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Polar Regions (Arctic and Antarctic)

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EXECUTIVE SUMMARY

In this summary we indicate our uncertainty in observations, mechanisms, and scenarios by using a five-point scale, from "very high confidence" (*****) to "very low confidence" (*).

Climate Changes in the 20th Century

Although there are some regional anomalies, there is strong evidence that climate change has had an impact in the Arctic and the Antarctic. Many documented changes already parallel those forecast to result from climate change:

- In the Arctic, extensive land areas show a 20th-century warming trend in air temperature of as much as 5°C. Over sea ice, there has been slight warming in the 1961–1990 period.***** Precipitation has increased.**
- Arctic sea-ice extent has decreased by 2.9% per decade over the 1978–1996 period; sea ice has thinned, and there are now more melt days per summer. Sea-ice extent in the Nordic seas has decreased by 30% over the past 130 years.***** It is not yet clear whether changes in sea ice of the past few decades are linked to a natural cycle in climate variability or have resulted explicitly from global warming.
- Atlantic water flowing into the Arctic Ocean has warmed, and the surface layer has become thinner. The mixed layer in the Beaufort Sea has become less saline.****
- Regions underlain by permafrost have been reduced in extent, and a general warming of ground temperatures has been observed in many areas.*****
- There has been a statistically significant decrease in spring snow extent over Eurasia since 1915.****
- In summary, many observations of environmental change in the Arctic show a trend that is consistent with warming and similar to that predicted by general circulation models (GCMs).
- In the Antarctic, over the past half-century there has been a marked warming trend in the Antarctic Peninsula.**** Elsewhere there is a general but not unambiguous warming trend.**
- Precipitation in the Antarctic has increased.*
- Satellite observations show no significant change in Antarctic sea-ice extent over the 1973–1996 period.***** Analysis of whaling records and modeling studies indicate that Antarctic sea ice retreated south by 2.8 degrees of latitude between the mid-1950s and the early 1970s.***
- Surface waters of the Southern Ocean have warmed and become less saline.***

Impacts

Substantial warming and increases in precipitation are projected for polar regions over the 21st century by almost all climate models. There are eight key concerns related to the impact of this climate change in the Arctic and Antarctic. Associated with these concerns will be changes to the atmosphere and the oceans that will propagate to other regions of the world:

1) *Changes in ice sheets and polar glaciers:* Increased melting is expected on Arctic glaciers and the Greenland ice sheet, and they will retreat and thin close to their margins. Most of the Antarctic ice sheet is likely to thicken as a result of increased precipitation. There is a small risk, however, that the West Antarctic and Greenland ice sheets will retreat in coming centuries. Together, these cryospheric changes may make a significant contribution to sea-level rise.****
2) *Changes around the Antarctic Peninsula:* This region has experienced spectacular retreat and collapse of ice shelves, which has been related to a southerly migration of the January 0°C isotherm resulting from regional warming. The loss of these ice shelves has few direct impacts. Projected warming is likely, however, to break up ice shelves further south on the Antarctic Peninsula, expose more bare ground, and cause changes in terrestrial biology, such as introduction of exotic plants and animals.****
3) *Changes in the Southern Ocean and impacts on its life:* Climate change is likely to produce long-term—perhaps irreversible—changes in the physical oceanography and ecology of the Southern Ocean. Projected reductions in sea-ice extent will alter under-ice biota and spring bloom in the sea-ice marginal zone and will cause profound impacts at all levels in the food chain, from algae to krill to the great whales. Marine mammals and birds, which have life histories that tie them to specific breeding sites, will be severely affected by shifts in their foraging habitats and migration of prey species. Warmer water will potentially intensify biological activity and growth rates of fish. Ultimately, this should lead to an increase in the catch of marketable fish, and retreat of sea ice will provide easier access to southern fisheries.***
4) *Changes in sea ice:* There will be substantial loss of sea ice in the Arctic Ocean. Predictions for summer ice indicate that its extent could shrink by 60% for a doubling of carbon dioxide (CO_2), opening new sea routes. This will have major trading and strategic implications. With more open water, there will be a moderation of temperatures

and an increase in precipitation in Arctic lands. Antarctic sea-ice volume is predicted to decrease by 25% or more for a doubling of CO_2, with sea ice retreating about 2 degrees of latitude.****

