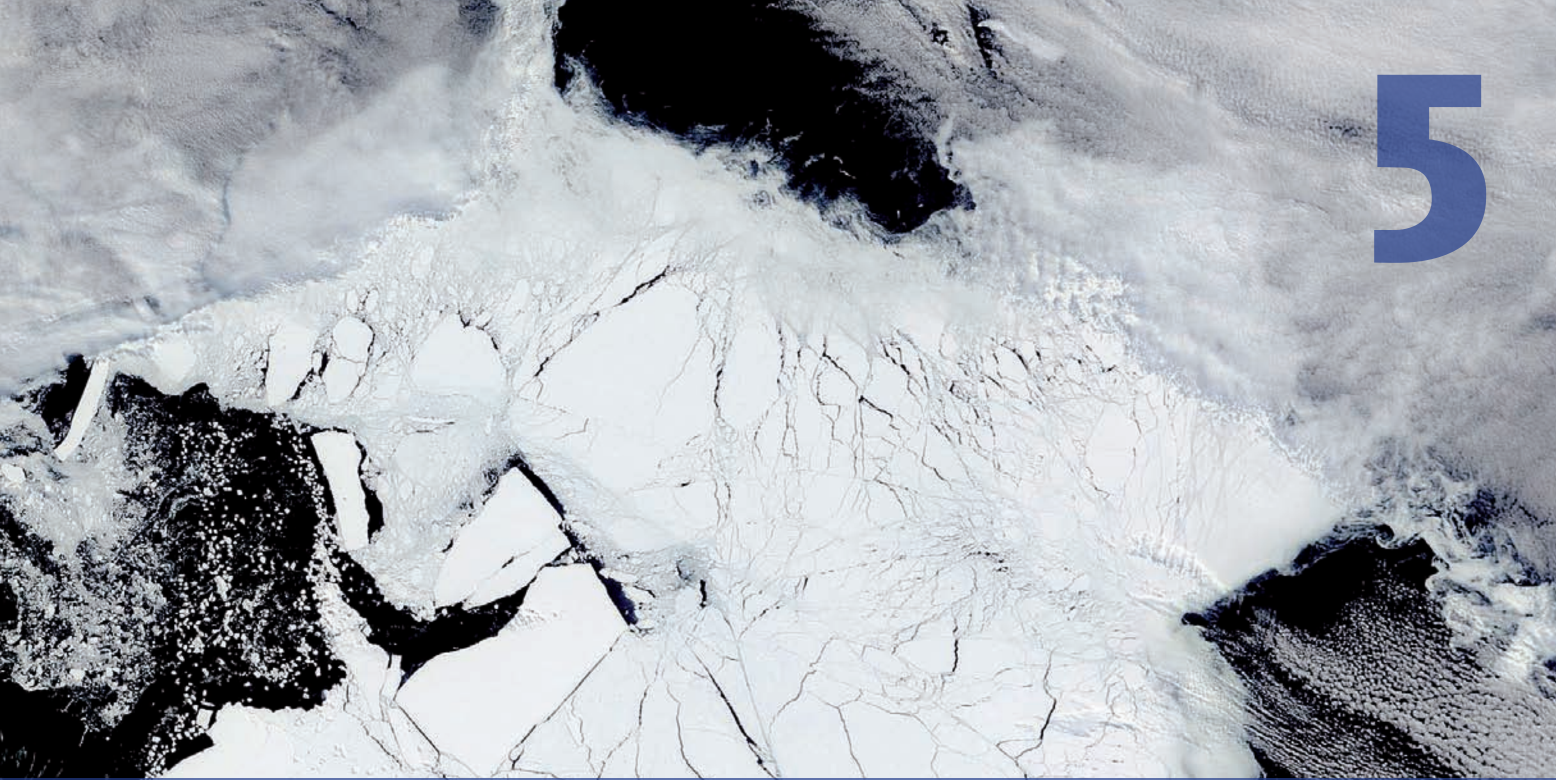


5

Ice in the Sea

Sebastian Gerland (lead author, Norwegian Polar Institute, Tromsø, Norway); **Jon Aars** (Norwegian Polar Institute, Tromsø, Norway); **Tom Bracegirdle** (British Antarctic Survey, Cambridge, UK); **Eddy Carmack** (Fisheries and Oceans, Canada, Institute of Ocean Sciences, Sidney, BC, Canada); **Haakon Hop** (Norwegian Polar Institute, Tromsø, Norway); **Grete K. Hovelsrud** (CICERO: Centre for International Climate and Environmental Research, Oslo, Norway); **Kit Kovacs** (Norwegian Polar Institute, Tromsø, Norway); **Christian Lydersen** (Norwegian Polar Institute, Tromsø, Norway); **Don K. Perovich** (U.S. Army ERDC – Cold Regions Research and Engineering Laboratory, Hanover, NH, USA); **Jackie Richter-Menge** (U.S. Army ERDC – Cold Regions Research and Engineering Laboratory, Hanover, NH, USA); **Stine Rybråten** (CICERO: Centre for International Climate and Environmental Research, Oslo, Norway); **Hallvard Strøm** (Norwegian Polar Institute, Tromsø, Norway); and **John Turner** (British Antarctic Survey, Cambridge, UK)

Ice in the Sea

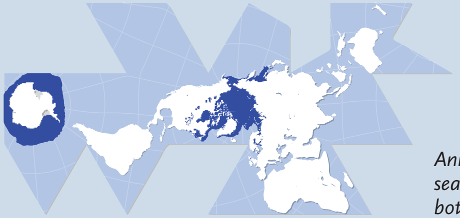
Source: NASA

Summary

Sea ice plays a key role for climate and is important as habitat and for human activities and economies. Observations show and models indicate that climate and sea-ice regimes are changing. Sea-ice extent in the Arctic decreased substantially during the last 30 years; Antarctic sea ice is decreasing in some areas, but overall it has shown a slight increase during this period. Climate models project further decreases in sea-ice extent in the Arctic during this century and comparable decreases in Antarctic sea-ice extent. There are uncertainties attached to the rate at which these changes will occur, and there is a risk of tipping points being crossed and abrupt reductions in sea ice occurring. To reduce these uncertainties, more large-scale continuous observations are needed, especially of ice and snow thickness.

Changes to sea ice will have major impacts on both the physical and biological environment at all scales from global to regional. The reduction in albedo (reflection of solar radiation) resulting from less ice cover is a feedback mechanism that accelerates the rate that sea ice declines and also the rate at which Earth warms. Changes in sea ice contribute to altering the ocean thermohaline circulation, especially in the North Atlantic.

Sea ice is a complex environment with a diversity of habitats and seasonal variation to which life in the polar seas is closely adapted. Many species are now being affected by changes in sea ice in the Arctic, and, if the changes continue, there is a strong risk of species extinctions. There is a range of direct consequences of changes in sea ice for economies and human well-being – including threats to indigenous cultures and opening of new sea routes and economic opportunities.



Annual maximum sea-ice extent in both hemispheres

Sea ice: ice found at sea which has originated from the freezing of sea water. Sea ice may be discontinuous pieces (ice floes) moved on the ocean surface by wind and currents, driven together into a single mass (pack ice), or a continuous sheet attached to the coast (land-fast ice).

Sea ice, Arctic and Antarctic (annual minimum ~ maximum):	
Area Covered (million square km)	19 ~ 27
Ice Volume (million cubic km)	0.019 ~ 0.025
Potential Sea-level Rise (cm)	0

Source: IPCC 2007[1a]

Introduction to sea ice

Seen from space, the Earth is dominated by the colours blue, white, and grey-brown. Blue from the ice-free ocean surfaces, white from snow, ice and clouds, and grey-brown from snow-free and ice-free land surfaces. The brighter the colour, the more the sun's rays are reflected back into space, and the less the Earth warms up. An important part of the Earth's white surface area is sea ice.

In the Arctic, winter sea ice extends over an area of approximately 15 million km^2 at its peak in March and up to 7 million km^2 in September, at the end of the summer melt season. Corresponding numbers for the Southern Ocean

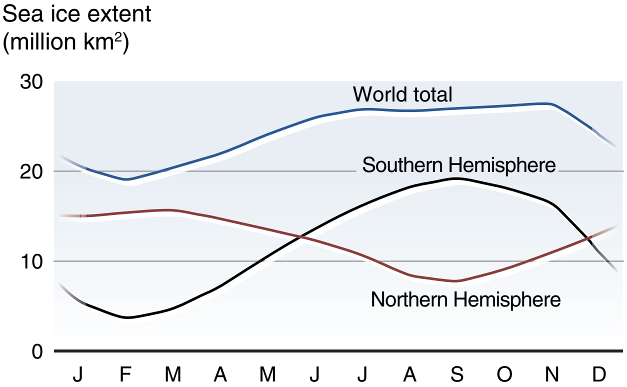


Figure 5.1: Monthly average variations in sea-ice extent in total and in both hemispheres.

Source: Based on Thomas 2004[1] *(amended from original by J. Comiso, NASA)*

around the Antarctic continent are approximately 3 million km^2 in February during the Antarctic summer and 18 million km^2 at the height of winter in September (Figure 5.1). In regions with seasonal sea ice, the ice cover achieves a thickness varying from less than 1 metre to more than 2 metres, depending on air and water temperatures and other conditions. In regions where ice survives the summer, thicker, multi-year ice is formed. But these conditions are changing. Sea ice has decreased in the Arctic and is projected to decline much more in both polar regions, with consequences to climate, ecosystems and human livelihoods.

Sea ice is extremely important to the climates of the polar regions because of the part it plays in insulating the atmosphere from the huge heat source in the ocean, its role in the formation of bottom water (the densest water found in the ocean, which is extremely important in the circulation of the ocean), and the part it plays in feedback and amplification processes. Snow-covered sea ice is highly reflective and returns a lot of sunlight back to space. In contrast, when sea ice is not present the dark ocean can absorb this heat from the Sun.

Sea ice is home to many ice-associated organisms, from tiny algae and crustaceans to penguins, polar bears and whales. Many organisms in Arctic and Antarctic marine food webs depend on the ice itself or on processes connected with sea ice. And sea ice is important to humans.

It affects transportation routes, navigation and access to resources such as fish and oil in polar waters and in seas with seasonal and periodic ice cover. It is crucial to the livelihoods and cultures of coastal Arctic indigenous people.

