oppel et al. (2008) identified three distinct wintering regions for king eiders in the Bering Sea that were several hundred km apart, among which no movements occurred from late December until April. The onset of spring migration was earlier for birds wintering farther south, but arrival time on breeding grounds was not correlated with wintering latitude. They concluded that high plasticity in migratory traits may render king eiders more likely to respond to environmental shifts than sea duck species that show stronger migratory connectivity (Oppel et al. 2008).

## **5. Marine Mammals**

Moore and Huntington (2008) categorize Arctic marine mammals as:

- “ice-obligate” for species reliant on sea ice as a platform for resting, breeding, and/or hunting (polar bear, walrus, bearded seal and ringed seal);

- “ice-associated” for species associated with sea ice and adapted to the marine ecosystem of which ice is a key part (beluga whale, bowhead whale, narwhal, hooded seal, harp seal, spotted seal, ribbon seal); and
- “seasonally migrant” species that by their movements encounter sea ice (fin whale, humpback whale, minke whale, killer whale, gray whale).

Laidre et al. (2008) provides the importance of different sea ice habitat and its associated biotic features for the seven marine mammal species discussed in this paper, as well as for four additional ice seal species in Table 2.

**Table 2.** (Laidre et al. 2008) Importance of physical and biotic Arctic habitat features for primary Arctic marine mammal species (X = used; XX = important; XXX= critical).

Habitat	Beluga Whale	Narwhal	Bowhead Whale	Ringed Seal	Bearded Seal	Walrus	Polar Bear	Harp Seal	Hooded Seal	Spotted Seal	Ribbon Seal
<b>Physical features</b>											
Shore-fast ice				XXX	X		XXX				
Loose annual pack ice	XXX	X	X	XX	XX	XX	XX	XX	XX	XX	XXX
Dense annual pack ice		XXX	XX	XX	XXX	XXX	XXX	XXX	XX	X	X
Multiyear pack ice	X			X	X	X	XX				
Shear zones/leads	XX	XXX	XX	X	XX	X	XX				
Polynyas	XXX		XX	X		XX					
Open water	XX	XX	XX	X		XX		XXX	XXX	XX	XX
Shallow water/ continental shelf	XXX		XXX	X	XX	XXX		XX		XX	XX
Shelf break	XX	XXX	X	X	XX	XXX		XX		XX	XX
Deep ocean basins		XXX		X					XXX		X
Estuaries/lagoons/ Fjords	XXX	XXX		X						XXX	
Land haul-outs				X	X	XXX				XX	
Land denning areas							XXX				
<b>Biotic features</b>											
Macroplankton /nekton			XXX	XX						X	X
Macrobenthos	X		XX	X	XXX	XXX		X		X	X
Midwater fish (polar/Arctic cod)	XXX	X		XXX	X			XXX	XX	XXX	XX
Benthic fish	X	XXX		X	XX				XXX	X	XX
Marine mammals as prey						X	XXX				
<b>Interactions</b>											
Pack ice / open water (ice edge)	XX	XX	XX							XX	XX
Pack ice / continental shelf				X	XX	XX		XXX	XX	XX	XX
Polynya / shallow water	XXX					X					

## 5.1 Population and trends

Very few species of marine mammals have been studied anywhere in the Arctic for long enough to allow an assessment of the possible effects of long-term environmental fluctuations, including climate warming, on population size and demographic parameters (Laidre et al. 2008). The *Arctic Report Card, Update for 2009* (Richter-Menge and Overland 2009) chapter on marine mammals (Simpkins 2009) includes a table of the current abundance and trends of many Arctic marine mammal populations. Table 3 summarizes current knowledge regarding the abundance and trends of these species.<sup>8</sup>

<sup>8</sup> Following the general discussion of marine mammals are species-specific discussions for animals which are found generally in the Arctic year round: ringed seal, bearded seal, polar bear, walrus, narwhal, beluga whale and bowhead whale. For selected species, there is additional discussion of population and trends if additional information became available after the publication of the Table 3 from Simpkins (2009).

Unfortunately, abundance estimates are not available for one or more populations of most species, and trends are unknown for even more populations. Further, some of the available estimates are outdated as they are based on data from the 1990s or earlier. Also, those species with sufficient data exhibit mixed population trends, with some populations of each species increasing while others are stable or declining. The available data are not sufficient for an analysis of trends by region (e.g., to highlight regions within which populations of several species are all increasing or all declining). However, it is likely that different species within a region will exhibit different trends because they occupy very different ecological niches, ranging from the bowhead whale that filters zooplankton out of the water to the polar bear that hunts seals on the sea ice. Sea ice extent, concentration and thickness differ between regions and interannually, further complicating the projection of trends.

**Table 3** (Simpkins 2009). Current abundance and trends of Arctic marine mammal species. Information on abundance, trends, and most recent data (year) are summarized by biological stock, except for ringed seals, bearded seals, and walruses, whose stock structure is unknown (see table footnotes). Where abundance estimates have been updated since the publication of Simpkins (2009), they have been noted in the table with an \*.

Species	Stock	Abundance	Year	Trend	Citation(s)
Bowhead whale	Bering-Chukchi-Beaufort Seas	10,500	2001	increasing	George et al. 2004
	E. Canada-W. Greenland	6,300	2002-2004	increasing	IWC 2008, Heide-Jørgensen et al. 2007
	W. Greenland	*1229	*2006		*NAMMCO 2009
	Spitsbergen	unknown	—	unknown	Rugh et al. 2003
	Okhotsk Sea	<400	1979	unknown	Rugh et al. 2003
Beluga whale	Cook Inlet	380	2007	Stable	Angliss and Allen 2009
	Eastern Bering Sea	18,100	2000	unknown	Angliss and Outlaw 2005
	Bristol Bay	3,300	2005	increasing	Angliss and Allen 2009
	Eastern Chukchi Sea	3,700	1989-1991	unknown	Angliss and Allen 2009
	Eastern Beaufort Sea	39,300	1992	unknown	Angliss and Allen 2009
	Foxe Basin	1,000	1983	unknown	Richard et al. 1990
	Western Hudson Bay	57,300	2004	unknown	Richard 2005
	Southern Hudson Bay	1,300	1987	unknown	COSEWIC 2004a
	James Bay	4,000	2004	unknown	Gosselin 2005
	St. Lawrence River	1,200	2005	Stable	Gosselin et al. 2007
	Eastern Hudson Bay	4,300	2004	declining	Hammill et al. 2005
	Ungava Bay	<50	2007	unknown	Hammill 2004
	Cumberland Sound	1,500	1999	increasing	Department of Fisheries and Oceans 2002
	E. High Arctic-Baffin Bay	21,200	1996	Stable	Innes et al. 2002
	West Greenland	7,900	1998-1999	unknown	Heide-Jørgensen and Aquarone 2002
	Greenland - North Water		*10,600	*2006	*increasing
		*2008	*2009	*unknown	*NAMMCO 2009
	3 stocks in Okhotsk Sea	18-20,000	1987	unknown	IWC 2000
	11 additional stocks	unknown	—	unknown	
Narwhal	Canadian High Arctic	>60,000	2002-2004	unknown	Richard et al. *NAMMCO 2009
	Northern Hudson Bay	3,500	2000	unknown	COSEWIC 2004b
	West Greenland	2,000	1998-1999	unknown	NAMMCO 2005, Heide-Jørgensen 2004, *NAMMCO 2009