5) *Changes in permafrost:* Thickening of the seasonally thawed layer above permafrost (active layer) is expected. Modeling studies indicate that large areas of permafrost terrain will begin to thaw, leading to changes in drainage, increased mass movements, thermal erosion, and altered landscapes in much of the Arctic and subarctic. Warming of permafrost, thawing of ground ice, and development of thermokarst terrain have been documented over the past several decades. In developed areas of the Arctic, continuation of such changes may lead to costly damage to human infrastructure.****
6) *Changes in Arctic hydrology:* The hydrology of the Arctic is particularly susceptible to warming because small rises in temperature will result in increased melting of snow and ice, with consequent impacts on the water cycle. There will be a shift to a runoff regime that is driven increasingly by rainfall, with less seasonal variation in runoff. There will be more ponding of water in some areas, but peatlands may dry out because of increased evaporation and transpiration from plants. In some areas, thawing of permafrost will improve infiltration. An expected reduction in ice-jam flooding will have serious impacts on riverbank ecosystems and aquatic ecology, particularly in the highly productive Arctic river deltas. Changes in Arctic runoff will affect sea-ice production, deepwater formation in the North Atlantic, and regional climate. A major impact would result from a weakening of the global thermohaline circulation as a result of a net increase in river flow and the resulting increased flux of freshwater from the Arctic Ocean.***
7) *Changes in Arctic biota:* Warming should increase biological production; however, the effects of increased precipitation on biological production are unclear. As warming occurs, there will be changes in species compositions on land and in the sea, with a tendency for poleward shifts in species assemblages and loss of some polar species. Changes in sea ice will alter the seasonal distributions, geographic ranges, patterns of migration, nutritional status, reproductive success, and ultimately the abundance and balance of species. Animals that are dependent on sea ice—such as seals, walrus, and polar bears—will be disadvantaged. High-arctic plants will show a strong growth response to summer warming. It is unlikely that elevated CO_2 levels will increase carbon accumulation in plants, but they may be damaged by higher ultraviolet-B radiation. Biological production in lakes and ponds will increase.***
8) *Impacts on human communities:* Climate change, in combination with other stresses, will affect human communities in the Arctic. The impacts may be particularly disruptive for communities of indigenous peoples following traditional lifestyles. Changes in sea ice, seasonality of snow, and habitat and diversity of food species will affect hunting and gathering practices and could threaten longstanding traditions and ways of life. On the other hand, communities that practice these lifestyles may be sufficiently resilient to cope with these changes. Increased economic costs are expected to affect infrastructure, in response to thawing of permafrost and reduced transportation capabilities across frozen ground and water. However, there will be economic benefits—including new opportunities for trade and shipping across the Arctic Ocean, lower operational costs for the oil and gas industry, lower heating costs, and easier access for ship-based tourism.*****

Feedbacks and Interactions

Climate change and global warming will affect key polar drivers of further climate change. These effects will have impacts that affect other regions of the world. Models indicate that once triggered, these impacts will continue for centuries and lead to further change elsewhere in the world:

- Warming will reduce sea-ice and snow extent, particularly in the Arctic, causing additional heating of the surface—which, in turn, will further reduce ice/snow cover.*****
- Deep ocean water around the Antarctic and in the north Atlantic is a crucial part of the ocean's thermohaline circulation. Its rate of production is likely to decrease because of freshening of waters from increased Arctic runoff from glacial icemelt, from increases in precipitation over evaporation, and from reduced sea-ice formation. Models indicate that the impact will be a prolonged, major slowing of the thermohaline circulation and ocean ventilation, even with stabilization of greenhouse gases (GHGs).***
- Polar regions have oceans, wetlands, and permafrost that act as major sources and sinks for atmospheric CO_2 and methane (CH_4) over vast areas. Projected climate change will alter these features and increase their contributions to GHGs. The Southern Ocean's uptake is projected to decline; CO_2 emissions from Arctic tundra may rise initially as a result of changes in water content, peat decomposition, and thawing of permafrost.***

Vulnerability and Adaptation

- Localities within the Antarctic and Arctic where water is close to its melting point are highly sensitive to climate change; this sensitivity renders their biota and socioeconomic life particularly vulnerable to climate change. In the Antarctic Peninsula, as ice melts, changes are likely to be rapid, but overall the Antarctic and the Southern Ocean are likely to respond relatively slowly to climate change, so there will be less impact in this region compared with elsewhere by 2100. Nevertheless, climate change in the Antarctic will initiate processes that could last for millennia—long after greenhouse emissions have stabilized—and these changes will cause irreversible impacts on ice sheets, oceanic circulation of water, and sea-level rise.

- The Arctic is extremely vulnerable to climate change, and major ecological, sociological, and economic impacts are expected. A variety of positive feedback mechanisms induced by climate change are likely to operate in the Arctic; these mechanisms will cause rapid and amplified responses, with consequential impacts on the thickness and extent of sea ice, thawing of permafrost, runoff into the Arctic Ocean, and coastal erosion.
- Biota are particularly vulnerable to climate change in the polar regions. Less sea ice will reduce ice edges, which are prime habitats for marine organisms. Habitat loss for some species of seal, walrus, and polar bear results from ice melt, and apex consumers—with their low-reproductive outputs—are vulnerable to changes in the long polar marine food chains.
- Adaptation to climate change in natural polar ecosystems is likely to occur through migration and changing species assemblages, but the details of these effects are unknown. Some animals may be threatened (e.g., walrus, polar bear, and some species of seal), whereas others may flourish (e.g., some species of fish and penguins).
- Loss of sea ice in the Arctic will provide increased opportunities for new sea routes, fishing, and new settlements, but also for wider dispersal of pollutants. Collectively, these changes emphasize the need for an adequate infrastructure to be in place before they occur. Disputes over jurisdiction in Arctic waters, sustainable development of fisheries and other marine resources, and construction of navigational aids and harbor facilities, as well as problems arising from oil and gas development, including pollution and environmental monitoring, will all have to be resolved by polar and associated nations as climate-induced change becomes widespread. Just as important is the need for new building codes for roads, railways, runways, and buildings to cope with the effects of permafrost thawing.
- Although most indigenous peoples are highly resilient, the combined impacts of climate change and globalization create new and unexpected challenges. Because their livelihood and economy increasingly are tied to distant markets, they will be affected not only by climate change in the Arctic but also by other changes elsewhere. Local adjustments in harvest strategies and in allocation of labor and capital will be necessary. Perhaps the greatest threat of all is to maintenance of self-esteem, social cohesion, and cultural identity of communities.

16.1. Polar Regions

For the purposes of this assessment, the Arctic is defined as the area within the Arctic Circle. It covers the Arctic Ocean and the islands and northern continental land areas (see Figure 16-1). Thus, it extends far enough south to include parts of the boreal forest and discontinuous permafrost zone. Note that the Arctic, thus defined, overlaps with other regions covered in this report—namely, North America, Asia, and Europe—and that important physical and biological processes that are typical of the Arctic also occur south of the Arctic Circle. The Antarctic is defined here as the Antarctic continent, together with the surrounding Southern Ocean south of the Antarctic Convergence (polar front), an oceanographic barrier that shifts with time and longitude but generally is close to 58°S. Also included in the polar regions are sub-Antarctic islands such as Campbell Island, Heard Island, and South Georgia, some of which are north of the Antarctic Convergence (see Figure 16-2).