People have been studying sea ice for millennia, from Arctic indigenous people who continue to study and adapt to sea-ice conditions as part of their daily lives, through 16th century commercial whalers, to the early polar scientific researchers of the 19th century (Figure 5.2). During the 20th century scientific research on sea ice became more sophisticated, with ship expeditions and ice drifting stations (mostly Russian) in the Arctic and various expeditions to Antarctica. Modern polar research is supported by ships or land-based stations with advanced instrumentation, satellite observations and moorings as well as advanced modelling. During the International Polar Year (2007–2008) research activity is aimed at improving understanding of sea ice, its interaction with atmosphere and ocean, its role in marine ecosystems, and the consequences of changes in sea ice brought about by global warming.

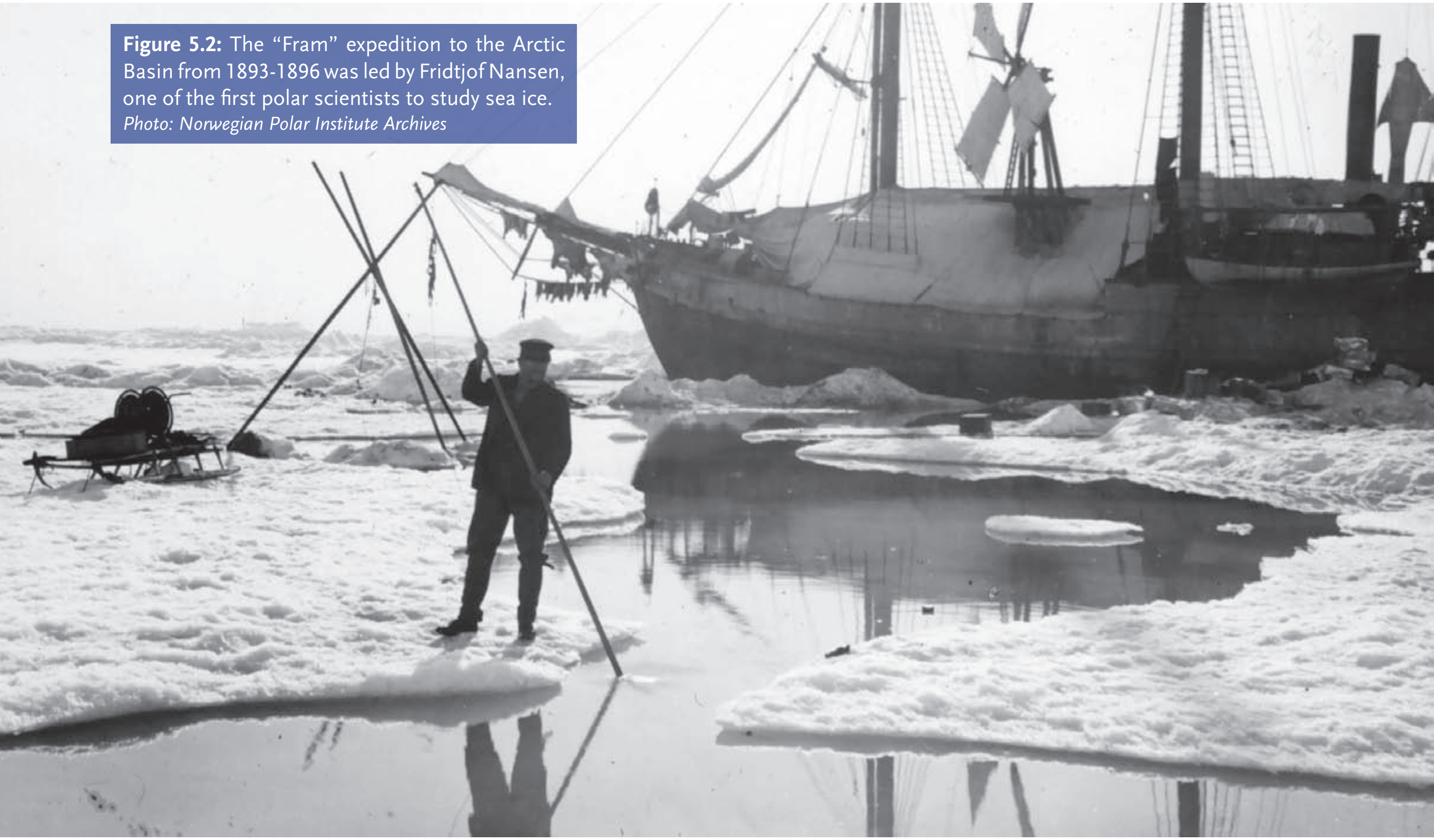


Figure 5.2: The "Fram" expedition to the Arctic Basin from 1893-1896 was led by Fridtjof Nansen, one of the first polar scientists to study sea ice. *Photo: Norwegian Polar Institute Archives*

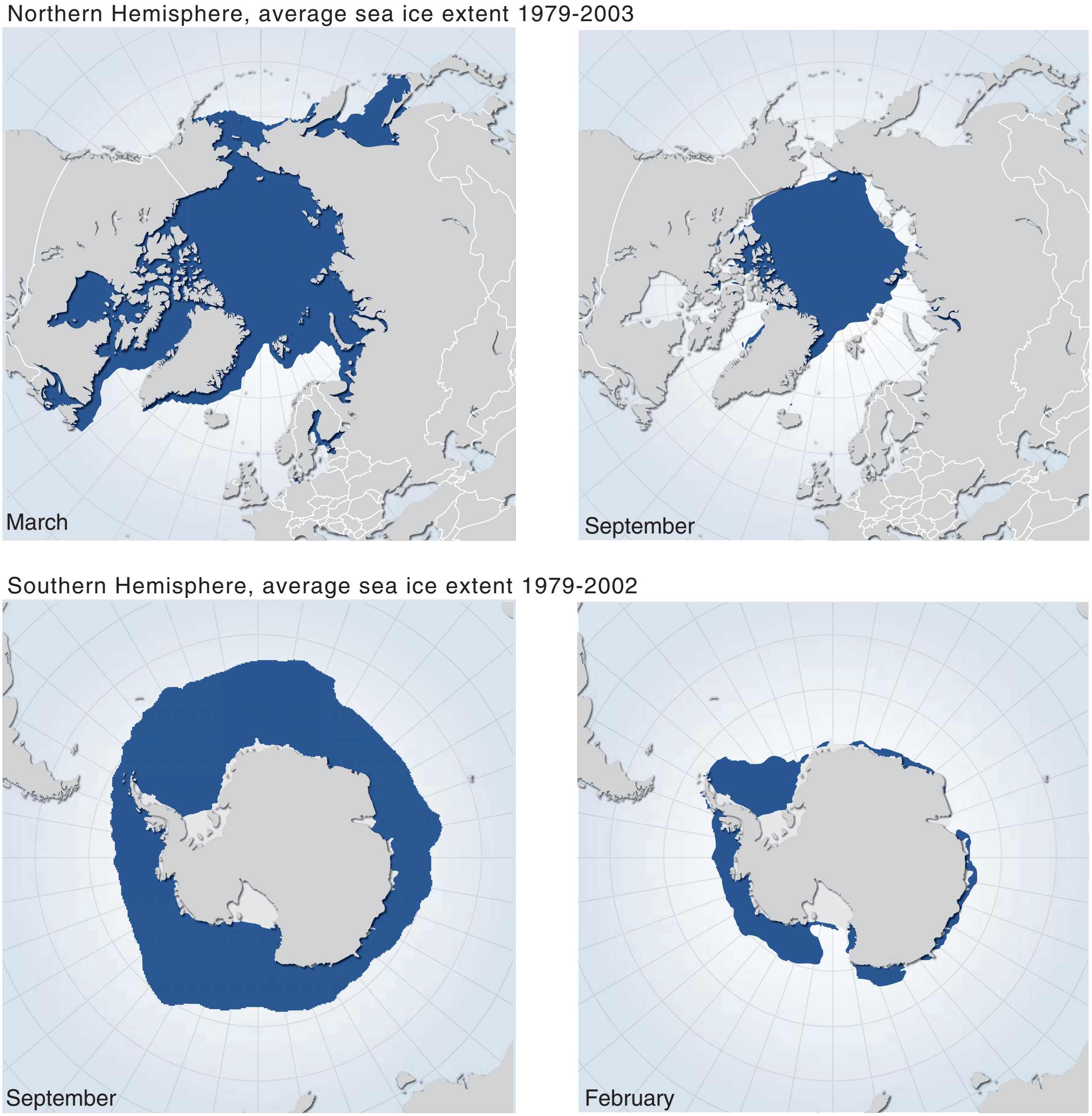


Figure 5.3: Maps of average sea-ice extent in the Arctic summer (September) and winter (March), and in the Antarctic summer (February) and winter (September). They represent average sea-ice extent from 1979 to 2002/2003, based on passive microwave satellite observations. The two polar regions are drawn to the same scale.

Source: Based on Stroeve and Meier 1999 updated 2005[3] (Antarctic); Armstrong and Brodzik 2005[4] (Arctic)

Trends in sea ice

Passive microwave sensors on satellites have monitored the extent of the sea-ice cover since 1978[2]. This technique is widely used to investigate fluctuations in ice extent over the seasons, variability between years, and long-term trends. The seasonal variation of ice extent is much greater in the Antarctic where there is about six times as much ice in winter as in summer. Currently, in the Arctic, ice approximately doubles from summer to winter. Figure 5.3 shows the average minimum and maximum extents of Arctic and Antarctic sea ice in recent decades.

Northern Hemisphere trends

Despite considerable year-to-year variability, significant negative trends are apparent in both maximum and minimum ice extents, with a rate of decrease of 2.5 per cent per decade for March and 8.9 per cent per decade for September[5–7] (Figure 5.4).

There are major regional differences (Figure 5.5), with the strongest decline in ice extent observed for the Greenland Sea (10.6 per cent per decade). The smallest decreases of annual mean sea-ice extent were found in the Arctic Ocean, the Canadian Archipelago and the Gulf of St. Lawrence. In the marginal Arctic seas off Siberia (the Kara, Laptev, East Siberian and Chukchi Seas) a slight negative, but not significant, trend in ice extent was observed between 1900 and 2000[8].