		*7,819	*2006-2008	*unknown	
	Inglefield Bredning	*8447	*2006-2008	*unknown	*NAMMCO 2009
	Melville Bay	*6,235	*2006-2008	*unknown	*NAMMCO 2009
	East Greenland	>1,000	1980-1984	*unknown	NAMMCO. 2005, Gjertz 1991
		*6,583	*2006-2008	*unknown	*NAMMCO 2009
Ringed seal <sup>a</sup>	Arctic subspecies	~2.5 million	1970s	unknown	Miyazaki 2002
	Baltic Sea subspecies	5,000-8,000	1990s	Mixed	Karlsson et al. 2007
	Lake Saimaa subspecies	280	2005	increasing	Sipilä and Kokkonen 2008
	Lake Ladoga subspecies	3,000-5,000	2001	unknown	Agafonova et al. 2007
	Okhotsk Sea subspecies	>800,000	1971	unknown	Miyazaki 2002
Bearded seal <sup>b</sup>	Bering-Chukchi Seas	250-300,000	1970s	unknown	Fedoseev 2000
	Canadian waters	190,000	1958-1979	unknown	Cleator 1996
	Atlantic and Russian Arctic	unknown	—	unknown	
	Okhotsk Sea	200-250,000	1968-1969	unknown	Fedoseev 2000
Walrus <sup>c</sup>	Bering-Chukchi Seas	*129,000	*2006	unknown	*USFWS 2010c
	Atlantic subspecies	18-20,000	2006	mixed	Witting and Born 2005, Lydersen et al. 2008, COSEWIC 2006, NAMMCO
	E. Greenland	*1429	*2009		
	W. Greenland	*3240	*2008		*NAMMCO 2010 (in press)
	Greenland - North Water	*2676	*2008		
	Laptev Sea	4,000-5,000	1982	unknown	Fay 1982
	Other regions	Unknown	—	unknown	
Polar bear <sup>d</sup>	Chukchi Sea	2,000	1993	unknown	Aars et al. 2006
	Southern Beaufort Sea	1,500	2006	declining	Aars et al. 2006
	Northern Beaufort Sea	1,200	1986	Stable	Aars et al. 2006
	Viscount Melville Sound	220	1992	increasing	Aars et al. 2006
	McClintock Channel	280	2000	increasing	Aars et al. 2006
	Norwegian Bay	190	1998	declining	Aars et al. 2006
	Lancaster Sound	2,500	1998	Stable	Aars et al. 2006
	Gulf of Boothia	1,500	2000	Stable	Aars et al. 2006

<sup>a</sup> Ringed seal stock structure unknown; information summarized for five recognized subspecies.

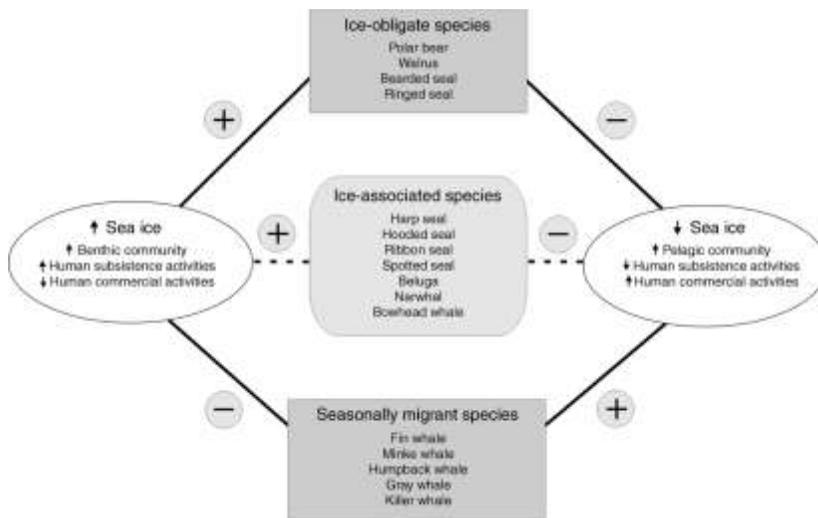
<sup>b</sup> Bearded seal stock structure unknown; information summarized for geographic regions.

<sup>c</sup> Walrus stock structure unknown; information summarized for Atlantic subspecies and geographic regions for Pacific subspecies.

<sup>d</sup> Recent analysis of genetic, ecological and life history data from Canadian polar bears suggests that their stock structure may need to be revised (Thiemann et al. 2008).

### 5.1.1 Area of future concerns

Moore and Huntington (2008) provide a conceptual model of the potential impacts of climate change to Arctic marine mammals based on the gain or loss of sea ice (Figure 8). Fitness for ice-obligate species is positively correlated to sea ice; increases in the seasonal and temporal extent and thickness of sea ice generally have a positive effect on populations (Laidre et al. 2008). Moore and Huntington (2008) anticipate decreases in sea ice to have a negative effect on ice-associated species, except perhaps through reduced risk of ice entrapment (Laidre and Heide-Jorgensen 2005), due to their adaptation to existing trophic regimes. They note that harp, hooded, ribbon, and spotted seals are ice associated species for the purpose of the conceptual model due to their reliance on sea ice for whelping (Reeves et al. 1992, Johnston et al. 2005). Finally, the five seasonally migrant cetacean species are likely to benefit from net loss in sea ice, due to greater access to a pelagic-dominated ecosystem (Moore and Huntington 2008).



**Figure 8.** (from Moore and Huntington 2008). A conceptual model of sea ice impacts on ice-obligate, ice-associated, and seasonally migrant marine mammal species: positive impacts are indicated by circled plus signs; negative impacts by circled minus signs. Dashed lines indicate uncertainty regarding potential impact of sea ice gain or loss for ice-associated species. Anticipated changes in benthic and pelagic community productivity are as presented in Bluhm and Gradinger (2008); anticipated change in human subsistence and commercial activities are as presented in Hovelsrud et al. (2008) (Moore and Huntington 2008).

Laidre et al. (2008) found few quantified studies that clearly demonstrate a direct relationship between ecological changes caused by climate warming and responses of individual species of Arctic marine mammals. There are, however, case studies in the scientific literature that have detected and quantified specific biological, physiological, or ecological effects of changing climate (Laidre et al. 2008). The 2009 Arctic Report Card summarizes some of the currently observed impacts and projects others (Simpkins 2009). Reduced sea ice has already been implicated in lower body condition and reduced survival of polar bears in western Hudson Bay, and similar impacts are likely elsewhere as sea ice breaks up earlier and bears are forced to fast on shore longer (Stirling et al. 1999, Regehr et al. 2007). The record sea ice retreat of 2007 caused Pacific walrus to haul out along the shores of Alaska and Russia in unusually large numbers and in new locations (Jay and Fischbach 2008). The immediate impact of this redistribution was an increase in trampling deaths as walrus on shore stampeded in response to terrestrial disturbances (Jay and Fischbach 2008).

Similar shifts in the seasonal distribution of all Arctic marine mammals are likely (Simpkins 2009). Species ranges are generally expected to shift northward to inhabit areas within their preferred metabolic temperature tolerances because conditions at the southern limits of their previous distribution will no longer meet their ecological needs (Laidre et al. 2008, Simpkins et al. 2007). For example, species that are strongly tied to sea ice habitats, such as the polar bear and ringed seal, may be limited in the future to areas with sea ice refugia (e.g., summer sea ice is predicted to persist longer in the Canadian Arctic Archipelago than elsewhere (Overland and Wang 2007)). Sub-Arctic or migratory species may be able to access areas where sea ice had previously excluded them (e.g. gray whales) (Moore 2008) with potential for increases in disease, predation, and competition for food (Laidre et al. 2008, Moore and Huntington 2008, Simpkins et al. 2007). Further, species or populations that either migrate with the sea ice edge or travel to the ice edge from coastal areas may have to travel farther and expend more energy as the summer sea ice edge retreats farther from the coast and from the location of the winter ice edge (Freitas et al. 2008, Durner et al. 2009a). It has been suggested that increased variability in sea ice and weather conditions could result in more frequent ice entrapments of narwhals and belugas (Heide-Jørgensen and Laidre 2004, Laidre and Heide-Jørgensen 2005). Further, changes in the seasonality of ice retreat could result in changes in the timing and location of phytoplankton blooms (e.g., associated with the melting ice edge or in open water following ice retreat), which in turn

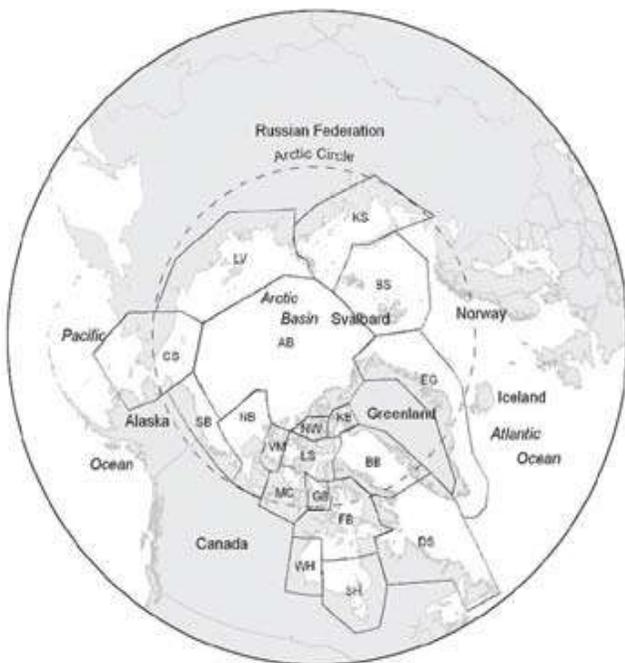
could influence both the total amount of primary production and the allocation of that production among pelagic and benthic food webs (Bluhm and Gradinger 2008).