The two polar regions are dominated by cold conditions and the presence of ice, snow, and water. They are different in that the Arctic is a frozen ocean surrounded by continental landmasses and open oceans, whereas Antarctica is a frozen continent surrounded solely by oceans. Antarctica tends to be thermally isolated from the rest of the planet by the surrounding Southern Ocean and the atmospheric polar vortex, whereas the Arctic is influenced strongly by seasonal atmospheric transport and river flows from surrounding continents. Both regions have major influences on the global ocean.

The Arctic and Antarctic influence climate over a significant part of the globe. Many unique climatic processes operate in these regions. Some involve complex interactions and feedback loops (Simmonds, 1998) that may lead ultimately to glacial-interglacial climate transitions (Petit *et al.*, 1999). Processes in polar regions greatly influence sea level. The Arctic and Antarctic have food webs and natural ecosystems with remarkable productivity. The Arctic is on the periphery of human settlement, where people must adapt to harsh, cold regimes; the Antarctic is uninhabited apart from research bases.

16.1.1. Previous Work—Summary of Special Report on Regional Impacts of Climate Change

The IPCC, in its *Special Report on Regional Impacts of Climate Change* (RICC), produced an assessment of the impacts of climate change on the Arctic and the Antarctic (Everett and Fitzharris, 1998). In addition, the impact of climate change on the cryosphere is discussed in the IPCC Second Assessment Report (SAR) (Fitzharris, 1996). The main points arising from the regional assessment were that the Arctic is extremely vulnerable to projected climate change—major physical, ecological, sociological, and economic impacts are expected. Because of a variety of positive feedback mechanisms, the Arctic is likely to respond rapidly and more severely than any other area on Earth, with consequent effects on sea ice, permafrost, and hydrology. On the other hand, the Antarctic would respond relatively slowly to climate change, with much smaller impacts expected by 2100, except in the Antarctic Peninsula.

RICC noted that substantial loss of sea ice in the Arctic Ocean would have major implications for trade and defense (Everett and Fitzharris, 1998) . With more open water, there would be moderation of temperatures and increased precipitation. Considerable thawing of permafrost would lead to changes in drainage, increased slumping, and altered landscapes over vast areas of northern parts of North America and Eurasia. RICC also purported that polar warming probably should increase biological production, but different species compositions are likely on land and in the sea, with a tendency for poleward shifts in major biomes and associated animals. Animals that are dependent on ice would be disadvantaged. Human communities in the Arctic—especially indigenous peoples following traditional lifestyles—would be affected by these changes.

RICC also pointed out that changes in polar climate are likely to affect other parts of the world through changes in sea level, decreased oceanic heat transport, and increased emissions of GHGs from thawing permafrost. However, there would be economic benefits as well as costs. Potential benefits include new opportunities for shipping across the Arctic Ocean, lower operational costs for the oil and gas industry, lower heating costs, and easier access for tourism. Increased costs could be expected from changes such as disruptions to land and infrastructure caused by thawing of permafrost and reduced transportation capabilities across frozen ground and water.

Since these IPCC reports, there have been important advances in knowledge about climate change in polar regions. These advances include more information about decreases in Arctic and Antarctic sea-ice extent, verification of substantial thinning of Arctic sea ice, documentation of important changes in polar oceans, and more analyses of continental snow-cover trends. Many observations of environmental change in the Arctic show a trend that is consistent with GHG warming and similar to that predicted by climate models.

This report is different from earlier IPCC reports in that it focuses on eight key concerns of climate impact. The risk of collapse of the West Antarctic ice sheet is now considered to be lower than first thought. Changes around the Antarctic Peninsula are given prominence, and the implications for the whole continent are discussed in more detail. Previous reports said little about the impacts on polar oceans and consequences for marine life. New information, especially for the Southern Ocean and its role in the global thermohaline circulation, is presented here. There also are improved predictions of sea ice over the 21st century, and the role of Arctic hydrology and the implications of altered river flows into the Arctic Ocean for the Atlantic driver of the thermohaline circulation are addressed. More information is now available regarding the impacts of climate change on Arctic biota. More detail is supplied about impacts on human communities, especially indigenous peoples following traditional lifestyles. This research has highlighted the role of climate change in the Arctic and Antarctic and its impact on polar drivers of the global system. New modeling has identified the large role of polar regions in affecting the global thermohaline circulation, sea-level rise, and greenhouse exchanges between the atmosphere, cold oceans, and tundra. It is now clearer that climate change could initiate processes that could last for millennia and persist long after greenhouse emissions have stabilized.