Figure 5.6 compares the Arctic sea-ice extent in September for the years 1982 (the record maximum since 1979) and 2005 (the record minimum). The ice extent was 7.5

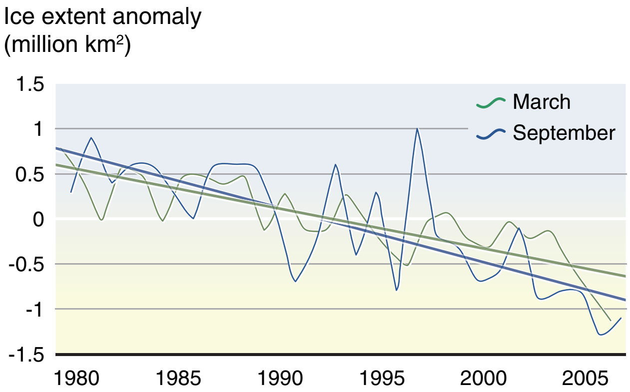


Figure 5.4: Time series of the difference in Arctic sea-ice extent in March (maximum) and September (minimum) from the mean values for the time period 1979–2006. Based on a linear least squares regression, the rate of decrease in March and September was 2.5% per decade and 8.9% per decade, respectively.

Source: Data courtesy of National Snow and Ice Data Center (NSIDC)

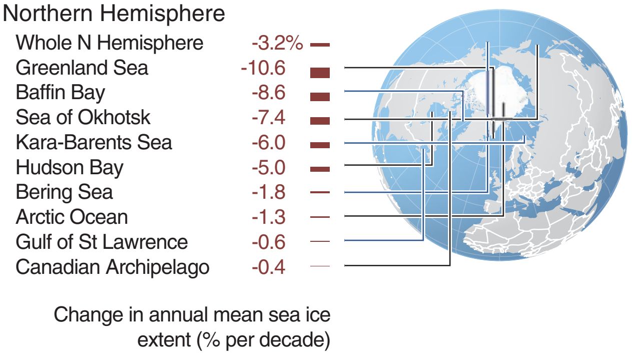


Figure 5.5: Regional changes in Arctic annual mean sea-ice extent (% per decade) for the period 1979–2004.

Source: Data courtesy of NASA 2007a[9] million km^2 in 1982 and only 5.6 million km^2 in 2005, a difference of 25 per cent. As has been observed in other recent years, the retreat of the ice cover was particularly pronounced along the Eurasian coast. Indeed, the retreat was so pronounced that at the end of the summer of 2005 the Northern Sea Route across the top of Eurasia was completely ice-free (see section below on shipping and tourism).

Ice extent is only part of the equation. To assess changes in ice cover it is also important to look at ice thickness – however ice thickness is difficult to monitor and measurements are much more limited. Satellite-based techniques have only recently been introduced and there is no comprehensive record of sea-ice thickness. There are many datasets of ice thickness from measurements taken opportunistically, including holes drilled through the ice, observations from ships, upward-looking sonars moored at the sea floor[10], and above-ice surveys using laser techniques and electromagnetic sensors[11].

The most comprehensive source of ice-thickness observations were the sonar profiles made from submarines cruising under the Arctic ice cover from the 1950s to the 1990s. These observations were made irregularly, but researchers were able to group them for comparison into seven regions and into two time periods. Rothrock and others[12] concluded from these records that a substantial thinning of the ice occurred in several regions between the period 1956–1978 and the 1990s, with an overall 40 per cent decrease in thickness from an average of 3.1 m to 1. 8 m. Other later publications dealing with analyses of submarine-based sonar data conclude that the thinning rates may have been less than this[13,14].

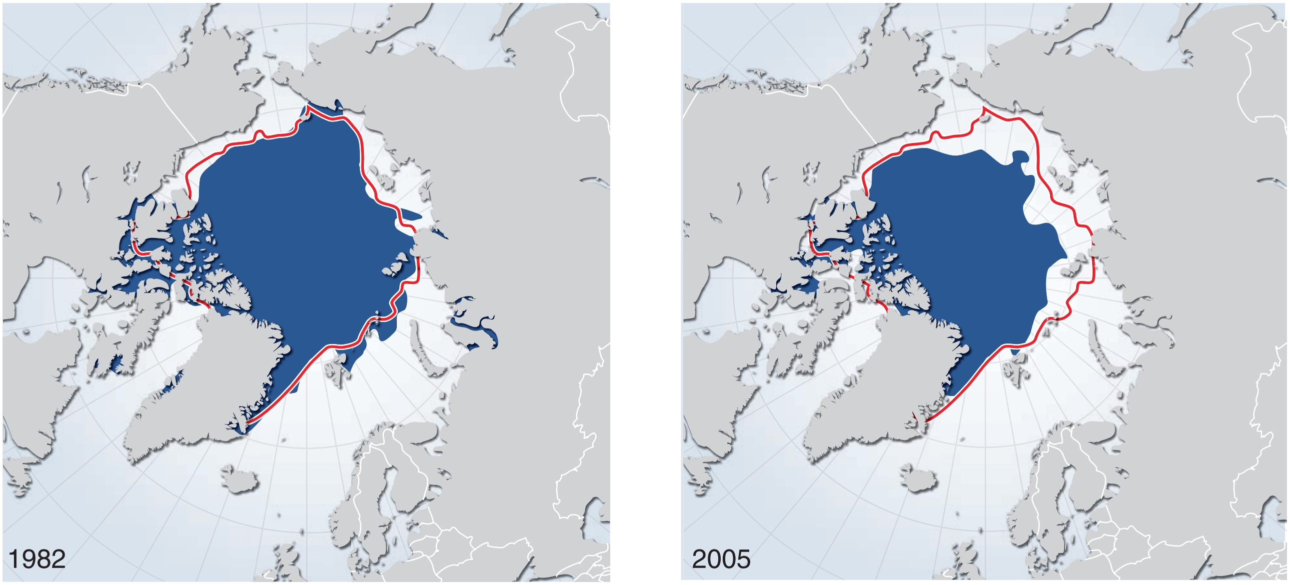


Figure 5.6: Arctic sea ice minimum extent in September 1982 and 2005. The red line indicates the median minimum extent of the ice cover for the period 1979–2000. The September 2005 extent marked a record minimum for the period 1979–2006.

Source: Data courtesy of National Snow and Ice Data Center (NSIDC)

Thickness of land-fast ice is monitored from coastal sites in Arctic Canada, Svalbard and Siberia[8,15,16]. Most sites show large variations among years and among decades. Data extending back to 1936 from sites off the coast of Siberia show, in general, no significant trends up to 2000[8]. Consistent observations at Svalbard do not go that far back in time, but monitoring during the last decade showed that during the warmer-than-normal winters of 2005/2006 and 2006/2007 the land-fast ice in most Svalbard fjords was less extensive, thinner and lasted for a shorter time than normal.

The age of sea ice in the Arctic is also changing. Studies show that in recent years there is a higher proportion of younger ice to older ice than was observed in the late 1980s[6] (Figure 5.7).

Southern Hemisphere trends

In contrast to the Arctic, there are signs of a slight increase in the extent of annual mean sea ice over the period 1979–2005 (+1.2 per cent per decade) based on the NASA Team retrieval algorithm[18]. The IPCC[20] concluded that this overall increase was not significant and that there are no consistent trends during the period of satellite observations. There are, however, indications that sea ice may be increasing more at the period of minimum coverage (March) than at the period of maximum sea-ice extent in September. There is also regional variation (Figure 5.8) with an increase, for example, in the Ross Sea (+4.8 per cent per decade) and a loss in the Bellingshausen Sea (–5.3 per cent per decade).

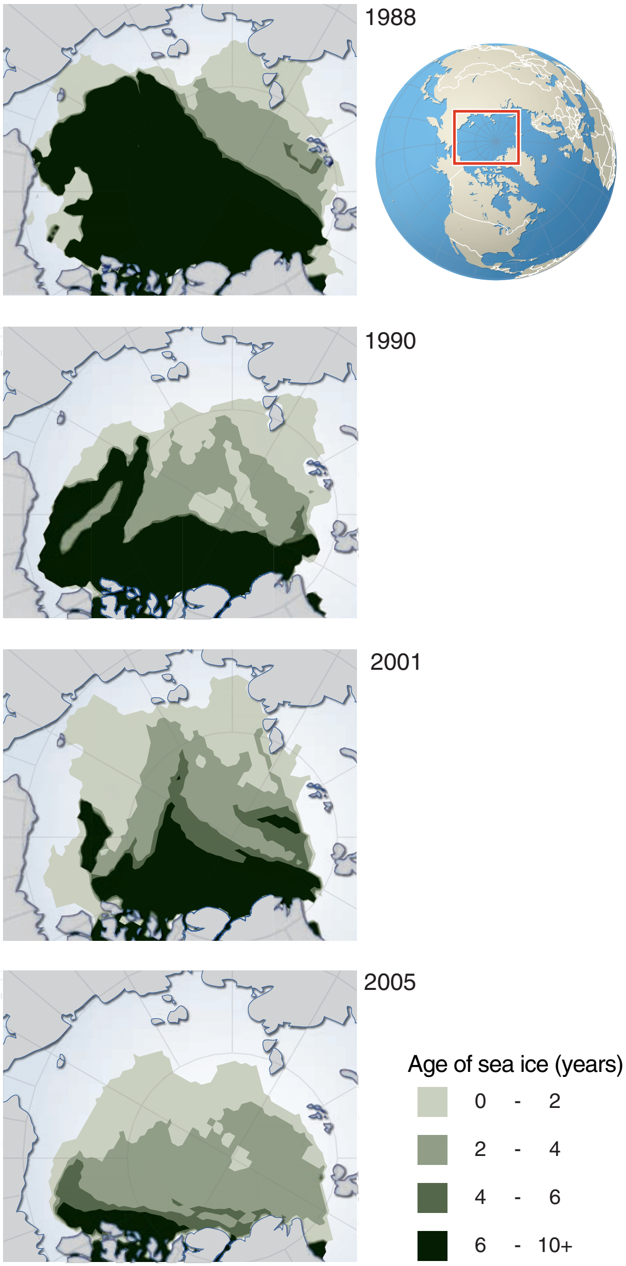


Figure 5.7: Change in the age of ice on the Arctic Ocean, comparing September ice ages in 1988, 1990, 2001 and 2005. This analysis is based on results from a simulation using drifting buoy data and satellite-derived ice-concentration data[17]. The darker the colour, the older the ice.

Source: Based on Richter-Menge et al. 2006[6]

Antarctic sea ice.
Photo: Mlenny/iStockphoto.com

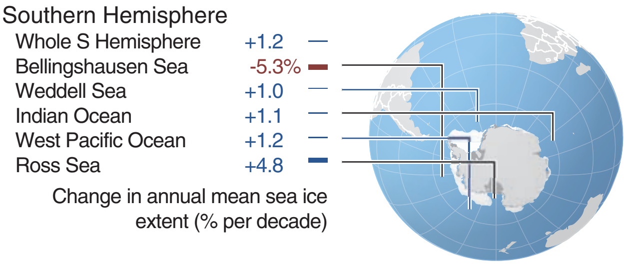


Figure 5.8: Regional changes in Antarctic annual mean sea-ice extent (% per decade) for the period 1979–2004.