A serious impact of climate change on marine mammals may not come directly from the effects of weather conditions, but rather indirectly from the role that regional warming, reduced sea ice and more open water play in changing human activities (Reeves 2009). In many regions, there will be opportunities for increased commercial shipping, coastal development, tourism, fishing, oil, gas and mineral exploration and development (Simpkins 2009) but less stable platforms for subsistence hunting (Moore and Huntington 2008). Such activities pose additional risks to Arctic marine ecosystems and marine mammals by increasing noise, entanglement risk, disturbance, contaminants, ship strikes, competition for prey, introduction of disease, and loss of essential habitat (Simpkins et al. 2007).

However, not all changes are predicted to have negative impacts. Bowhead whales might benefit from any increased productivity that might be associated with more open water in their current summer foraging habitats (Moore and Laidre 2006). Milder winters can result in less ice entrapments for narwhals and belugas. For example, in West Greenland, “no ice entrapments of belugas have been observed since 1990, which suggest a reduction in large-scale natural mortality events” (Heide-Jørgensen et al).

The following sections discuss seven marine mammal species that are present in the Arctic year-round and depend or associate with sea ice for life functions - polar bear, ringed seal, bearded seal, walrus, narwhal, beluga whale and bowhead whale (Laidre et al. 2008, Ragen et al. 2008, Moore and Huntington 2008).

## 5.2 Polar bear (*Ursus maritimus*)



**Figure 9.** (from USFWS 1009b) Polar bears occur throughout the circumpolar Arctic and are recognized as 19 populations based on movement patterns, genetics, and ecology.

There are nineteen relatively discrete polar bear subpopulations distributed throughout the ice-covered waters of the circumpolar Arctic<sup>9</sup> (Fig. 9) (Aars et al. 2006, Stirling 1988). They rely on sea ice as their

<sup>9</sup> There is uncertainty about the discreteness of the less studied subpopulations, particularly in the Russian Arctic and neighboring areas, due to very restricted data on live capture and tagging.

primary habitat and are uniquely adapted to life in a sea ice environment: (1) white pelage with water-repellent guard hairs and dense under-fur; (2) a short, furred snout that minimizes heat loss to the environment; (3) small ears with reduced surface area; (4) teeth specialized for a carnivorous rather than an omnivorous diet; (5) feet with tiny papillae on the underside, which increase traction on ice; (6) large, paddle-like feet; and (7) short claws that are strongly curved to provide traction on the ice and catch and hold its prey (Stirling 1988, Amstrup 2003).

They depend fundamentally upon sea ice as a platform for hunting seals, resting, traveling, finding mates, breeding and sometimes for maternal denning (USFWS 2010a,b, Stirling and Derocher 1993). Although ringed seals and to a lesser extent bearded seals are their primary prey, polar bears occasionally take much larger animals, such as walruses, narwhal, and beluga whales (Kiliaan and Stirling 1978, Smith 1980, 1985, Lowry et al. 1987, Calvert and Stirling 1990, Smith and Sjare 1990). In some areas and under some conditions, carrion or remains of subsistence harvested bowhead whales may be important to polar bear sustenance as short-term supplemental forms of nutrition.

The distribution and movements of polar bears are closely tied to the seasonal dynamics of sea ice extent as it retreats northward during summer melt and advances southward during autumn freeze. In particular, polar bear movements are influenced by the accessibility of ringed seals and bearded seals. Water depth, sea ice concentration, and proximity to the ice edge appear to be the important characteristics of the preferred polar bear feeding and movement habitat (USFWS 2009a, Durner et al. 2004). Polar bears prefer the annual sea ice over the shallower (300 m or less) waters of the continental shelf (Durner et al. 2004, Durner et al. 2009a) which is consistent with the distribution of ringed and bearded seals. During the winter period, when energetic demands are the greatest, nearshore lead systems and polynyas are important for seals, and are thus important foraging habitat for polar bears (USFWS 2009a). During the spring period, nearshore lead systems continue to be important hunting and foraging habitat for polar bears (USFWS 2009a). The shore-fast ice zone, where ringed seals construct birth lairs in the snow for pupping, is also an important foraging habitat during the spring (USFWS 2009a, Stirling et al. 1993).

In the polar basin and adjacent areas, some bears remain on sea ice year-round (Laidre et al. 2008). In more southerly areas (i.e., Hudson Bay, Foxe Basin, Baffin Bay/Davis Strait), the annual ice melts completely and all bears are forced to spend up to several months on land fasting until freeze-up allows them to return to the ice again (e.g., Stirling et al. 1999, Taylor et al. 2001, Stirling and Parkinson 2006).

### 5.2.1 Trends

In June and July 2009, IUCN’s Polar Bear Specialist Group (PBSG) reevaluated the status of the 19 recognized polar bears subpopulations. The PBSG concluded that 1 of 19 subpopulations is currently increasing, 3 are stable, 8 are declining and there is insufficient data to assess a current trend for 7 subpopulations (Table 4) (IUCN 2009). The total number of polar bears is still thought to be between 20,000 and 25,000, however, the varied quality of information on the different subpopulations means there is much room for error in establishing that range (IUCN 2009).

**Table 4. Current Trends of 19 Polar Bear Subpopulations (IUCN 2009).**

<b>Increasing</b>	<b>Stable</b>	<b>Declining</b>	<b>Data deficient</b>
M'Clintock Channel	Northern Beaufort Sea	Chukchi Sea	E. Greenland
	Gulf of Boothia	Southern Beaufort Sea	Barents Sea
	Southern Hudson Bay	Norwegian Bay	Kara Sea
		Lancaster Sound	Laptev Sea
		Western Hudson Bay	Viscount Melville
		Kane Basin	Foxe Basin
		Davis Strait	Arctic Basin
		Baffin Bay	

## 5.2.2 Concerns for the Future

Within the sea ice ecosystem, polar bears have experienced perhaps the most obvious impacts from reduced sea ice. Recent sea ice declines have been associated with reduced body condition, reproduction, survival, and population size for polar bears in parts of their range (Stirling et al. 1999, Obbard et al. 2007, Stirling and Parkinson 2006, Regehr et al. 2007a). Moline et al. (2008) provided a list of the documented and cited effects of reduced sea ice on polar bears by location (Figure 10). These include:

1. A decrease in body condition in western Hudson Bay (Stirling et al. 1999).
2. A population decline of 22% in western Hudson Bay (Regehr et al. 2005).
3. Increasing bear–human interactions at Churchill (Stirling and Derocher 1993).
4. Mortality associated with extended swimming in the Beaufort Sea (Monnett and Gleason 2006<sup>10</sup>).
5. Smaller cub size and apparent survival in the southern Beaufort Sea (Rode et al. 2007).
6. Shifting to landed dens in northern Alaska (Fischbach et al. 2007).
7. Shifting to landed dens in the Beaufort Sea population (Amstrup and Gardner 1994, Durner et al. 2009b).
8. Pregnant females experiencing increased travel to denning habitat (Bergen et al. 2007).
9. Northern Beaufort Sea population is stable (Stirling et al. 2007).
10. Declines in body condition (but not numbers) in southern Hudson Bay (Obbard et al. 2007).
11. Declines in reproductive success negatively correlated with the Arctic Oscillation in Svalbard (Derocher 2005).



**Figure 10** (from Moline et al. 2008). Numbers indicate locations of documented and cited effects of declining sea ice on polar bears. See above list for information associated with each number.

In addition, Amstrup et al. (2006) report of cannibalism among polar bears in the southern Beaufort Sea.

<sup>10</sup> While Moline et al. (2008) cite Monnett and Gleason to support mortality associated with extended swimming, Monnett and Gleason speculate on the casualty, stating “We speculate... mortalities due to offshore swimming... may be an important and unaccounted source of natural mortality... We further suggest that drowning-related deaths of polar bears may increase...”