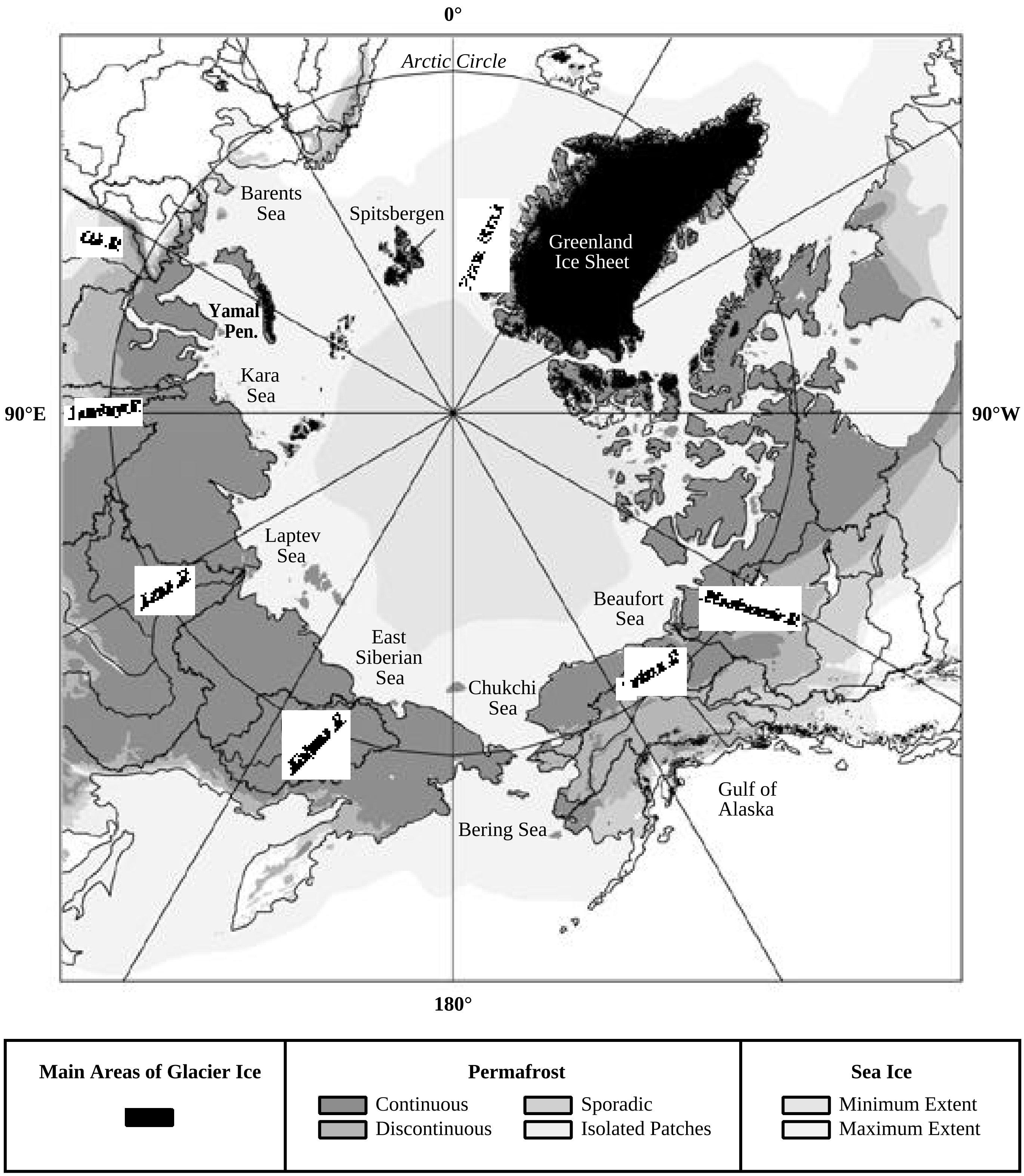

Figure 16-1: Location map for the Arctic. Permafrost zonation, drainage basins, sea ice, and main areas of glacier ice are shown. Drainage basins are delimited by solid black lines. Permafrost zonation is based on a digital version of the map by Brown *et al*. (1997).

16.1.2. Distinctive Characteristics of Polar Regions

The most distinctive feature of polar regions is the large seasonal variation in incoming solar radiation—from very little in winter to 24 hours of continuous sunlight in summer. Although the poles receive less solar radiation annually than equatorial locations, near the time of the solstices they receive more per day. The high albedo of the snow- and ice-covered polar regions, together with the large loss of long-wave radiation through the very clear and dry atmosphere, ensures a net loss of radiation in most months of the year. These losses of radiation are particularly large during the long polar night and help