Source: Data courtesy of NASA 2007a[9]

There are far fewer observations of sea-ice thickness for the Antarctic than for the Arctic because of the lack of submarine measurements. It is therefore not possible to detect any trends in Antarctic sea-ice thickness over recent decades.

The reasons for the very different trends in Arctic and Antarctic sea-ice extent over recent decades are not known at present and resolving this important question is a high research priority. Researchers are examining changes in the atmospheric circulation of the two polar regions as well as changes in ocean circulation.

Outlook for sea ice

Northern Hemisphere

Climate models project a continuing decrease of ice extent in the Arctic[19,20] accompanied by thinning of the ice. The most dramatic change, projected by about half the current climate models developed as part of the IPCC assessment report 4 (AR4), is a mainly ice-free Arctic Ocean in late summer by 2100 (Figure 5.9 upper right). The projected change in the winter is smaller: 15 per cent decrease in sea-ice extent (Figure 5.9 upper left). The annual average decrease projected is 25 per cent by 2100. These seasonal differences will result in increased amplitude of the seasonal cycle of sea-ice extent (greater differences between seasons). A model that examines sea-ice volume projects that it will decrease even more than the ice extent, with reductions of annual means of about 60 per cent by 2100[21].

In the transition zone between high Arctic and subarctic, and in the subarctic, where seasonal ice dominates now (including the Barents, Baltic, Bering and Okhotsk Seas), expected trends are: reduced ice extent, shorter ice seasons and thinner ice. More frequent winter warm spells may also result in snow melting and refreezing as superimposed ice. The two most recent northern winters (2005/2006 and 2006/2007) were warmer than normal in the European Arctic and several of these effects were clearly visible in, for example, the Barents Sea and the Baltic Sea.

Southern Hemisphere

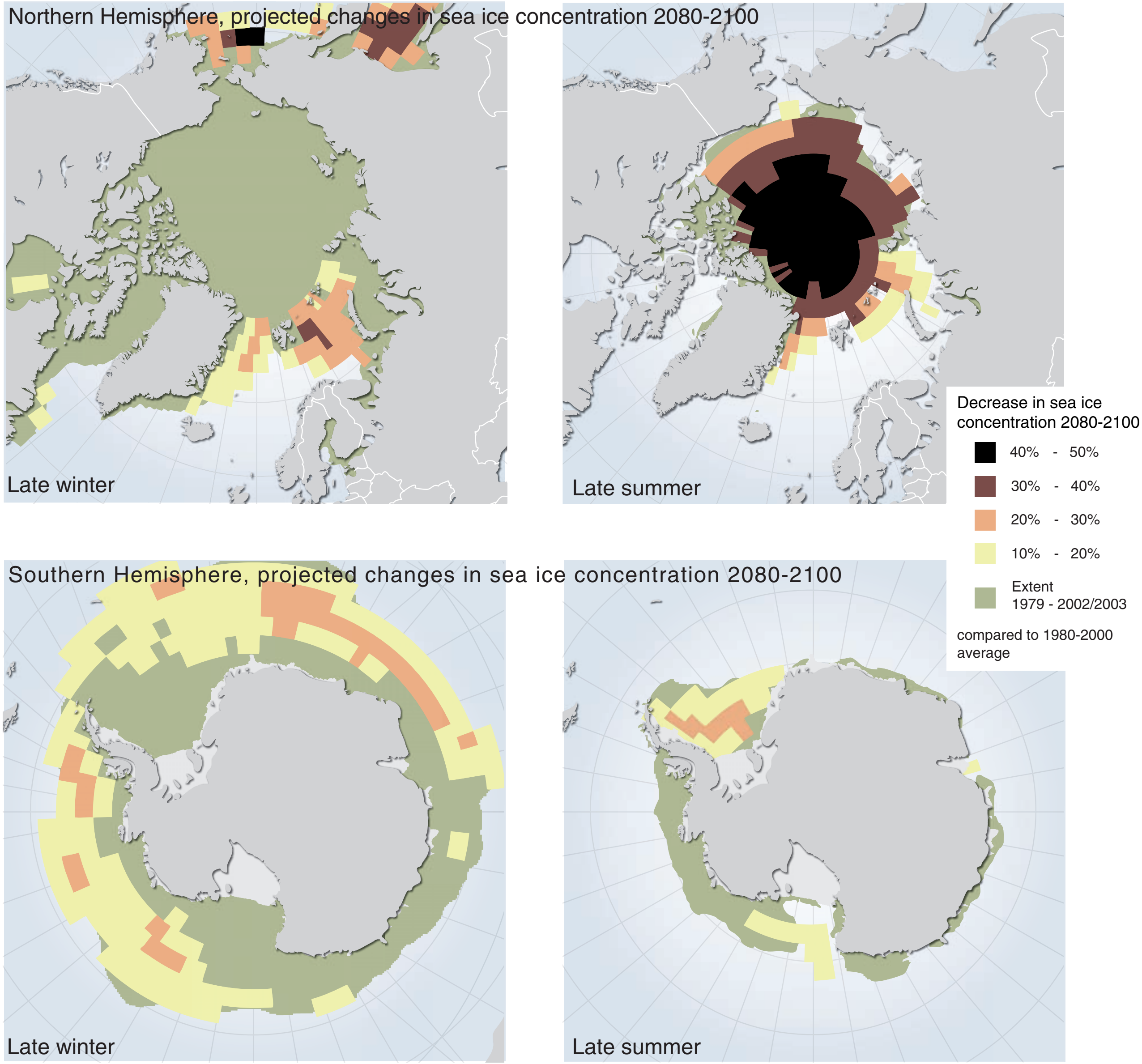
Around Antarctica the projected annual average decrease of sea-ice extent is similar to the Arctic, at around 25 per cent by 2100. Both polar regions show the largest percentage changes in late summer (Figure 5.9 upper and lower right) and an increase in the amplitude of the annual cycle. However, in Antarctica the projected change in sea-ice volume of around 30 per cent is about half the value projected for the Arctic, and the increase in amplitude of the seasonal cycle is also less pronounced[21]. The difference in sea-ice volume change can be explained by the finding that the most rapid thinning of sea ice occurs in regions of thicker ice. On average the sea ice over the Arctic is thicker than around Antarctica at present.

Sea-ice retreat: potential for tipping points and enhanced rates of change

There is evidence for the occurrence of tipping points in the future, manifested as periods of abrupt decrease of Arctic sea-ice occurrence[22]. These abrupt changes may result when the ice thins and the rate of retreat becomes more rapid for a given melt rate. Typically they would

▶ **Figure 5.9: Sea-ice concentration change over the 21st century as projected by climate models.** The data are taken from climate model experiments of 12 (out of 24) different models that were conducted for the IPCC Assessment Report 4 using the SRES A1B greenhouse gas emission scenario. Plots on the right show changes in late summer and those on the left show changes in late winter.
Notes:
1) Sea-ice extent is the area in which a defined minimum of sea ice can be found. Sea-ice concentration is the proportion of the ocean area actually covered by ice in the area of the total sea-ice extent.
2) Small ocean inlets, such as those in the Canadian Archipelago, while not showing a decrease on these plots, are also expected to experience a decrease in sea-ice concentration – this is an issue related to the resolution of the climate models.

Source: Based on data from T. Bracegirdle, British Antarctic Survey


Northern Hemisphere, projected changes in sea ice concentration 2080-2100
Late winter
Late summer
Decrease in sea ice concentration 2080-2100
40% - 50%
30% - 40%
20% - 30%
10% - 20%
Extent 1979 - 2002/2003
compared to 1980-2000 average
Southern Hemisphere, projected changes in sea ice concentration 2080-2100
Late winter
Late summer

occur over a period of five to ten years, during which time almost all the summer ice can disappear. There are indications that abrupt reductions early in the 21st century could result in a largely ice-free Arctic in the summer as early as 2040[23]. However, most current climate models do not project that the Arctic will be free of ice in summer this early in the century, so there is still significant uncertainty over this issue.

Another mechanism for enhanced Arctic sea-ice retreat, although not for abrupt changes, is linked to the transition from perennial to seasonal sea ice, which introduces new regions to seasonal sea-ice cover. Increased seasonal production and loss of sea ice along the Siberian Continental Shelf appears to be one explanation for an enhanced ocean heat transport into the Arctic Ocean from the Atlantic Ocean[24]. This enhanced heat transport is a positive feedback since it contributes to the further loss of sea ice. As most of the sea ice around Antarctica is already seasonal, this mechanism is only relevant to the Arctic.

Global significance of sea-ice changes

Changes in patterns of sea-ice formation and melting have widespread influences, including on global climate and ocean circulation patterns. Ocean circulation is driven partly by gradients in the density of water (known as thermohaline circulation, described in Chapter 2). Sea water density is determined by heat (“thermo-“) and salinity (“-haline”). Most of the salt from the water that freezes is added to the water mass below the sea ice. This process leads to an increase of salinity in the surface water in locations where sea ice forms and to freshwater