As the summer sea ice edge retracts to deeper, less productive polar basin waters, polar bears will face increasing competition for limited food resources, increasing energetic demands and increased risk of drowning because of swimming greater distances, and declining population (USFWS 2009a). Substantial portions of polar bear populations will be seasonally redistributed into marginal ice or terrestrial habitats with fewer opportunities for feeding, and increasing the susceptibility of bears to other stressors. Sea ice reductions will likely reduce productivity of most ice seal species, resulting eventually in a decrease in seal abundance (Derocher et al. 2004) which will likely decrease availability of seals as food for polar bears. Ringed seals will likely remain distributed in shallower, more productive southerly areas that are losing their seasonal sea ice and becoming characterized by vast expanses of open water in the spring, summer and fall periods (Harwood and Stirling 1992). As a result, the seals will remain unavailable as prey to polar bears during critical times of the year. These factors may, in turn, result in a steady decline in the physical condition of polar bears, preceding population-level demographic declines in reproduction and survival (Stirling and Parkinson 2006, Regehr et al. 2007a).

Population and habitat modeling have projected substantial future declines in the distribution and abundance of polar bears (Amstrup et al. 2007, Hunter et al. 2007, Durner et al. 2009a). For both the Southern Beaufort Sea and Western Hudson Bay subpopulations, declines are already linked to the impacts of climate warming and loss of sea ice habitat on body condition and demographic rates of polar bears (Stirling et al. 1999, Stirling and Parkinson 2006; Hunter et al. 2007, Regehr et al. 2006, 2007a,b, Rode et al. 2007). These populations are vulnerable to large-scale dramatic seasonal fluctuations in ice movements, decreased abundance and access to prey, and increased energetic costs of hunting (USFWS 2010a,b).

### **5.3. Ringed seal (*Phoca hispida*)**

There are five sub-species of ringed seals which have a circumpolar distribution from approximately 35N to the North Pole, occurring in all seas of the Arctic Ocean (Frost and Lowry 1981, Kelly 1988), but they are also found in more southern regions such as the Baltic and Bering seas. Ringed seals depend on sea ice and are the only seal in the Northern Hemisphere that regularly inhabits the fast ice (Frost 1984). When on pack ice, they prefer large floes (i.e., > 48 m in diameter) and are often found in the interior ice pack where the sea ice coverage is greater than 90% (Simpkins et al. 2003). They use ice year-round, for mating, birthing, pup rearing, molting and as haul-outs to rest (Frost 1984). They have a unique ability to create and maintain breathing holes in the sea ice by using sharp claws on their fore-flippers (Burns 2002). This allows them to live in areas where other ice-associated seals cannot reside and their range extends farther north and encompasses areas of heavier ice than any other marine mammal except the polar bear (Burns 2002). Ringed seal adults excavate lairs or snow dens on the sea ice surface for giving birth to and rearing their young, as well as for protection from predators and for shelter (Stirling and Smith 2004, Burns 2002, Frost 1984). Of particular importance, ice deformations like pressure ridges and ice hummocks facilitate thicker snow accumulation and provide more suitable habitat for lairs (Smith and Stirling 1975). The lairs provide a warm micro-climate, reducing the energy required for keeping warm.

During ringed seal molt, the growth of new hair depends on high skin temperatures which occur only when the seals are out of the water on the ice during the spring (Feltz and Fay 1966, Kelly 1988). During molt, feeding reflexes are inhibited and overall activity decreases, with ringed seals spending most of their time sleeping on ice during this physiologically demanding period through June (Fedoseev 2000). Resting periods on sea ice may be particularly critical for adult female ringed seals. Carlens et al. (2006) found that adult female ringed seals haul out for long periods (up to 141 hours of continuous haul out), likely due to an increased need for rest after a demanding nursing period.

The ringed seal diet consists primarily of fish, especially Arctic and saffron cod, amphipods, euphausiids, shrimp, and other small crustaceans (Frost and Lowry 1981, Belikov and Boltunov 1998,

Gjertz and Lydersen 1986, Siegstad et al. 1998; Holst et al. 2001, Labansen et al. 2007) with Arctic cod dominating.

### 5.3.1 Area of future concerns

Many aspects of the ringed seal's life cycle depend on their ice habitat, and many of their activities are governed by the timing of the formation and break-up of sea ice. The reduction of winter sea ice and shrinking length of the sea ice season may interrupt the timing of ringed seal breeding activities, including courtship, birthing, and nursing, with consequent negative impacts on fecundity (Tynan and DeMaster 1997). Ringed seal breeding depends on the availability of sufficient ice, at the correct time of year in areas with sufficient food nearby. Both ice and snow must be stable enough in the spring season to successfully complete the six week period of lactation. If the landfast ice breaks up too soon, pups may be separated prematurely from their mothers before weaning, resulting in high pup mortality (e.g., Harwood et al. 2008). Prematurely weaned pups will be in poor body condition and suffer higher mortality due to lack of sufficient blubber reserves, increased exposure to hypothermia, and increased risk of predation. Thus, ringed seals may experience an increased frequency of breeding failures due to changing climate conditions, with resultant population declines.

Ringed seals in some areas are already showing relatively long-term declines in reproductive rates and pup survival. In the southern Baltic Sea, from 1989 to 1995, a series of nearly ice-free winters led to very high pup mortality rates (Härkönen et al. 1998). In 1998, ice in the western Arctic broke up three weeks earlier than usual, sending pups into the water before they had been weaned (NSIDC undated).<sup>11</sup> Studies of western Hudson Bay ringed seals have indicated reduced reproduction, pup survival, and recruitment of ringed seals possibly correlated with decreased snow depth, a general warming trend, and changes in the timing of breakup of sea ice (Ferguson et al. 2005, Stirling 2005). Kovacs and Lydersen (2008) report: "During 2006 and 2007 many of the fjords on the west coast of Svalbard did not freeze for the first time in recorded history. Ringed seal reproduction was virtually non-existent in areas where many hundreds of pups are normally born. It is not known if the seals that normally pup in this region established themselves elsewhere early enough to set up territories and build lairs, etc., but it seems highly unlikely." They further state: "If the extremes predicted for losses of sea ice do occur, it is difficult to envisage how this ice-breeding seal will survive beyond the small refugia-areas where ice-cover will remain, despite its currently broad range and high abundances." "Marked decreases in ringed seal abundance are likely to have cascading effects in Arctic food webs. They are the most important species in the diet of polar bears and are themselves top trophic consumers of significant magnitude" (Kovacs and Lydersen 2008).

In recent years there has been a low level of ice coverage in the Sea of Okhotsk but it is unclear what effect this has on ringed seals and bearded seals (Trukhin 2009). However, Trukhin states that seasonal migrations and distributions of seals in the northern parts of the Sea of Okhotsk have been affected by late ice formation in the autumn and early breakup in spring (Trukhin 2009). A shortage of ice cover and its comparatively short presence in the Sea of Okhotsk can affect the reproductive success and pup survival of seals (Trukhin 2009).

While researchers believe that ringed seals will be adversely impacted by the loss of summer sea ice and earlier break up of sea ice in the spring, Harwood et al. (2008) analyzed harvest-based sampling near Ulukhaktok from 1992-2007 and Sachs Harbor from 2003-2007 in northern Canada and found that during years with a longer open water period ('light' ice years), such as 1998, 2001, 2006 and 2007, ringed seals were in better body condition than in other years in the data series, and pup production and ovulation rates were high. The opposite was the case in heavy ice years (e.g. 1974, 2005).

The persistence of sea-ice habitat from March through July is particularly critical for the success of ringed seal molt completion and reproduction. However, sea-ice extent has declined during March

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<sup>11</sup> [http://nsidc.org/seaice/environment/mammals\\_seals.html](http://nsidc.org/seaice/environment/mammals_seals.html).

through July in recent decades in many regions inhabited by the ringed seal, including the seasonally ice-covered Okhotsk and Bering Seas, Hudson Bay, Baffin Bay, Greenland Sea, Canadian Archipelago, Barents Sea, Kara Sea, Laptev Sea, Beaufort Sea, Chukchi Sea, and Arctic Ocean (Meier et al. 2007). Earlier ice breakups are predicted to occur more frequently. With early sea-ice breakup, ringed seals may suffer physiological stress and associated mortality from being forced into the water before molt completion.

Based on modeling, Freitas et al. (2008) predicted that migrations to offshore ice edges will become energetically unprofitable for ringed seals if the sea ice retreats further than 600–700 km from Svalbard.

Declining sea-ice extent will likely alter the ice-based food web and may result in a decline in Arctic cod, which is the ringed seal's main prey item, negatively affecting ringed seals (Bluhm and Gradinger 2008). Furthermore, throughout the Arctic, ringed seals are heavily preyed upon by polar bears (Kelly 1988, Stirling and Archibald 1977, Hammill and Smith 1991, Stirling and Øritsland 1995).