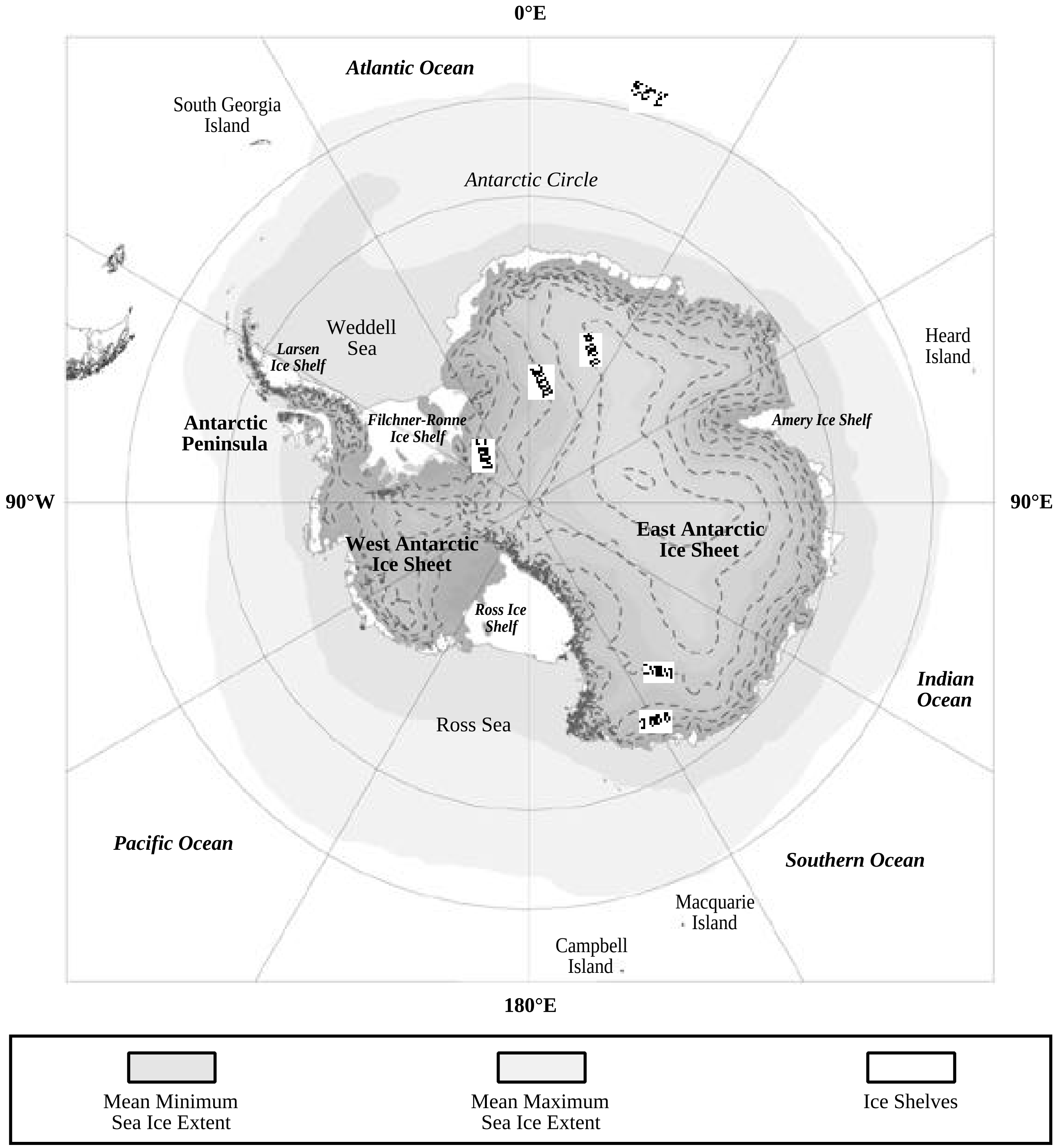

Figure 16-2: Location map for the Antarctic. Elevations on Antarctic continent are indicated by dashed contour lines (500-m interval). Topography and ice shelf outlines are from U.S. Geological Survey and British Antarctic Survey data. Sea-ice extent data are from Couper (1989).

create a deep, stable boundary layer of very cold, dry air at the surface.

These processes ensure sustained, very low temperatures in winter. Even in the summer, many areas—especially in the Antarctic—remain below freezing. Thus, much water remains frozen throughout the year. In Antarctica, snow and ice have continued to accumulate on the continent for millions of years. On the other hand, there are large volumes of liquid water in polar regions in the Arctic and Southern Oceans, although their surface is partially covered with sea ice, whose extent varies seasonally over vast areas. Sea ice insulates the underlying water from heat loss and, because of its high albedo, reflects much of the incoming solar radiation.

Formation of sea ice has important oceanographic consequences in that much latent heat is released, and highly saline, dense water is created. The dense water sinks in the north Atlantic and Southern Oceans, helping maintain the ocean conveyor belt and carrying nutrients and carbon. Production of deep ocean water is a consequence of processes that are operating in both polar regions. There is little evaporation from the vast tracts of sea ice and glacier ice. Extensive areas of the polar regions have very low precipitation; most comes from cyclonic storms that penetrate from the surrounding belt of subpolar depressions.

The polar regions incorporate important environmental thresholds, many of which are associated with water-phase changes. Together with the large seasonal changes in solar radiation, polar regions stimulate important geophysical and biological processes with high sensitivity to impacts. Sustained warming or cooling across the freezing threshold brings dramatic physical changes over land and sea. As a result, the physical environment, biota, and socioeconomic factors are all vulnerable to climate change. The climate and vast areas of ice make the polar regions very inhospitable and marginal for many species, including humans. However, specially adapted species thrive in some terrestrial and marine polar ecosystems. Consequently, the Arctic and Antarctic are characterized by the presence of highly distinctive biomes and are important places for many migratory species. Although the Antarctic continent essentially is a pristine wilderness, the great whales and some species of seals in the Southern Ocean were commercially exploited to virtual commercial extinction in the 19th and 20th centuries. Human activities on many sub-Antarctic islands have altered their biota dramatically.

The Antarctic has limited resource use, apart from growing fishing and tourism industries. There is a multinational approach to natural resources and environmental management, with mineral exploration and exploitation banned by international agreement. The area is managed by the Consultative Parties to the Antarctic Treaty to the dedication of science and peace (UNEP, 1997). By contrast, the Arctic has been populated for thousands of years. There is considerable economic activity, based on fishing, herding, and shipping. Recent decades have seen the establishment of urban areas and resource developments, based on the petroleum, gas, and mining industries. The extreme environment requires unique cold-region engineering and infrastructure solutions. There is a distinct contrast—and sometimes conflict—between the developments of modern society and indigenous peoples. The Arctic lies within the political boundaries of some of the world's richest and most powerful nations. During the Cold War, it was a critical strategic area, and substantial defense establishments remain in the region.

16.1.3. Climate Change in the 20th Century

There has been substantial climate change during the past 2 million years in the Arctic and the Antarctic. These changes are well documented in several natural archives, such as ice cores and marine sediments. The quasi-periodic sequence of glacial-interglacial periods and corresponding changes in GHGs is shown clearly in the record of atmospheric composition and climate derived from the ice cores for the past 420,000 years (e.g.,White and Steig, 1998; Petit *et al.*, 1999). Longer term climate changes are not discussed in this chapter, which focuses on observed 20th-century changes as well as those predicted for the 21st century. The following subsections provide a brief discussion of the main climatic changes in the 20th century. More details are provided in TAR WGI Chapter 2.