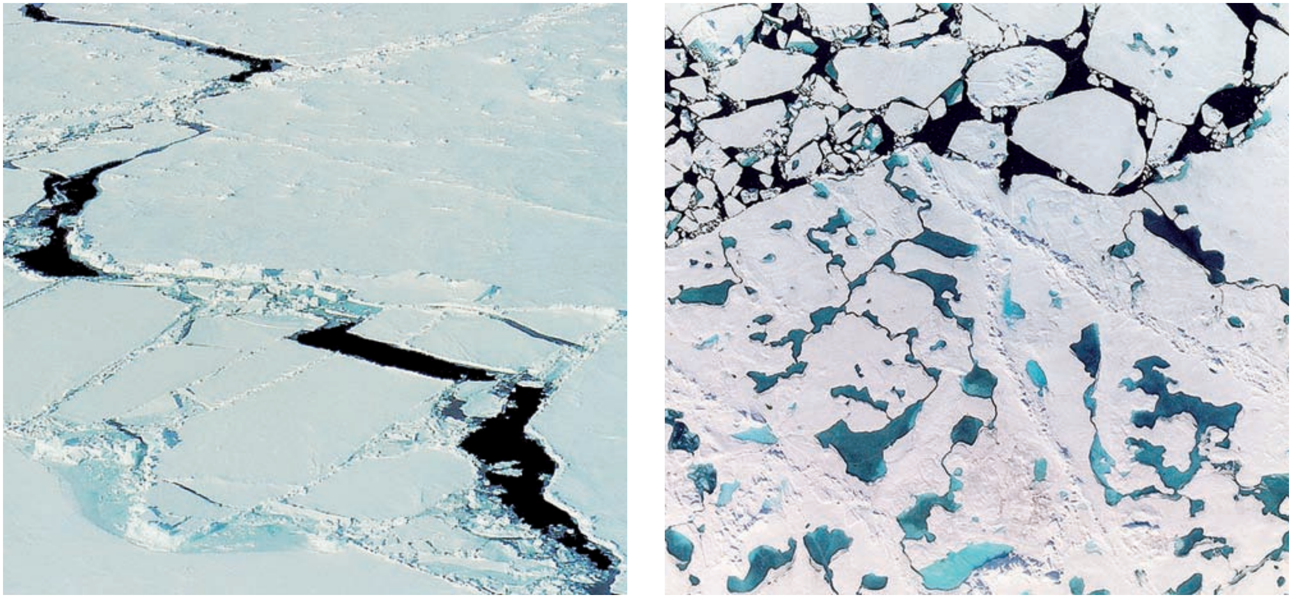


Figure 5.10: Aerial photographs of the Arctic sea-ice cover prior to melt (left) and during the summer melt season (right).
Photos: Don Perovich

input to surface waters in locations where sea ice melts. This means that a significant volume of fresh water is exported as sea ice through Fram Strait and the Canadian Archipelago – this is a major component of the North Atlantic Ocean's salt balance. Changes in sea-ice export will impact both the thermohaline circulation and the location where the warm but relatively salty northward flowing North Atlantic Current sinks beneath the cold but relatively fresh surface water and flows into the Arctic basin (see Figure 2.1 in Chapter 2).

Changes in sea-ice cover are also significant on a global scale because of the potential to amplify climate change through positive feedback mechanisms[25,26]. A key mechanism is the ice–albedo feedback[27]. Albedo is a simple but powerful geophysical parameter. It is simple because it is just the fraction of the incident sunlight that is reflected by a surface. If all the sunlight is reflected the albedo is 1 (or 100 per cent reflection), if none is reflected the albedo equals zero. It is powerful because sunlight is the primary planetary heat source and how much of that sunlight is reflected is a key factor determining climate.

Aerial photographs of Arctic sea-ice cover in spring and in summer are shown in Figure 5.10. The spring photo is representative of much of the year when the surface is a combination of highly reflecting snow-covered ice and highly absorbing dark areas of open water. Conditions become more complex in the summer with a mixture of melting snow, bare ice, ponds, and an overall increase in the amount of open water.

The albedos for these different surface conditions are plotted in Figure 5.11a. They range widely, from roughly 85 per cent of radiation reflected for snow-covered ice to 7 per cent for open water[28,29]. These two surfaces cover the range from the largest to the smallest albedo on earth. Melting snow, bare ice and ponded ice lie within this range. There is a general decrease in the albedo of the ice cover during the melt season as the snow-covered ice is replaced by a mix of melting snow, bare ice, and ponded ice[30]. As the melt season progresses, the bare-ice albedo remains fairly stable, but the pond albedo decreases. During summer the ice cover retreats, exposing more of the ocean, and the albedo of the remaining ice decreases as the snow cover melts and melt ponds form and evolve. These processes combine to form the ice–albedo feedback mechanism (Figure 5.11b).

Impacts of changes in sea ice

Overview

Changes in ice within the Arctic Ocean will also have impacts on Arctic marine ecosystems and three 'tipping points' can be hypothesized[31]: the first would occur if and when the seasonal ice routinely retreats past the edge of the continental shelf, thus allowing wind-driven upwelling which would result in increases in primary productivity; the second would occur if and when the Arctic becomes ice-free in summer, thus eliminating multi-year ice and associated ecosystems; the third would occur if and when significant regions within the Arctic basin remain ice-free in winter, thus impacting the distribution of seasonally migrating marine mammals.

Reductions in ice-cover thickness, extent and duration, and changes in current patterns and fronts will likely have both gradual (predictable) and catastrophic (surprise) consequences[32]:

- bottom-up controls (such as stratification, mixing and upwelling of seawater) will certainly change;
- keystone predators within a given region may move into the region, move away from the region, or become extinct; and
- linkages between the open ocean ecoystems and the ocean bottom ecosystems may weaken.

Arctic shelf ecosystems are likely to be more sensitive to climatic perturbations than those of temperate shelf areas because a greater degree of warming is expected and because these ecosystems are characterized by comparatively simple food webs and low biodiversity (meaning that loss of one part of the food web has greater consequences).

In the remainder of this chapter we discuss sea ice in relation to ocean and climate processes, summarize the impacts of observed and projected changes on polar marine biodiversity and ecosystems, and look at how both the physical ice changes and the changes in ice-related ecosystems are affecting human economies and well-being.

Sea ice as a dynamic, complex environment

When observers aboard a ship watch ice floes drifting through Fram Strait (the area between Greenland and Svalbard) they can assume that each piece of ice has a long history. Sea ice that ends up in Fram Strait (and most multi-year ice that exits the Arctic Ocean flows through Fram Strait) often originates from the Siberian

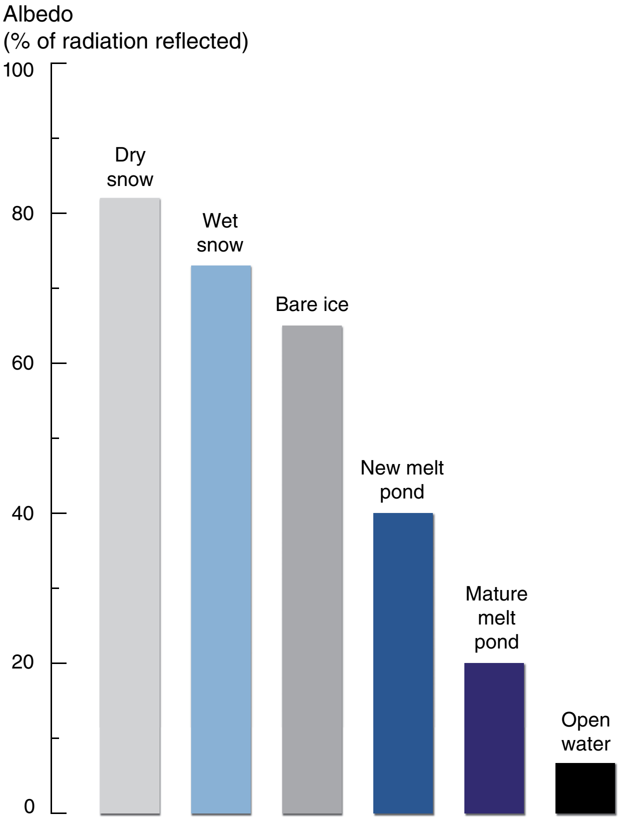


Figure 5.11a: Albedos of basic thick sea-ice surface types.

Source: Based on Pegau and Paulson 2001[28]; Perovich and others 2002[29]

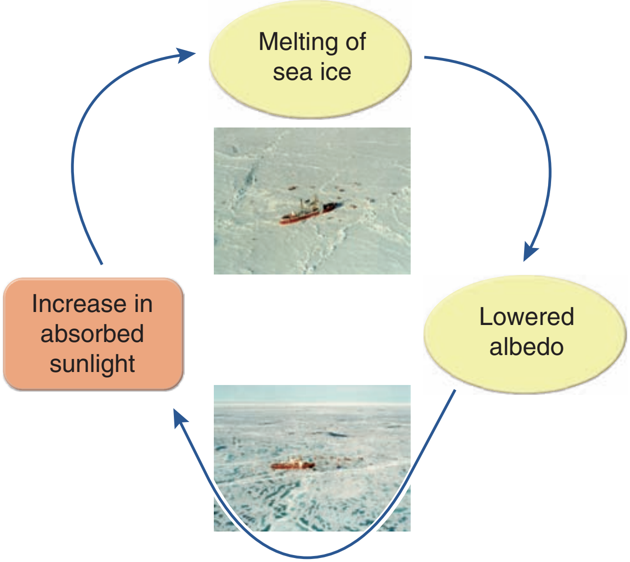


Figure 5.11b: Schematic illustrating the ice–albedo feedback. In spring, the ice is snow-covered and there is very little open water. Most sunlight is reflected, but some is absorbed. This absorbed sunlight leads to melting, which in turn reduces the ice albedo and increases the amount of open water. This causes the albedo to further decrease, increasing the rate of heating and further accelerating melting.

Source: Based on material from D.K. Perovich

Sea-ice research: making sense of sea-ice observations

Cold air, cold water and calm conditions are needed for sea ice to form. Observed changes in ice abundance and thickness can point towards changes in any of these environmental conditions. Ice thickness can also increase due solely to ice dynamics when ice is extensively rafted and ridged.

The fact that pack ice drifts and is constantly changing location makes the interpretation of changes in sea ice in relation to climate change even more difficult, as the following example illustrates. If sea-ice floes start to drift from the East Siberian Sea to Fram Strait at a faster rate, the thickness of the ice for a given temperature history will change because the ice has less time to grow. If the drift speed stays as it was, but the environmental temperature rises, the thickness of the ice will be also less. And, as a third scenario, if snowfall increases and freezing and melting conditions are changed the thickness will be affected. This illustrates how important the physical parameters of the atmosphere and ocean are for the sea ice and for the analysis of sea-ice observations.

Sea-ice research in the Fram Strait.
Photo: Sebastian Gerland, Norwegian Polar Institute

Sea-ice research: International Polar Year and looking to the future

Research on sea ice is a strong focus in the programme of the International Polar Year (2007-2008), with many nations combining resources and expertise to collaborate on large-scale studies aimed at furthering understanding of sea ice, oceans and the atmosphere. These research campaigns involve integration of in situ observations and use of modern technology (automatic sensors, autonomous drifters and floats, and satellites), along with improved climate modelling.

Further development of satellite sensor technology is underway, and this should soon result in higher accuracy and better spatial and temporal resolution of measurements[33,34]. The new ice-specialist satellite CryoSat-2 (Figure 5.12), to be launched in 2009, and new developments beyond that, will hopefully lead to a much better capacity to observe and understand the status of Arctic and Antarctic sea ice and the processes and factors controlling it.