#### **5.4 Bearded seals (*Erignathus barbatus*)**

The bearded seal contains two currently recognized subspecies. The Pacific bearded seal, *Erignathus barbatus nauticus*, and the Atlantic bearded seal, *Erignathus barbatus barbatus*. Bearded seals are circumpolar in their distribution, extending from the Arctic Ocean (85EN) south to Hokkaido (45EN) in the western Pacific (Kelly 1988a). The Pacific bearded seal inhabits the Arctic Ocean and the Bering and Okhotsk Seas. They are found near Hokkaido, Japan, and, rarely, off the coast of NE China (Burns 1981, Kelly 1988a). The Atlantic bearded seal is found in the western Laptev Sea, Barents Sea and north Atlantic Ocean and as far south as the Gulf of St. Lawrence in the western Atlantic and in Iceland and Norway in the eastern Atlantic (Burns 1981, Kelly 1988a). They generally inhabit areas of shallow water of less than 200 m that are at least seasonally ice covered, although they may remain in or near the sea ice year round (Laidre et al. 2008). During winter they are most commonly found in broken pack ice (Burns 1967) in areas of between 70% and 90% sea ice coverage (Angliss and Outlaw 2006). In some areas they also inhabit shorefast ice (Smith and Hammill 1981). In winter, bearded seals require regions of thin or broken ice cover over suitably shallow depths to forage on benthic invertebrates such as crabs, clams and shrimp and also benthic fish (Finley and Renaud 1980; Burns et al. 1981, Lowry et al. 1980, Antonelis et al. 1994). They migrate seasonally following the advance and retreat of the sea ice to maintain access to the ice (Burns 1981). Pupping, molting and hauling out take place on the ice, primarily on drifting pack ice over shallow water where the ice is in constant motion producing leads, polynyas and other openings (Bengtson et al. 2005, Burns 1981).

Similar to ringed seals, bearded seals also use the sea ice for their annual molt, molting from April through August (Burns 1981, Kovacs 2002). During May through July they haul out during a concentrated molting period (Burns 1981, Gjertz et al. 2000) when increased summer temperatures and day length raise their skin temperature to facilitate epidermal growth (Feltz and Fay 1966).

Bearded seals give birth in March through May on the sea ice and nurse the pup on the ice for three weeks. Sea ice allows bearded seals to avoid excessive predation on their dependent young by terrestrial predators (Burns 2002). Similar to other ice seals, the sea ice also provides an important resting platform for pups during the nursing period as they spend 50% of the time during the nursing period resting and half of that sleeping (Lydersen et al. 1994, Lydersen and Kovacs 1999).

As bearded seals rest on sea ice or actively follow ice floes while foraging, they are transported over great distances. A primary advantage of passive transportation by sea ice is that new feeding areas are constantly opening up as the ice moves (Ray and McCormick-Ray 2004). Associating with sea ice allows Pacific bearded seals to continually move to new unexploited foraging areas after depleting local resources, vastly broadening their foraging range and opportunities.

Polar bears (Stirling and Archibald 1977, Burns 1981, Derocher et al. 2002) and walrus (Lowry and Fay 1984) prey upon bearded seals.

#### 5.4.1 Area of future concerns

The bearded seal will be vulnerable to reductions in sea ice and an earlier breakup as it will increasingly lose its breeding, resting, and molting habitat, and its range will shift northward. Sea-ice extent has declined significantly during March through July in recent decades in many regions inhabited by the bearded seal, including the seasonally ice-covered Okhotsk and Bering Seas, Hudson Bay, Baffin Bay, Greenland Sea, Canadian Archipelago, Barents Sea, Kara Sea, Laptev Sea, Chukchi Sea, and Arctic Ocean (Meier et al. 2007). Sea ice loss during the birthing and nursing period from March-June and for molting from May-July and for resting throughout the year will likely adversely impact these critical life functions (Kelly 1988).

Increasingly earlier sea-ice breakup may result in premature separation of pups from their mothers during the lactation period. Prematurely weaned pups will likely have a lower body condition and may suffer higher mortality from lack of adequate blubber reserves. If bearded seals have to enter the water before completing their molt due to loss of sea ice, they may experience physiological stress and associated mortality. If bearded seals are forced to haul out on land to complete molt, they could suffer predation from terrestrial predators. Without adequate sea ice, bearded seals may not haul out to rest and suffer physiological stress.

Because bearded seals forage over shallow waters for benthic prey, the increasing retreat of sea ice northward in summer and fall may result in much of the remaining sea ice being located over water that is too deep for them to forage (Tynan and DeMaster 1997). For example, bearded seals occur on the pack ice front over the Chukchi Sea shelf in summer (Burns and Frost 1979), but were not associated with the ice front when it receded over deep water (Kingsley et al. 1985).

Sea ice loss and rising temperatures may transform the benthic dominated ecosystem rich in prey for bearded seals to one dominated by pelagic fish. This is already occurring in the northern Bering Sea (Grebmeier et al. 2006, 2006a). The presence or absence of sea-ice cover influences the timing of primary production which in turn plays a primary role in shaping ecosystem structure. The seasonally ice-covered Bering Sea currently experiences two primary production blooms: an early "ice edge bloom" followed by an "open-water bloom" after the ice has melted. The intense, spring ice-edge bloom follows the melting sea-ice edge and the melting ice releases nutrients and fresh water that promote phytoplankton growth. Due to cold spring water temperatures, spring zooplankton populations are low and do not consume much of the organic matter before it settles to the bottom. The net result of the high primary production over these shallow shelves and relatively low grazing pressure is that a heavy rain of organic matter settles to the sea floor where it supports a rich benthic community (Grebmeier et al. 2006).

#### 5.5 Walrus (*Odobenus rosmarus*)

There are two species of walrus, Pacific walrus (*Odobenus rosmarus divergens*) and Atlantic walrus (*Odobenus rosmarus rosmarus*) (USFWS 2009c).<sup>12</sup> The Pacific walrus is found throughout the Arctic

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<sup>12</sup> In some current systematic schemes, the walrus is divided into three subspecies: *O. r. rosmarus* in the North Atlantic, *O. r. divergens* in the North Pacific and *O. r. laptevi* in the Laptev Sea. These three subspecies have been described as differing in body size, but the taxonomic status of *O. r. laptevi* is disputed. Lindqvist et al. (2009) do not support the recognition of three walrus subspecies and recommend that *Odobenus r. laptevi* be abandoned and the Laptev walrus instead be recognized as the westernmost population of the Pacific walrus, *Odobenus r. divergens*. However, they recommend further research to assess whether the Laptev walrus could be considered as a significant unit in terms of conservation and management because it is unique in several ecological parameters (Lindqvist et al. 2009).

continental shelf waters of the Bering and Chukchi Seas as well as the Laptev Sea to the west and the Beaufort Sea to the east (USFWS 2009c). The Atlantic walrus occurs in or adjacent to the North Atlantic in four regions: the Hudson Bay–Davis Strait, eastern Greenland, Svalbard and Franz Josef Land, and Kara Sea and Novaya Zemlya (Fay 1982, NAMMCO). Born et al. (1995) identified four putative stocks of walrus in Canada: North Water (Baffin Bay–Eastern Canadian Arctic); Foxe Basin; Northern Hudson Bay–Hudson Strait–Southeastern Baffin Island–Northern Labrador; and Southern and Eastern Hudson Bay. Stewart (2007) suggests further subdivision of some walrus stocks in Canada.

Pacific walrus appear to be more dependent on sea ice than Atlantic walrus (USFWS 2009c). The Pacific walrus uses floating sea ice as a substrate for birthing and nursing calves, resting, isolation from predators and for passive transport to new feeding areas (Lowry 1984). As walrus follow the edge of the sea ice throughout the year, the sea ice acts as a floating conveyor belt between the Bering and Chukchi seas that keeps walrus over the shallow, productive continental shelf waters and continually transports them to new foraging grounds (Ray et al. 2006, Ray and McCormick-Ray 2004).

Walrus are highly specialized benthic feeders, feeding primarily on bivalve mollusks (clams and mussels), and secondarily on other benthic invertebrates including snails, shrimp, crabs, worms, and sea cucumbers (Fay 1982). They also feed occasionally on fish, birds or seals (Fay 1985, Mallory et al. 2004, Lowry and Fay 1984, Gjertz and Wiig 1992, Born et al. 1994). Walrus usually feed in shallow waters of 100 meters (328 feet) or less (Kelly 2001).