16.1.3.1. The Arctic

Instrumental observations of climatic parameters over the 20th century are available from standard climate stations on land and measurements taken on drifting ice floes in the Arctic Ocean. The land stations show that warming in the Arctic, as indicated by daily maximum and minimum temperatures, has been as great as in any other part of the world. Although not geographically uniform, the magnitude of the warming is about 5°C per century, with areas of cooling in eastern Canada, the north Atlantic, and Greenland (Koerner and Lundgaard, 1996; Borzenkova, 1999a,b; Jones *et al.*, 1999; Serreze *et al*., 2000). Data from ice floe measurements show a slight warming on an annual basis, with statistically significant warming in May and June over the 1961–1990 period. Air temperature anomalies in the Arctic basin have been strongly positive since 1993. In the period 1987–1997, air temperature in the Arctic increased by 0.9°C (Alexandrov and Maistrova, 1998).

Significant warming from the beginning of the 20th century has been confirmed by many different proxy measurements (Maslanik *et al.*, 1996; Bjorgo *et al.*, 1997; Smith, 1998). Magnuson *et al*. (2000) found consistent evidence of later freeze-up (5.8 days per 100 years) and earlier breakup (6.5 days per 100 years) of ice on lakes and rivers around the northern hemisphere from 1846 to 1995 and an increase since 1950 in interannual variability of both dates. Glaciers and ice caps in the Arctic also have shown retreat in low-lying areas since about 1920. Numerous small, low-altitude glaciers and perennial snow patches have disappeared. However, no increasing melting trend has been observed during the past 40 years (Jania and Hagen, 1996; Koerner and Lundegaard, 1996; Dowdeswell *et al*., 1997). Glaciers in Alaska have receded, with typical ice-thickness decreases of 10 m over the past 40 years, but some glaciers have thickened in their upper regions (BESIS, 1997). Greenland's ice sheet has thinned dramatically around its southern and eastern margins. Above 2,000-m elevation, the ice sheet is in balance, on average. The net effect is a loss of about 51 km^3 yr^{-1}. (Krabill *et al*., 1999, 2000).

Snow-cover extent in the northern hemisphere has been reduced since 1972 by about 10%, largely as a result of spring and summer deficits since the mid-1980s (Brown, 2000; Serreze *et al.*, 2000). Most Arctic regions have experienced increases in precipitation since at least the 1950s (Groisman *et al.*, 1991; Groisman and Easterling, 1994; Georgiyevskii, 1998). Measurements from Spitsbergen show a statistically significant increase in precipitation during all seasons, except winter (Hanssen-Bauer and Forland, 1998).

Groisman *et al*. (1994) analyzed seasonal snow extent in the northern hemisphere and demonstrated an inverse relationship with near-surface air temperature. Recent findings have provided evidence of a significant decrease in spring snow extent since 1915 over Eurasia (Brown, 1997) and southern Canada (Brown and Goodison, 1996). Such trends may be related to low-frequency fluctuations in hemispheric atmospheric circulation patterns (Serreze *et al*., 2000).

Arctic sea-ice extent decreased by approximately 3% per decade between 1978 and 1996 (Cavalieri *et al.*, 1997; Parkinson *et al*., 1999; Johannessen *et al.*, 1999; Serreze *et al*., 2000). The most significant contractions were detected in 1990, 1993, and 1995 (Maslanik *et al*., 1996). Ice composition also has changed, with a reduction in the area of multi-year ice in winter. Summer sea-ice extent has shrunk by 20% (880,000 km^2) over the past 30 years in the Atlantic part of the Arctic Ocean (Johannessen *et al*., 1999), but the shrinkage has only been 5% in the Canadian Arctic Sea. Sea-ice extent in the Bering Sea experienced a dramatic reduction when a regime shift occurred in 1976 and has continued to decrease (BESIS, 1997). New compilations of Arctic sea-ice extent, using historical

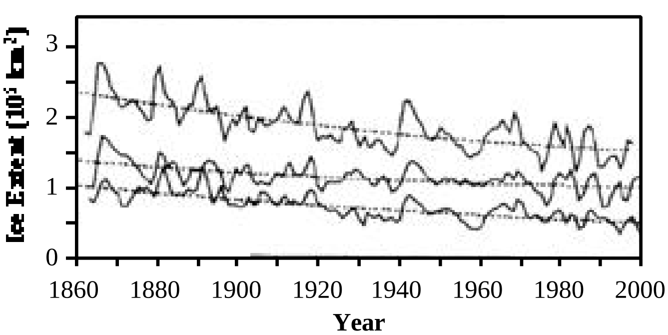

Figure 16-3: Time series of April sea-ice extent in Nordic Sea (1864–1998) given by 2-year running mean and second-order polynomial curves. Top: Nordic Sea; middle: eastern area; bottom: western area (after Vinje, 2000).

data from the past 135 years (Vinje, 2001), show that overall sea-ice extent in April has been reduced in the Nordic seas by 0.79 x 10^6 km^2 (33%) (see Figure 16-3). Nearly half of this reduction took place between 1860 and 1900. Although there are large interannual and seasonal variations in sea-ice extent, the reduction is greatest in spring. This is consistent with the 1912–1996 temperature record from Svalbard, which shows significant warming (3°C) in spring (Hanssen-Bauer and Forland, 1998). There is an approximate 10-year climate signal in the Arctic and subarctic, with a clockwise propagating signal in sea-ice concentration anomalies and a standing oscillation in sea-level pressure anomalies—the latter linked to the two phases of the North Atlantic Oscillation (NAO) (Mysak and Venegas, 1998). Comparison of these trends with outputs from climate models (forced by observed GHGs and tropospheric sulfate aerosols) reveals that the observed decrease in northern hemisphere sea-ice extent agrees with transient simulations (see Figure 16-6) and that both trends are much larger than would be expected from natural climate variations (Vinnikov *et al*., 1999).