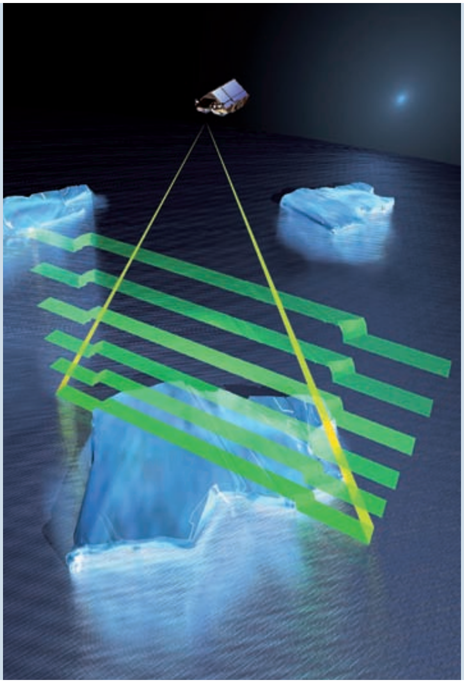


Figure 5.12: CryoSat-2, artist's impression. CryoSat-2, to be launched in 2009, will improve monitoring of ice thickness. Its altimeter measures distances to sea ice and open water and the difference between the two is used to derive ice thickness

Illustration: ESA – AOES Medialab

shelf seas, the East Siberian Sea and the Laptev Sea. There, sea ice forms during the Arctic autumn and winter, grows thicker and joins the transpolar drift towards and over the North Pole. Finally, after some two to seven years, the ice floe enters Fram Strait. This transport of ice influences, among other things, the processes governing ocean circulation and the flow of nutrients in Arctic marine ecosystems.

Many factors influence the formation, evolution and degradation of sea ice. Monitoring and research is underway to improve understanding of these factors, how they are linked, and the influence of climate change (see boxes on sea ice research).

Large parts of the Arctic are characterized by complex, multi-year ice[35]. During Arctic summers, ponds form as snow melts on the ice surface. In autumn the melt ponds freeze over, snow falls on the surface and new ice forms at the underside of the ice floe. Individual floes freeze together to form larger floes. Rafting and ridging occurs (Figure 5.13) and leads (narrow channels of open water) are formed. Ridges, which can be several metres high, and ice keels, which can extend more than 20 m below sea level, affect wind drag and water drag. Dust and sediments are incorporated into snow and ice through atmospheric and oceanic processes, and ice algae and other organisms colonize the brine channels and the under-sides of ice floes.

In the Southern Hemisphere sea-ice conditions are very different. The Southern Ocean surrounds the Antarctic continent, in contrast to the Arctic Ocean, which is surrounded by land. Since the highest latitude areas in the south are land covered, Antarctic sea ice is on average further away from the South Pole than is Arctic sea ice from

Figure 5.13: Several metre-high pressure ridge on a multi-year sea ice floe in Western Fram Strait. *Photo: Sebastian Gerland, Norwegian Polar Institute*

the North Pole. During the Antarctic summers, most sea ice breaks up, drifts northward and eventually melts. Consequently, most Antarctic sea ice is first-year ice.

Snow plays an important role in the formation and nature of sea ice in both polar regions, and changes in patterns of precipitation, both as snow and as rain, will have impacts on sea ice. Young ice without a snow cover thickens faster than young ice with an insulating snow cover. Snow properties such as grain shapes and sizes influence the snow's albedo, and the extent and properties of snow are the dominating factors controlling how much energy in the form of solar radiation reaches the ice. Snow can also contribute to the ice mass through transformation into ice. Superimposed ice forms when mild weather melts snow at the surface, or when rain falls. Water percolates downwards through the snow cover and reaches the snow–ice transition zone where it is cold enough that the snow-water mixture freezes. Snow can also be added to ice when seawater seeps into the snow–ice transition through cracks in the ice or from the side of an ice floe, resulting in "snow ice".

Changes in wind strength and wind patterns would also affect many characteristics of sea ice. More wind or more extreme wind events would lead to more ice rafting and ridging and increased ice thickness in some areas. Changes in winds would especially affect coastal areas. Land-fast ice formation and evolution is highly dependent on winds. Ice conditions in bays, fjords and sounds especially will be substantially different in a climate with different wind patterns than at present.

Marine biodiversity associated with sea ice and implications for food webs

Arctic and Antarctic sea ice provides habitats for a wide range of ice-associated organisms[36]. The diversity of life associated with sea ice is largely dependent on the type and age of the ice. Habitats range in complexity from flat and uniform under-surfaces of newly-formed fast-ice, through relatively flat areas with brine channels in first-year ice, to three-dimensional and often very complex habitats in older, multi-year ice. In the Antarctic, most sea ice is first-year ice, but additional habitat diversity is provided by the small amounts of multi-year ice, extensive ice shelves, and anchor ice in coastal areas.

Changes in these habitats will have many impacts on ice-associated organisms. Impacts on one type of organism in turn have impacts on other organisms through the polar food webs (see box on sea ice and food webs). Some of the consequences of changing sea ice habitat:

- If multi-year ice disappears, long-lived amphipods and the larger ice algae will decline drastically. If summer pack ice disappears in the Arctic Ocean, the ice-associated macrofauna as well as some of their predators will likely vanish from Arctic drift ice.
- The Arctic system will change from ice-dominated to open-water, with enhanced production in the open water but weaker connections between the pelagic and the benthic systems, meaning less food for bottom-dwelling organisms and their predators[37].
- Reduction in ice thickness and extent in the Arctic Ocean is expected to decrease the southward transport of ice-associated organisms on drifting ice, reducing prey availability and carbon input to subarctic seas.
- Changes in the timing of spring may also be important: earlier ice break-up and an earlier onset of the annual bloom in plankton may lead to a temporary mismatch between primary production (algae) and secondary production (the animal life that feeds on the algae) in some areas.
- In the Antarctic, reductions in sea ice may be linked to declines in krill populations, with cascading effects on survival and reproduction of krill predators, such as penguins. However, the relationship between variations in krill stocks and sea-ice extent may be influenced by long-term cyclical patterns as well as climate-induced trends[38–40].

Adelie penguins on sea ice.
Photo: Armin Rose/iStockphoto.com

Sea ice and food webs: complex linkages among ice, oceans and many forms of life

Ice amphipods and polar cod are preyed upon by seabirds and marine mammals[41,42]. The younger polar cod, which can be found in drifting pack ice, are a particularly important and available food source for seabirds and marine mammals feeding in the marginal ice zones[43].

The annual biomass of ice fauna transported with the transpolar ice drift to Fram Strait and the Barents Sea is in the range of a million metric tons[37,44].This biomass is released to the open ocean and ocean bottom systems as the ice melts[45] and is an important source of nutrients.

In the Antarctic, krill represent the primary food source for squid, penguins, some seals and baleen whales, while copepods dwelling in the sea ice are an important food source for adult krill. When krill populations are low, in years following reduced ice extent, salps (gelatinous, barrel-shaped organisms that look rather like jellyfish) are able to exploit the spring bloom of phytoplankton (free-floating algae) and undergo explosive population growth in Antarctic waters[39].

Figure 5.14: The ice alga *Melosira arctica* on the underside of Arctic multi-year sea ice.
Photo: Haakon Hop, Norwegian Polar Institute

Ice algae – the primary producers

Ice algae are the primary producers in ice-associated food webs, and consist primarily of diatoms, but also include other types of algae originating from the pelagic (open-water) system[46,47]. Large strands of the ice diatom *Melosira arctica* (Figure 5.14) are found in Arctic multi-year ice[48]. The algae attach to ice-crystal structures on the underside of Arctic ice[49], whereas in Antarctica, an important feature of the sea ice is the infiltration communities of algae, associated with the nutrient-rich snow–ice interface[50].

Ice algal production may constitute up to 20 to 25 per cent of the total primary production in Arctic waters[46,51] and 10 to 28 per cent of primary production in Antarctic ice-covered waters[1]. In the Arctic, the production of ice algae starts in February and March, about two months earlier than the phytoplankton (free-floating algae) bloom. During the seasonal ice melt, ice algae contribute substantially to the vertical movement of organic matter in the water column and provide food for the invertebrates and fishes living in the depths of the ocean[52]. Areas with extensive ice and algal biomass thus represent “hot spots” with high biomass. These areas can have rich shrimp grounds and abundant clam populations, providing food for marine mammals – for example the walrus, who feed extensively on clams.

Ice fauna – the secondary producers

The smallest animals (less than 1 millimetre) associated with Arctic sea ice include nematode and turbellarian worms, crustaceans and other tiny invertebrates such as rotifers[47]. These organisms feed on algae and microbes[53]. The macrofauna (animals large enough to be seen with the naked eye) in drifting sea ice consist mainly of several species of ice amphipods (Figure 5.15b), but also include polychaete worms and a species of copepod crustacean[54,55]. The abundance and biomass of the macrofauna varies with the type of ice as well as the under-ice topography[54]. Land-fast ice may also house amphipods as well as mysids (another small crustacean)[56] that feed on a mix of ice algae, ice-associated fauna, zooplankton and detritus. Polar cod are often associated with sea ice, where they feed on ice-amphipods as well as the floating zooplankton[57,58].

In the Antarctic copepods are the dominant crustaceans found in the small spaces within the sea ice, but amphipods and krill (the shrimp-like crustaceans that are so important to Antarctic food webs) are also associated with ice[59]. Adult krill are mainly herbivorous, feeding on diatoms, although they have a flexible feeding behaviour and are capable of capturing other types of food from different habitats. Adult krill are generally in open water, but can also be found underneath the ice cover. However, the sea-ice habitat is of most important for larvae and juvenile stages of the krill species *Euphausia superba*. Concentrations up to 3000 individuals per square metre have been observed in under-ice crevices during spring[60]. Sea-ice algae and bacterial assemblages on the underside of ice floes enable the krill larvae to survive the winter months when food in the water column is absent. Sea ice also provides them with an important refuge from predators.

Mammals and birds dependent on sea ice

Marine mammals endemic to polar regions have evolved into specialists that deal extraordinarily well with conditions that would be considered very harsh for most other mammals[61–63]. Their morphology, life history and behaviour patterns are all finely tuned to deal with cold temperatures and the high degree of variation in temperatures and conditions between seasons and from year to year.

The presence of extensive areas of sea ice is of overriding importance to many polar marine mammals. Most of the marine mammals that are year-round residents of the Arctic or the Antarctic spend much of the year in close association with sea ice. Predictions for changes in sea-ice conditions in polar regions due to global warming are a cause for great concern with respect to polar marine mammal populations. Worst case scenarios certainly include the extinction of some species in the coming decades in the Arctic[31,64].