Sea ice is also important for reproduction. Breeding occurs from January through March, in the water in polynyas or areas of drifting pack ice (Fay 1982, Sjare and Stirling 1996). Pacific walrus give birth to a single calf on the sea ice in the Bering Sea. The sea ice and its location protect calves from predation because polar bears typically cannot reach walrus birthing areas (Burns 2002). The sea ice provides a platform for nursing during the lengthy lactation period which lasts up to two years (Fay 1982). Also, the sea ice provides calves with a platform on which to rest while their mothers forage and during the seasonal migration.

Pacific walrus distribution varies seasonally and is limited by water depth and ice conditions. Females, young, and immature walrus spend the summer months on the sea ice edge over the continental shelf of the Chukchi Sea, but several thousand animals, primarily adult males, use coastal haulouts in the Bering Sea during the ice-free season (USFWS 2009c, Fay 1982, Fay 1985). In contrast, all sex and age categories of Atlantic walrus use terrestrial haulouts during the summer months (Born 2005). In winter and early spring, the entire Pacific walrus population overwinters in large aggregations in the seasonal pack ice of the Bering Sea (Burns 2002, Ray et al. 2006). Most walrus occupy the broken pack ice where ice floes are thick and large enough to support the weight of large groups of animals, low enough to haul out on, and separated by leads and polynyas that allow access into and out of the water (Ray et al. 2006).

Atlantic walrus use both sea ice and terrestrial haul-outs as a hub for feeding excursions on shallow nearshore banks with substantial bivalve mollusk production (Born et al. 1994, Laidre et al. 2008). In summer, Atlantic walrus often leave their ice-based haul-outs for terrestrial haulouts, although many terrestrial haul-outs, especially in Greenland and Svalbard, have been abandoned because of excessive hunting pressure (Gjertz and Wiig 1994, Born et al. 1995, Laidre et al. 2008). In East Greenland walrus are forced to leave terrestrial haul-outs and move offshore to winter in waters greater than 100 m deep (Born 2005, Laidre et al. 2008).

### **5.5.1 Population and trends**

#### *Atlantic walrus*

The current total abundance of Atlantic Walrus is very poorly known, but the most recent information suggests a population size of perhaps 18,000-20,000 (Lowry et al. 2008, COSEWIC 2006, NAMMC

undated). Modeling indicates that the walrus populations in West Greenland and the North Water have been in steady decline, while the population in East Greenland has been increasing (Witting and Born 2005). Walrus numbers at Svalbard have increased slowly during 1993-2006 (Lydersen et al. 2008). The current global population trend is unknown (Lowry et al. 2008).

### *Pacific walrus*

Scientists conducted aerial surveys of Pacific walrus at 5 year intervals from 1975 to 1990, and the resulting minimum population estimates ranged from 200,000 to 250,000 animals (USFWS 2010c). However, the counting methods varied during this period, which means that the estimates cannot be compared to estimate a population trend during that period (USFWS 2010c). It also means that the estimates from 1975-1990 should be used cautiously as a baseline for current estimates (USFWS 2010c).

In 2006, the American and Russian scientists conducted the first comprehensive survey of Pacific walrus since 1990 (Speckman et al. 2009). The number of Pacific walrus within the surveyed area was estimated at 129,000 (USFWS 2010c, Speckman 2010). Trends in abundance will be examined in more detail once all aspects of the analysis of the 2006 survey data have been completed (USFWS 2010c).

### **5.5.2 Area of future concerns**

Some impacts of the loss of summer sea ice on Pacific walrus have been documented (USFWS 2010c). Summer sea-ice extent in the Chukchi Sea has decreased rapidly in recent years (Meier et al. 2007, Stroeve et al. 2008), retreating off the shallow continental shelf and over deep Arctic Ocean waters where walrus presumably can not feed. The Chukchi shelf was effectively ice-free during the summer in five of the six years from 2002-2007, but only once (in 1999) between 1979-2001 (Jay et al. 2008). In the Bering Sea, winter sea ice cover declined significantly by approximately -5% per decade during the March breeding season and even more in fall (-43% per decade in October and -20% per decade in November) (Meier et al. 2007); this suggests that that sea ice resting platforms are less available for walrus on their southward migration and that the winter sea ice is forming later.

Over the past decade, the number of walrus coming to shore along the coastline of the Chukchi Sea in Russia has increased (Kavry et al. 2008). Female and young walrus are arriving earlier and staying longer at coastal haulouts as summer ice disappears (USFWS 2009c). Tens of thousands have been reported anecdotally from some haulouts in Chukotka (Kavry et al. 2008). In the fall of 2007 for the first time and again in 2009, large walrus aggregations were also observed along the Chukchi Sea coast likely because of reductions or loss of sea ice over the Chukchi Sea continental shelf waters (USFWS 2010c, Funk et al. 2010, Fischbach et al. 2009, Jay and Fischbach 2008, Kochnev 2004). The ability of the food supply within foraging range of coastal haulouts to support large numbers of walrus over the long term is unknown, although Fay et al. (1984) show the history of use of terrestrial haul outs featuring many abandonments and reoccupations over a century in Russia and Alaska. Thin walrus that appear to be physiologically stressed have also been reported from Chukotka and Alaska (USFWS 2010c, Ovsyanikov et al. 2008, Pungowiyi 2000). Walrus at dense coastal haulouts are vulnerable to disturbance, which has resulted in high mortality at land-based haulouts on the Chukotka coast due to trampling during stampedes (Kavry et al. 2008) and presumably in Alaska where 131 young walrus carcasses were found near Icy Cape (USFWS 2009c, Fischbach et al. 2009). Calves separated from their mothers may have a greater risk of trampling injury without the protection afforded by their mothers on haulouts (Fischbach et al. 2009). Ice-free conditions in recent years have been associated with separation of calves from their mothers with researchers having observed calves alone in deep open water areas typically covered with sea ice during summer (Cooper et al. 2006).

The continued loss of summer sea ice, delayed formation in the fall and declines in ice thickness raise several concerns for the Pacific walrus. The Pacific walrus may lose access to large parts of its

foraging habitats on the Chukchi and Bering Sea shelves if loss of summer sea ice and delay in the formation of ice in the fall occurs. Without sea ice resting platforms over the Chukchi Sea shelf in summer, females and young will be concentrated at land-based haulouts for extended periods, foraging within range of land, to which they will return to rest. Walruses, especially calves, concentrated at land-based haulouts will likely suffer high mortality and injury from trampling during stampedes, as was observed in 2007 and 2009. The winter distribution of walruses is likely to be more concentrated as the progressively smaller ice area retreats northward.

The loss of sea ice haulouts will likely contribute to increasing physiological stress of Pacific walrus adults and young because they will be unable to rest and nurse their calves while foraging. In fall, winter, and spring, the reduced and thinner sea ice will likely require females and young to swim farther before finding adequate sea ice floes for these essential behaviors, increasing their energetic costs. Concentrated groups of walruses can quickly deplete local benthic prey resources near haulout sites, and walruses would be forced to swim further distances from shore to reach unexploited areas, increasing their metabolic costs (Lowry 2000). As sea ice decreases, calf mortality may increase as a result of increased metabolic stress during foraging trips and higher risk of abandonment without sea ice haulouts (Cooper et al. 2006).

In addition, females and young may be at greater risk of predation by polar bears and terrestrial predators at land-based haulouts during summer (Lowry 2000, Kelly 2001).

In the Atlantic where the use of coastal haulouts is more widespread, reduced sea ice cover could increase feeding opportunities for Atlantic walruses (Lowry et al. 2008, Born 2005).

## **5.6 Cetaceans – narwhal, bowhead whale and beluga whale**

Three species of cetaceans occupy Arctic waters year round - the narwhal, the beluga whale and the bowhead whale. The narwhal and beluga, medium-sized toothed whales, overlap somewhat in ecological niche, prey choice, and focal area use. The bowhead whale, the only baleen whale endemic to the Arctic, exploits the ecosystem in a very different way. The bowhead whale and the beluga have a circumpolar distribution, while the narwhal only occurs in the Atlantic sector of the Arctic. Few studies have documented links between cetacean demography and Arctic climate (Laidre et al. 2008). It has been suggested that decreases in summer ice extent and resultant increases in open water may initially benefit whales via enhanced local production of prey, extension of the foraging period, or both (Laidre et al. 2008, Moore and Laidre 2006).

In addition, changes in sea-ice may directly influence anthropogenic mortality by affecting the availability of cetaceans to local hunters (Heide-Jørgensen et al, in press). Large scale natural mortality may be affected by the frequency of ice-entanglements (Heide-Jørgensen et al, in press).