The most effective method for determining the thickness of sea ice is to use sonar, directed upward at the floating ice from submarines or moorings (Melling *et al.*, 1995). The results indicate great variability. Average thinning of sea ice has been observed since 1976 on some transects of the Atlantic and Arctic Oceans (Wadhams, 1997). A thinning by about 0.13 m over the period 1970–1992,with the maximum decrease detected in the eastern Siberian Sea, was found by Russian scientists (Nagurduy, 1995). Rothrock *et al.* (1999) found that ice draft at the end of the melt season has decreased by about 1.3 m in most of the deepwater portion of the Arctic Ocean, from 3.1 m in 1958–1976 to 1.8 m in the 1990s (~15% per decade). The decrease is greater in the central and eastern Arctic than in the Beaufort and Chukchi seas (Rothrock *et al.*, 1999). Vinje *et al*. (1998), however, claim that no significant change in ice thickness can be observed in Fram Strait. Their conclusion is in agreement with submarine observations from 1960–1982. Although there is large variability, ice cover has continued to become thinner and has decreased by 40% over the past 3 decades (Rothrock *et al*., 1999). Analysis of the duration of summer melt over a large fraction of the perennial Arctic sea ice from 1979 to 1996 reveals an increase of 5.3 days (8%) per decade in the number of melt days each summer (Smith, 1998).

Changes to below 1,000 m in the Arctic Ocean have been observed, with less sea ice and freshening of the Beaufort Sea mixed layer (Maslanik *et al.*, 1996; and McPhee *et al.*, 1998). Atlantic water inflow to the Arctic Ocean has warmed (Carmack *et al*., 1995). The halocline, which isolates the surface from this warmer Atlantic water, has grown thinner (Steele and Boyd, 1998). Data gathered from submarines indicate that sea-surface temperature (SST) in the Arctic basin increased by 1°C over the past 20 years, and the area of warm Atlantic water in the polar basin increased by almost 500,000 km^2 (Kotlyakov, 1997). Field measurements in 1994 and 1995 showed consistent Arctic seawater warming of 0.5–1.0°C, with a maximum detected in the Kara Sea (Alekseev *et al.*, 1997). It is not yet clear whether these changes are part of low-frequency natural variability or whether they represent the early impacts of long-term climate change.

Thickening of the active layer and changes in the distribution and temperature of permafrost are further important indicators of warming in the Arctic. Permafrost thawing has led to major erosion problems and landslides in the Mackenzie basin (Cohen, 1997a) and has caused major landscape changes from forest to bogs, grasslands, and wetland ecosystems in Alaska, affecting land use. In central and western Canada and in Alaska, contraction in the extent of permafrost has occurred during the 20th century (Halsey *et al*., 1995; Weller, 1998; Weller and Lange, 1999; Osterkamp *et al*., 2000). However, a cooling trend has been noted for permafrost in eastern Canada (Allard *et al*., 1995; Allard and Kasper, 1998). Permafrost degradation during the 20th century in subarctic and boreal peatlands of Quebec is discussed by Laberge and Payette (1995).

Temperatures at the top of permafrost along a several hundred kilometer north-south transect in central Alaska warmed by 0.5–1.5°C between the late 1980s and 1996. Thawing rates of about 0.1 m per year were calculated for two sites (Osterkamp and Romanovsky, 1999). On the north slope of Alaska and in northwestern Canada, the temperature-depth profile indicates a temperature rise of 2–4°C over the past century (Lachenbruch and Marshall 1986). In the western Yamal Peninsula, temperatures at a depth of 10 m in ice-rich permafrost increased 0.1–1.0°C between 1980 and 1998; the largest increases in Siberian permafrost temperatures have occurred in relatively cold permafrost in the continuous zone.

Palaeoclimate reconstructions based on dendrochronology also indicate a steady increase in temperature during the past 150 years (Bradley and Jones 1993; Szeicz and MacDonald 1995; see TAR WGI Chapter 2). Growth rings in Larix Sibirica from northern Siberia show that mean temperatures during the 20th century were the highest in 1,000 years, exceeding even those during the Medieval Warm Period (Briffa *et al*., 1995). Changes in diatom assemblages in lake sediments in the High Arctic over the same period also are thought to be a consequence of climatic warming (Douglas *et al.*, 1994).

Other changes in terrestrial ecosystems include northward movement of the treeline, reduced nutritional value of browsing for caribou and moose, decreased water availability, and increased forest fire tendencies (Weller and Lange, 1999). There are altered plant species composition, especially forbs and lichen, on the tundra. In the marine ecosystem, northern fur seal pups on the major Bering Sea breeding grounds declined by half between the 1950s and the 1980s. In parts of the Gulf of Alaska, harbor seal numbers are as much as 90% below what they were in the 1970s. There have been significant declines in the populations of some seabird species, including common murres, thick-billed murres, and kittiwakes. Comprehensive interviews by Gibson and Scullinger (1998) have revealed notable impacts on food sources and natural environments of native Alaskan communities. Warmer climate has increased growing degree days by 20% for agriculture and forestry in Alaska, and boreal forests are expanding northward at a rate of about 100 km per °C (Weller and Lange, 1999).