Climate change also poses risks to these polar marine mammals beyond the direct impacts on habitat brought about by alterations to the physical environment. These include[31,65–67]:

- changes to their forage base (such as shifts in the species, density and distribution of prey species);
- increased competition from temperate species expanding northward;

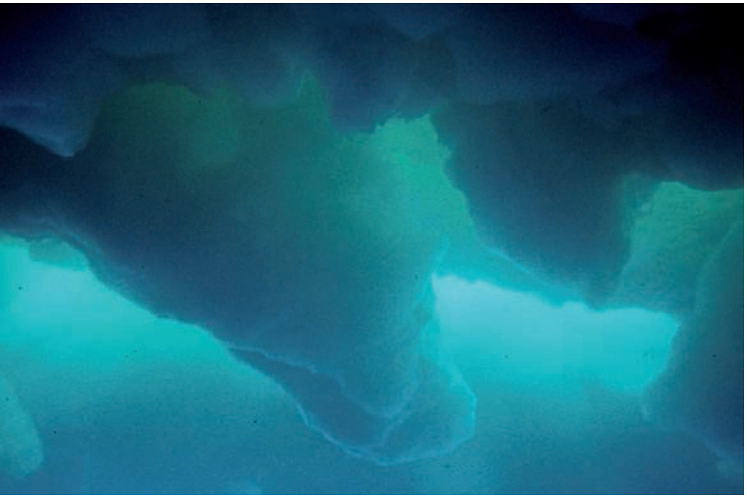


Figure 5.15a: Underside of multi-year sea ice.
Photo: Haakon Hop, Norwegian Polar Institute

Figure 5.15b: *Gammarus wilkitzkiii*, one of the most abundant ice amphipods associated with under-ice habitats.
Photo: Haakon Hop, Norwegian Polar Institute

Weddell seals.
Photo: Michael Hambrey, Swiss-Educ (www.swisseduc.ch) and Glaciers online (www.glaciers-online.net)

- increased predation rates from killer whales (Orcas);
- increased risks from disease and parasites;
- greater potential for exposure to increased pollution loads due to long range transport of pollutants such as PCBs and mercury; and,
- impacts via increased human traffic and development in previously inaccessible, ice-covered areas.

Predicted changes in sea ice in combination with other climate change impacts on Arctic ecosystems, and resultant changes in human activity patterns, will undoubtedly affect the abundance and distribution patterns of species within polar marine mammal communities. The full-time, ice-associated residents of the Arctic and Antarctic are likely going to be negatively impacted, while the seasonal and summer migrants will likely increase in abundance and extend their ranges in a warmer Arctic that is ice-free in summer.

Seals

Many polar seal species depend on sea ice as a birthing, moulting and resting platform, and some seals also do much of their foraging on ice-associated prey[64,68–72]. Ross seals, crabeater seals and leopard seals in the Antarctic and harp seals, hooded seals, ribbon seals, and spotted seals in the Arctic all breed in drifting pack-ice. Arctic bearded seals breed in areas of shallow water along coast-lines on small pieces of ice that break away from the annually-formed land-fast ice in the late spring. Ringed seals in the Arctic and Weddell seals in the Antarctic breed on land-fast ice. These two species occupy extensive areas of ice that form along coastlines because they are able to maintain breathing holes, even in sea ice that can reach 1 to 2 metres in thickness (see box on ringed seals). All of the ice-associated seals require temporally predictable, extensive areas of sea ice. Current projections suggested for the

The "classic" Arctic ice seal in a changing climate

Ringed seals are the "classic" Arctic seal in many regards, being found as far north as the Pole because of their ability to keep breathing holes open in ice that can reach 2 metres in depth. This species is certainly one of the most vulnerable of the high-Arctic seals to the declines in the extent or quality of sea ice because so many aspects of their life-history and distribution are tied to ice.

Ringed seals also require sufficient snow cover on top of the ice to construct lairs for resting, giving birth and caring for their young (Figure 5.16). The pups are born weighing only 4 kg and both ice and snow must be stable enough in the spring season to successfully complete the six week lactation period[73]. Premature break-up of the land-fast ice can result in the pups being separated from their mothers, leading to high rates of pup mortality[74,75]. Spring rains, or high temperatures in spring, can cause the roofs of lairs to collapse, leaving ringed seals subject to increased predation and risks from exposure[76]. Years in which insufficient snowfall takes place prior to breeding results in a similar phenomenon[77].

Ringed seals are the principle prey for the top predator in the Arctic food chain – the polar bear. Declining sea-ice quality, extent and season have potentially dire consequences for both of these Arctic animals.

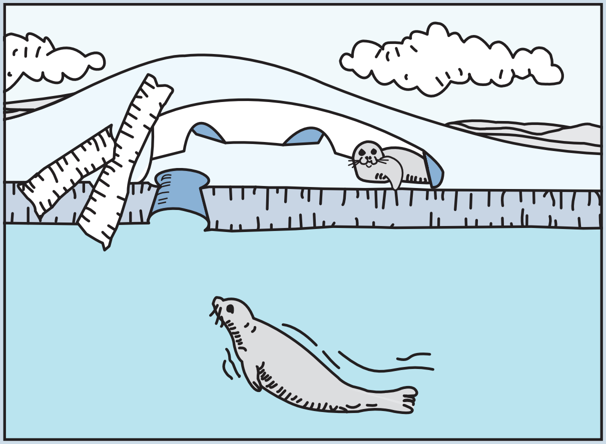


Figure 5.16: Ringed seal pupping lair, with the pup in the lair and the female approaching the haul-out hole from the water. Pups excavate the side tunnels.

Source: R. Barnes, based on Gjertz and Lydersen 1983[78]

rate and extent of decreases in the reach of Arctic sea ice in the coming decades represents major challenges to Arctic seals.

Polar Bears

This largest member of the bear family is a sea-ice specialist. Ice-dwelling seals make up the majority of the polar bear's diet. Like their seal prey their continued existence probably depends on the availability of their primary habitat – the Arctic sea ice. In some parts of the Arctic, polar bears build their maternity dens in snow drifts on multi-year sea ice. In other areas where dens are usually located on islands, the bears are still dependent on the availability of sea ice in the autumn to reach their denning areas and again in the spring when they leave the dens with their cubs and travel to the prime hunting grounds along the northern ice edge.

Concerns regarding the impacts of climate change on polar bears have been voiced since the time of the first suggestions that Arctic sea ice was thinning and becoming reduced in extent and season[79]. Prolongation of the ice-free period was seen immediately as a threat to polar bears. During the past decade it has become increasingly clear that polar bears are already showing declines in body condition and reproductive output that are attributable to physical changes in the southern parts of their range, particular the decline in the duration of the sea-ice season[80–83].

Photo: Jon Aars, Norwegian Polar Institute

Survival rates of both young and older animals are negatively affected during years with little sea ice in western Hudson Bay in Canada[84]. Additional analyses of climate variability in the past across broader parts of the polar bears' range strengthen the case for pessimism regarding the future of polar bears[70,85].

The current situation of polar bears in Hudson Bay, along with the uncertainty regarding their future across the Arctic, led the IUCN (International Union for the Conservation of Nature) Polar Bear Expert Group to suggest upgrading the status of polar bears on the IUCN Red List from "Least Concern" to "Vulnerable"[86]. This has increased pressure to place the polar bear on the United States list of threatened species under the Endangered Species Act. Statements suggesting that the polar bear likely faces global extinction in the wild by the end of this century as a result of global warming are becoming commonplace[87]. While the timing or certainty of extinction is difficult to predict – it is clear that polar bears are "on thin ice".

Ivory gull.
Photo: Georg Bangjord

Whales

In the Arctic a small number of whale species have also become sea-ice specialists. Bowhead whales, white (beluga) whales and narwhals have all "lost" their dorsal fins as an adaptation to ice-living, and live in tight association with sea ice through much of the year.

The actual linkages that bind these species to sea ice are not completely understood, because all three species do spend time in ice-free waters. One commonly-cited suggestion for the attractiveness of ice to these whales is the avoidance of killer whale (Orca) predation[88], but the extent of their movements into sea-ice areas appears to be excessive for what would be needed to avoid killer whales[89] and actually can expose them to predation by polar bears[90] as well as increase the risk of entrapment in the ice. Thus, it seems likely that food availability and lack of competition from other whale species in ice-filled waters is also a major attractant, although few data are available to test this hypothesis. Whether these species could live in an Arctic with no summer sea ice is uncertain. At very least they would face increased competition from temperate whale species that would expand their ranges northward, as well as increased predation risk[31,64].

Seabirds

The abundance and distribution of many seabirds species in polar regions are related to sea ice distribution, particularly to the location of ice edges. Some of the largest seabird colonies in the world occur in the Arctic and Antarctic[91,92] and changes in sea-ice cover are likely to impact seabirds indirectly through changes in prey availability[93]. Seabirds, because they respond to anything that affects food availability, are good indicators of a system's productivity[94]. Although seabirds are quite mobile compared to other organisms, changes in the spatial and temporal availability of food can have dramatic effects on their reproduction and survival[95].


Photo: Bjørn Frantzen

Seabirds tend to aggregate at ice edges or in marginal ice zones where suitable prey is abundant and easily available. Wind-driven upwelling along ice-edges often concentrates important invertebrate and fish prey and thus improves foraging conditions. Diving seabirds also exploit the fauna associated with the subsurface of sea-ice as well as other sorts of prey found in leads deep inside the ice.

In the Arctic, species such as ivory gulls and little auks are very likely to be negatively impacted by reductions in sea ice and the subsequent changes to the communities in which they live[96]. Ivory gulls in the Canadian Arctic have shown significant declines in recent years and these declines have been attributed to changes in sea-ice cover[97].

In the Antarctic, species such as the emperor penguin, the snow petrel and the Antarctic petrel are likely to be negatively impacted if sea-ice extent changes markedly in the Southern Oceans[98]. However, as with polar marine mammals, reductions in sea-ice cover will also benefit many seabird species as new feeding areas become available and primary production increases[99].

Impacts of sea-ice changes on culture and livelihoods of Arctic Indigenous Peoples

Environmental and seasonal cycles are an integral part of the human-environment system in Arctic regions, and the peoples of the north have a long tradition of adapting to shifting environmental conditions. However, the rapidity and pervasiveness of current and projected climate change pose new and unprecedented challenges to the adaptive capacity of local communities and Arctic societies[31].

Nearly four million people live in the Arctic today, including indigenous and non-indigenous people. Some are hunters and herders living on the land, and others are city dwellers. Many indigenous groups are exclusive to the Arctic, such as the Chukchi in the Russian Federation, the Iñupiat and Yup'iit in Alaska, USA, the Inuvialuit and Inuit in Arctic Canada, and the Greenlanders. Each of these indigenous groups continues to practice traditional, natural resource-based activities while simultaneously participating in and adapting to the contemporary world[91].