### **5.6.1 Narwhal (*Monodon monoceros*)**

Narwhals spend their whole lives in Arctic waters, bordering Canada, Greenland, Norway and Russia, and are seldom seen south of 61°N (COSEWIC 2004b). Narwhals from East Greenland and the Barents Sea are separated from those from West Greenland and Arctic Canada and the population structure of West Greenland and Arctic Canada is complex. After spending July to September spread over several inshore locations of northeastern Canada and Greenland, narwhals travel long-distance to their wintering grounds (Dietz et al. 2008, 2001, Dietz and Heide-Jørgensen 1995, Heide-Jørgensen et al. 2002, 2003) which are covered with dense pack ice from November to July (Koski and Davis 1994, Laidre et al. 2004c).

No other cetacean species occupies such dense winter sea ice cover for such a long period of time as the narwhal (Laidre et al. 2008). They are highly adapted to pack ice habitat where there is limited open water throughout the winter (Laidre et al. 2004b, Laidre and Heide-Jørgensen 2005). The quality

of the ice habitat, particularly the presence of leads in fast ice and the density of broken pack ice, appears to be a key aspect of their habitat selection (COSEWIC 2004b, Koski and Davis 1994). The ice may also provide refuge from predation by killer whales (COSEWIC 2004b). Narwhals from Canada and West Greenland have high site fidelity to the winter pack ice of Davis Strait and Baffin Bay in regions along the continental slope with high gradients in bottom temperatures, predictable adequate open water (<5%), and relatively high densities of Greenland halibut, a major prey item (Laidre et al. 2004a). Sightings suggest that the Greenland Sea may be an important wintering area for narwhals from East Greenland and/or Svalbard (Gjertz 1991), and it has been speculated that some narwhals occupy Hudson Strait in winter (Richard 1991).

Narwhals eat a small variety of fish and invertebrates (COSEWIC 2004b). Their diet composition varies with season and location, likely in response to dietary preferences and the seasonal or geographical availability of prey species (Neve 1995). The summer diet consists of squid and fish, with a large proportion of Arctic cod (COSEWIC 2004b). The wintering grounds may be the most critically important habitat for narwhals (Laidre et al. 2008). Between November and March, researchers have documented intense benthic feeding behavior on Greenland halibut and squid in narwhals from northern Canada and West Greenland (Laidre et al. 2003, Laidre and Heide-Jørgensen 2005a). This contrasts with low feeding activity during the summer, suggesting a major portion of the annual energy intake is obtained in Baffin Bay in winter (Laidre et al. 2008, 2004a, Laidre and Heide-Jørgensen 2005a). This may also be true for the Greenland Sea, but not been documented yet (Laidre et al. 2008).

#### **5.6.1.1 Area of future concerns**

In 2008, researchers ranked narwhals as the Arctic marine mammal most vulnerable to climate-induced habitat change due to its small range, narrow migration routes, limited world population, restricted diet and low genetic diversity (Laidre et al. 2008). It is unclear exactly what the climate changing impacts on narwhals will be. One possibility is that there will actually be cooling in some regions, reducing the scant open water that ensures winter survival and increasing the possibility of ice entrapment (Laidre et al. 2008). There have been numerous reports of narwhals being entrapped by ice since 1951 (COSEWIC 2004b, NAMMCO 2009). In 2008, there were two reports of entrapments – one in Canada where 629 narwhals were either taken by hunters or died from suffocation and one in Greenland where ice entrapped 35-40 narwhals (NAMMCO 2009).

In areas where ice decreases, killer whales may move into areas that have been previously inaccessible. Killer whales are observed in North Baffin areas and are now being seen in the area of Pelly Bay where they have not been seen in the past (NAMMCO 2009). Incidence of narwhal predation have been reported by local people and observed by researchers (Laidre and Heide-Jørgensen 2005b, NAMMCO).

#### **5.6.2 Beluga whale (*Delphinapterus leucas*)**

Beluga whales are considered to be a relatively flexible species because they can inhabit different types of habitat and eat a variety of prey species (Heide-Jørgensen et al.) Beluga whales are widely distributed in discrete populations around the Arctic Ocean and adjacent seas in estuaries, continental shelf and slope waters, and deep ocean basins in conditions of open water, loose ice, and heavy pack ice (Laidre et al. 2008). The beluga population is subdivided into 29 management units to reflect distinct groups of beluga at summering locations in Alaska, Canada, West Greenland, Svalbard and Russia (IWC 2000). Belugas generally prefer to overwinter in shallow or coastal areas, usually with light or highly moveable ice cover (Barber et al. 2001, Richard et al. 2001, Suydam et al. 2001, Heide-Jørgensen et al. 2003a). Belugas occur in the Russian Arctic in the Barents, Kara and Laptev seas (Belikov and Boltunov 2002, Boltunov and Belikov 2002). Some belugas undertake large-scale annual migrations between summering and wintering sites, while others remain in the same area year round, shifting offshore only when excluded from coastal habitat by fast ice formation (Hobbs et al. 2005). Large numbers of migratory belugas occur along the northwest and northern part of the Alaskan coast,

in the Canadian High Arctic, and western Hudson Bay. At certain times of the year, those whales migrate thousands of kilometers, in some cases as far as 80° N into dense pack ice (Suydam et al. 2001) or thousands of kilometers into the North Water polynya or to the pack ice off West Greenland (Richard et al. 1998a,b, 2001, Heide-Jørgensen et al. 2003b). Some populations (for example, the Cook Inlet, Cumberland Sound, Svalbard, and the Gulf of St. Lawrence populations) are geographically isolated and live in those locations all year round (Lydersen et al. 2001, Kingsley 2002, Hobbs et al. 2005).

Belugas feed on a large variety of fish species including Arctic cod, polar cod, saffron cod, salmon and smelt, as well as invertebrates such as shrimp, crabs, octopuses and marine worms (Reeves 2009, Boltunov and Belikov 2002). Belugas are preyed upon by killer whales and polar bears, the latter at cracks in sea ice where the whales become particularly vulnerable (Reeves 2009).

Laidre et al. (2008) explore the connection between why belugas move into deep, ice-covered waters and conclude it is unclear. One potential reason would be to avoid killer whale predation (Frost et al. 1992), but the movements into the ice appear excessive for what would be needed to avoid killer whales (Suydam et al. 2001). Moreover, traveling into this area actually could expose belugas to predation by polar bears (Lowry et al. 1987) as well as increase the risk of ice entrapment (Laidre et al. 2008). It is possible belugas move into ice-covered offshore regions for feeding, primarily on Arctic cod, but few data are available to support this hypothesis (Laidre et al. 2008).

### **5.6.2.1 Area of future concerns**

Eight surveys since 1981 conducted in West Greenland to estimate beluga abundance have established a clear relationship between decreasing sea ice cover and an increasing offshore distance of beluga sighting (Heide-Jørgensen et al., NAMMCO 2009). Heide-Jørgensen et al. suggest that belugas expand their distribution westward as new areas on the banks of West Greenland open up earlier in spring with reduced sea ice coverage or early annual ice recession. These results are among the first available evidence showing a shift in distribution of an Arctic cetacean in response to changes in sea ice coverage (Heide-Jørgensen et al.).

Long term changes in the North Water pack ice between Northwest Greenland and the northeastern Canadian High Arctic such as increasing ice concentrations or increasing variability in the pattern of ice breaking up and refreezing could result in ice entrapments of belugas and affect the abundance of beluga stocks (Reeves 2009, Laidre et al. 2008). Dense or complete ice cover may act as a barrier to belugas being able to breathe at the surface (Lowry 2000). When sufficient open water is not available, large-scale mortality events may occur (Laidre et al. 2008). Ice entrapments are best documented for belugas and narwhals, where sudden changes in weather conditions cause leads and cracks to freeze up rapidly, thus eliminating access to oxygen (Siegstad and Heide-Jørgensen 1994, Heide-Jørgensen et al. 2002a). Approximately 15,000 belugas move through the system of recurrent open-water leads and cracks in the North Water polynya in winter, situated at the entrance to Smith Sound between Northwest Greenland and the northeastern Canadian High Arctic (Vibe 1950, Finley and Renaud 1980, Reeves and Mitchell 1987, Richard et al. 1998b, 2001). Historically there are several examples of belugas being entrapped in the North Water pack ice (Heide-Jørgensen and Laidre 2004). In addition, beluga mortality from entrapment in sea ice has been observed in Senyavina Strait in Chukotka, Russia (Mymrin 2006). The frequency and scale of mortality from ice entrapment may increase in some regions that experience colder temperatures as the climate changes (Reeves 2009). However, in West Greenland, the frequency of ice entrapments of belugas has reduced with a decrease of sea-ice coverage since the early 1990s (Heide-Jørgensen et al.).