Throughout history, a majority of the indigenous peoples of the Arctic have subsisted on the resources of the sea, and they continue this form of livelihood today[100–102]. Ringed and bearded seals, beluga, narwhal and bowhead whales, walrus and polar bears are animals used by Arctic indigenous groups for food, clothing and other secondary products. These animals figure predominantly in the mixed cash-subsistence economy of local households and communities. Notably, all of these species depend on sea ice for their survival. Any changes in climatic and sea-ice conditions will therefore have consequences for marine mammals and their habitats, with inevitable impacts for the communities that depend on them.

Climate variability has been shown to affect the abundance and availability of marine mammals in the past and will continue to shape the ability of Arctic peoples to harvest and process these animals in the future. Significant changes with respect to the geography of species distribution and composition, animal health, and disease vectors are expected under future climate change. These changes will in turn affect the hunting activities of the local communities.

Participation in marine mammal harvesting among Arctic indigenous groups is not only important for economic purposes but is a crucial factor in the maintenance of cultural identity and social relationships. A significant amount of the time spent hunting is presently devoted to educating younger generations about weather, ice conditions and the biology of marine species. These skills and attitudes, which are required for the successful harvesting of marine mammals, are transferable to modern community life and are critical to the preservation of the local indigenous culture and the mixed cash and subsistence economy[103].

Arctic communities continue to rely on traditional, local knowledge about their environments for travelling and hunting activities as well as for survival. Unfortunately, such knowledge may prove less valuable as ice conditions, weather, and prey distribution become less predictable and more variable, and as available species and hunting ranges change.

Figure 5.17: A hunter's grandchild in her grandfather's skiff in Qeqertarsuaq, Western Greenland. These skiffs are about to replace dog teams as means of transport to the winter hunting grounds. Due to lack of solid ice in the winter time, skiffs are now used all year round by the hunters in Qeqertarsuaq.
Photo: Stine Rybråten

The availability of sea ice as routes for transportation and migration is already reduced in many areas of the Arctic region (Figure 5.17), and evidence of increasingly unpredictable sea ice and weather conditions highlights that hunters are already confronted with increased risks and hazard. In addition to requiring more fuel to reach geographically dispersed prey, adaptation among hunters to climate change may require improved access to advanced technology, larger boats and new navigational aids such as Global Positioning Systems (GPS). These adaptations will require substantial resources and investments on the part of individual hunters and communities, something that may not be possible given the lack of economic investment and opportunities for the inhabitants of these areas at present.

Although Arctic societies have proven to be dynamic and capable of confronting past changes, climate change and its associated effects on sea ice and human activities present new challenges to the adaptive capacity of Arctic communities. The net effects of sea ice changes on communities in the Arctic are difficult to assess. While some changes might be for the better, others might have profound negative effects. To get a more thorough understanding of the actual impacts of changing sea ice conditions and their consequences for influenced communities, further studies where scientists and local stakeholders interact to produce knowledge that is both scientifically substantial and locally valuable are required.

Sea ice changes and economic activities

Reductions in sea-ice thickness and coverage in the Arctic will have large potential impacts on the economic activities in the region. Development of the offshore continental shelves and greater use of coastal shipping routes are likely to have significant social, political and economic consequences for all residents of Arctic coastal areas[31]. These consequences will have extended effects outside the Arctic region, as will the possible impacts of sea-ice reduction on exploration and production of oil and gas. Simultaneously, increased activity will contribute to an increased risk of environmental damage, e.g. through oil spills and other industrial accidents[91]. If the projected changes in climate and Arctic economic activities occur, they will present new challenges for trans-national cooperation and jurisdiction, for example with regard to the management of fisheries, pollution, and the establishment of a common policy for emergency response.

Arctic and Antarctic fisheries

A retreat in sea ice accompanied by changes in ocean temperatures is likely to affect the distribution of fish stocks in both the Arctic and the Antarctic regions. In areas of sea-ice retreat, light penetration in the upper ocean will increase, enhance phytoplankton blooms, and bring about changes in marine food webs[31]. Some species are expected to become more productive with warmer seawater temperatures, while others might suffer a loss in production through, for example, improved conditions for competing species or changes in ocean currents resulting in poorer nutrient conditions. Since migratory patterns as well as competition between species might change, it is likely that positive effects on fishing and fish recruitment in some areas will occur along with negative impacts in the same or additional areas[104].

For Arctic nations, as well as for many nations outside the Arctic region, Arctic marine fishing is an important food and income source. In terms of scale and income, the catch is also an important export commodity and constitutes a large share of the economy of some parts of the Arctic. In 2002 the total catch of wild fish in the Arctic amounted to 7.26 million tonnes, which corresponds to around 10% of the world catch of fish[104]. Although access to fish grounds might generally increase, the complexity of changes in

Photo: Jeremy Harbeck

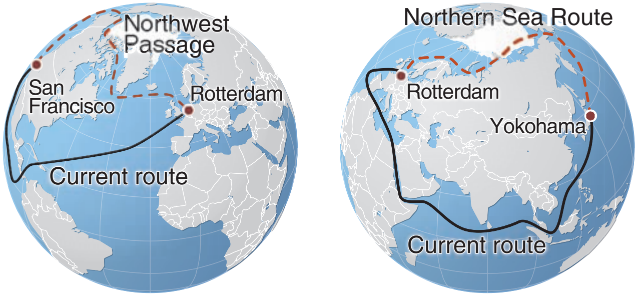


Figure 5.18: The Northern Sea Route and the Northwest Passage compared with currently used shipping routes.

Source: Based on material from Aftenposten, Norway

ocean currents, temperature and nutrient availability makes predictions about how fisheries might be affected by sea-ice reductions in the Arctic uncertain[104].

Fisheries in the Antarctic region involve about 18 nations from around the world, including Russia, Ukraine, France, Chile, Argentina and Japan. The total reported catch of toothfish and icefish in 2005/2006 in the regulated Antarctic fishery was 19 890 tonnes, and the krill catch was 106 591 tonnes[105]. The krill fishery, which provides feed for aquaculture as well as human food and dietary supplements, is expanding – the krill catch for the 2006/2007 season is projected to be as high as 368 000 tonnes, tripled from the previous year[106].

Projected reductions in the amount of Antarctic sea ice might limit the development of the sea-ice marginal zone, with consequences for the biota[107]. On the other hand, greater freshening of the mixed ocean layer from increased precipitation and melting ice might have a compensating effect. The krill fishery, which is restricted to ice-free periods, could become more attractive to nations not already involved if there is a retreat of sea ice in Antarctica[107]. Simultaneously, extensive seasonal ice cover is known to promote early krill spawning and favour the survival of krill larvae through their first winter. A possible decrease in the frequency of winters with extensive sea-ice development might lead to increased krill recruitment failures and population decline[107]. With krill being a key species in the Antarctic ecosystem, a decline in the population will in turn influence higher trophic levels. The combined pressures of exploitation and climate change are thus likely to result in considerable changes to Antarctic fisheries.

Arctic oil and gas

The Arctic holds a great share of the world's reserves. At present the Arctic shares of global oil and gas production are 10.5 per cent and 25.5 per cent, respectively. Additionally, Arctic basins are estimated to hold around 24 per cent of the world's undiscovered petroleum resources[104]. These reserves represent enormous wealth as well as significant potential for economic growth and development in Arctic regions, and offshore oil exploration and production is likely to benefit from less extensive and thinner sea ice. However, diminishing sea-ice cover will lead to more icebergs and increased wave activity[107]. This, in turn, will create new challenges for the offshore industry, such as the need for costlier equipment.

A cruise ship lands in Antarctica.
Photo: Steve Estvanik/iStockphoto.com

Shipping and tourism

Climate models project that summer sea ice in the Arctic Basin will retreat further and further away from most Arctic landmasses, opening new shipping routes and extending the navigation season in the Northern Sea Route (see box) by between two and four months[91]. Previously-frozen areas in the Arctic may therefore become seasonally or permanently navigable, increasing the prospects for marine transport through the Arctic and providing greater access to Arctic resources such as fish, oil and gas (Figure 5.18).

In addition to increased cargo shipping, opening of sea routes such as the Northern Sea Route and Northwest Passage will probably increase the number of tourist cruises and passenger vessels in Arctic waters. In the Antarctic, reduced sea ice might provide safer approaches for tourist ships and new opportunities for sightseeing around Antarctica, but may also increase the risk of environmental impacts (see Chapter 9). Increased calving of icebergs from the Antarctic Peninsula may, however, affect navigation and shipping lanes[93]. Although tourism is expected to experience a longer season in both the Arctic and Antarctic, the industry is highly dependent upon weather conditions. A more unpredictable and rainier climate might reduce the attractiveness of some areas.

The Northern Sea Route

The Northern Sea Route (NSR) is a seasonally ice-covered marine shipping lane along the Russian coasts, from Novaya Zemlya in the west to the Bering Strait in the east. The NSR is administered by the Russian Ministry of Transport and has been open to marine traffic of all nations since 1991. For trans-Arctic voyages, the NSR represents a saving in distance of up to 40 per cent from Northern Europe to northeastern Asia and northwestern North America, compared to southerly routes via the Suez or Panama Canals.

Projected reductions in sea-ice extent are likely to improve access along the NSR. The navigation season is often defined as the number of days per year with navigable conditions, generally meaning days with less than 50 per cent sea-ice cover. For the NSR, the navigation season is projected to increase from the current 20 to 30 days per year to 90 to 100 days per year by 2080 (Figure 5.19). An extended navigation season could have major implications for transportation and access to natural resources[31,91].

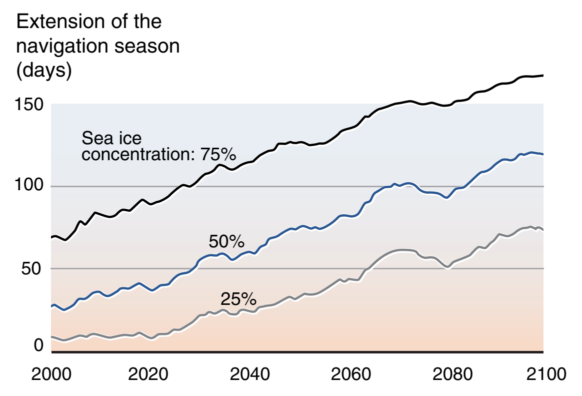


Figure 5.19: Projected increase (days) of the navigation season through the Northern Sea Route as an average of 5 ACIA model projections[91].

Source: Based on ACIA 2004[91]

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