As Arctic waters become warmer and patterns of circulation, salinity and nutrient input change, species that previously were not present in the Arctic will be able to move further north and remain there for longer which may negatively affect belugas (Reeves 2009). Species such as minke and humpback whales as well as seals and other predators may directly compete with belugas for food resources

(Reeves 2009). In addition, killer whales may have more opportunities to prey on belugas (Reeves 2009). Killer whales are observed in North Baffin areas and are now being seen in the area of Pelly Bay where they have not been seen in the past (NAMMCO 2009). Incidence of beluga predation have been reported by local people and observed by researchers (Higdon 2007, NAMMCO 2009).

### 5.6.3 Bowhead whale (*Balaena mysticetus*)

The bowhead whale has a nearly circumpolar distribution in the northern hemisphere and ranges from 54° to 85°N latitude, spending their entire lives near the ice in arctic and sub-arctic waters. Bowhead whales occur in areas that range from open water to thick, unconsolidated pack ice and are seldom found far from ice-floes (Moore and Reeves 1993). They can easily move through extensive areas of nearly solid sea ice cover (Ellison et al. 1987, George et al. 1989, Heide-Jørgensen et al. 2003b, 2006, Heide-Jørgensen and Laidre 2004). They can break through ice over 20 cm thick with the crown of the head to breathe (George et al. 1989).

Bowhead whales summer in Arctic waters but migrate to subarctic seas to winter (Laidre et al. 2008). When the bowhead migrates south to its summer range, it follows fractures in the sea ice and stays near the ice edge, migrating north and south as the ice retreats or expands. Bowhead whales often inhabit polynyas and the marginal ice zone in winter and early spring (Moore and Reeves 1993, Bogoslovskaya 2003). In the western Arctic, they select open water or light to moderate sea ice cover (10–70%) in summer and autumn (Moore et al. 2000).

The International Whaling Commission (IWC) Scientific Committee recognizes four stocks: (1) Okhotsk Sea population, presumably confined to that sea year-round; (2) Bering-Chukchi-Beaufort (BCB) population, which summers in the eastern Beaufort Sea and Amundsen Gulf and winters in the central and eastern Bering Sea; (3) the Eastern Canada-West Greenland population, (EC-WG) which summers in Baffin Bay, the Canadian High Arctic, Foxe Basin, and northwestern Hudson Bay and winters in northern Hudson Bay, Hudson Strait, and along the ice edge in Davis Strait and off West Greenland;<sup>13</sup> and (4) Svalbard (Spitsbergen) population, centered in the Barents and Greenland Seas.<sup>14</sup>

The bowhead whale is the Arctic's largest and most zooplankton-dependent predator (Laidre et al. 2008). The most well studied Bering-Chukchi-Beaufort bowhead population eats mostly a variety of pelagic and epibenthic crustaceans, with copepods (primarily *Calanus* spp.) and euphausiids (*Thysanoessa* spp.) as the most important prey (Lowry 1993, Lowry et al. 2004). Diets differ regionally and over time, suggesting their diet is related to seasonal prey availability and that they locate prey concentrations that presumably result from oceanographic features such as upwelling and fronts (Laidre et al. 2008). It is unclear whether bowhead whales feed offshore or between late fall and early spring. Stable isotope studies suggest that a significant amount of feeding may occur in those areas and times for the Bering-Chukchi-Beaufort population (Lee et al. 2005).

#### 5.6.3.1 Population and trends

The Bering-Chukchi-Beaufort Sea stock is estimated to be about 10,000 whales and increasing at 3.4% a year (George et al. 2004), having tripled over the past 30 years. Consistent growth of the western Arctic bowhead population for the period 1978–2001 indicates positive demographic changes during a period of sea ice reduction.

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<sup>13</sup> The EC-WG population was recently recognized as encompassing the Eastern Canadian Arctic population which was considered 2 stocks: Davis Strait-Baffin Bay and Hudson Bay-Foxe Basin, and the West Greenland stock (COSEWIC 2009).

<sup>14</sup> A recent study of nucleotide sequence variation in the mitochondrial control region of bowhead whales from the putative Svalbard and BCB populations found only minor differences in nucleotide and haplotype diversity, leading the authors (Borge et al. 2007) to question the current IWC scheme of population delineation.

The pre-whaling population of bowheads has been estimated at about 50,000 worldwide, with about 30,000 in the Bering-Chukchi-Beaufort sea stock. Commercial whaling, which is regarded as having ended about 1910, reduced the world bowhead population to fewer than 3,000 animals. More than 90% of the Bering-Chukchi-Beaufort Sea stock was harvested, and the other stocks were virtually decimated. The other stocks have been very slow to recover, and with the exception of the Hudson Bay stock, number just a few hundred animals. Recent data indicates the Hudson Bay stock is showing signs of growth and may now number close to 1,000 whales (COSIMO 2009).

A series of estimates have been produced for the Eastern Canada-West Greenland population based on aerial surveys in 2002 and 2003 (COSEWIC 2009). Although relatively imprecise, all estimates suggest that the population currently numbers in the thousands and has increased significantly since bowheads were protected from commercial whaling in the early 20th century (COSEWIC 2009).

In 2006, the stock off west Greenland has been estimated at 1,230 or 490-2,940 with a 95% confidence limits (IWC 2006) after having very low sightings in the 1980s and 1990s (Heide-Jørgensen et al. 2007). This estimate was surprisingly large because a recent or rapid growth in population size cannot explain the abundance change (Heide-Jørgensen et al. 2007). One possible explanation is that the population, which demonstrates high age and sex segregation, has recently attained a certain threshold size elsewhere, and a higher abundance of mature females appears on the winter and spring feeding ground in West Greenland (Heide-Jørgensen et al. 2007). This in combination with the latest severe reduction in sea ice facilitating access to coastal areas might explain the surprising increase in bowhead whale abundance in West Greenland (Heide-Jørgensen et al. 2007).

### **5.6.3.2 Area of future concerns**

Indirect effects of climate change include regional or seasonal shifts in prey availability, which can affect nutritional status and reproductive success, alter the timing or patterns of migrations, and cause changes in distribution and population structure (Laidre et al. 2008). For example, Inuit in the high Arctic report that bowheads are now moving farther west in Barrow Strait in the summer with the retreat of the ice edge (COSIMO 2009).

It is unclear how the loss of sea ice will affect bowhead whales, with some projections of increased food availability and some of less availability. Bowhead whales might benefit from any increased productivity that might be associated with more open water in their current summer foraging habitats (Moore and Laidre 2006). A study reported in George et al. (2006) showed that landed bowheads landed between 1982 and 1999 had better body condition during years of light ice cover (Laidre et al. 2008). Local increases in primary production due to reduced sea ice cover in the eastern Beaufort Sea (improved feeding opportunities) have been hypothesized as the reason for improved body condition (Laidre et al. 2008). This, together with high calf production in recent years, suggests that the stock is currently tolerating the recent ice-retreat (Angliss and Allen 2009, Moore and Huntington 2008).

Increased food availability and more open water may be attracting sub-Arctic species into bowhead whale habitat. Gray whales and bowhead whales have been observed feeding in proximity to one another near Barrow, Alaska from late summer through autumn which was not seen before in the 1980s (Moore et al. 2010). It appears that gray whales are delaying their southbound migration and expanding their feeding activity along the migration route, with some overwintering northeast of Barrow in 2003-04 (Moore et al. 2010). It is not clear how increased competition for food may affect bowheads.

Alternatively, some project that there will be less available food for bowheads. In the high Arctic, a seasonal bloom of phytoplankton starts during the spring melt as algae on the underside of sea ice are mobilized into the surrounding water column (Alexander 1995). Ice-edge habitat thereby generates a restricted zone of high productivity (Sakshaug et al. 1994). Many species of copepods, which are the primary prey of bowheads, reproduce under the ice before the phytoplankton bloom and feed on ice algae (Drolet et al. 1991). With a loss in ice habitat, less ice algae will be produced and this could

result in less food for copepods (COSIMO 2009). Species, including the bowhead, that rely on the ice-edge community for foraging could be adversely affected by a reduction in the areal extent and a latitudinal shift of ice-edge habitat (Tynan and DeMaster 1997).

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