16.1.3.2. The Antarctic

Instrumental records analyzed by Jacka and Budd (1998) and summarized in Figure 16-4 have shown overall warming at

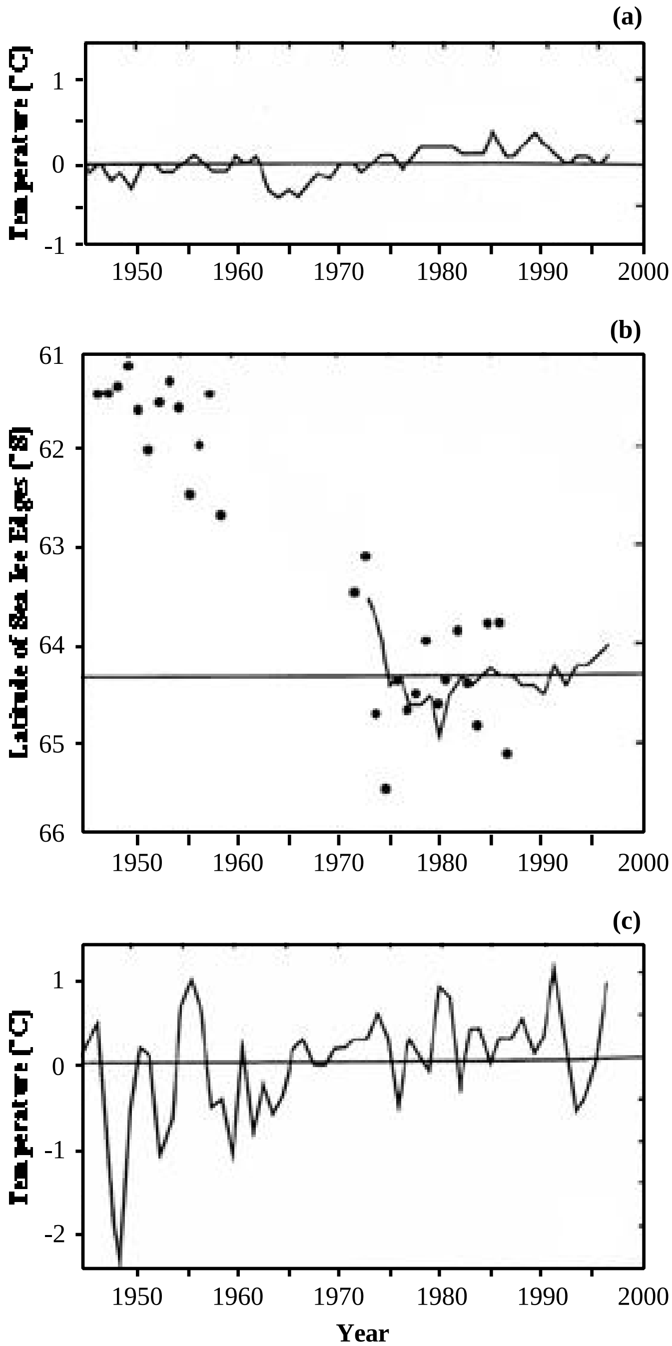

Figure 16-4: (a) Mean temperature anomalies for Southern Ocean climate stations; (b) summer sea-ice extent [dots are from estimates based on southernmost positions of whaling-factory ships (de la Mare, 1997)]; (c) mean temperature anomalies of coastal Antarctic climate stations (after Jacka and Budd, 1998).

permanently occupied stations on the Antarctic continent (1959–1996) and Southern Ocean island stations (1949–1996). Using two different statistical techniques, they found that the 16 Antarctic stations have warmed at a mean rate of 0.9–1.2°C per century, and the 22 Southern Ocean stations have warmed at 0.7–1.0°C per century. Antarctic Peninsula stations show a consistent regional rate of warming that is more than twice the average for other Antarctic stations. King and Harangozo (1998) suggest that this warming is associated with an increase in the northerly component of the atmospheric circulation over the Peninsula and perhaps changes in sea-ice extent. For Antarctic stations, warming trends are largest in winter and smallest in autumn. For the Southern Ocean stations, warming trends are largest in autumn and smallest in spring and summer. However, three GCMs were unable to reproduce these trends (Connolley and O'Farrell, 1998).

Another analysis of a 21-station data set from Antarctica by Comiso (1999) found a warming trend equivalent to 1.25°C per century for a 45-year record beginning in the 1950s but a slight cooling trend from 1979 to 1998. The slight cooling trend for this later 20-year period also was confirmed via analysis of surface temperatures over the whole continent, as inferred from satellite data. These changes can be placed in a long-term context by comparison with results from the high-accumulation ice coring sites on Law Dome, East Antarctica, which show clear climate signals with sufficient resolution to identify seasonal variations (van Ommen and Morgan, 1996, 1997; Curran *et al.*, 1998). There was a cooling period in the late 1700s and 1800s and a warming over the 19th century, with greater variability and change in winter than in summer.

Changes in precipitation in the Antarctic are more poorly understood. Model estimates from Smith *et al.* (1998a) indicate that the accumulation rate for the East Antarctic ice sheet surface has increased by a rate of 1.9 mm yr^{-1} (water equivalent) over the period 1950–1991. Their estimate of sensitivity is 12.5 mm yr^{-1} per degree of warming. Examination of water-mass properties of oceans shows that significant changes have occurred over the past 30 years. Bindoff and McDougall (2000) and Wong *et al.* (1999) point out that sub-Antarctic mode water (SAMW) and Antarctic intermediate water (AAIW) have become less saline and cooler, and both water masses are now deeper. These changes indicate surface warming in the source region of SAMW and increased precipitation in the source region of AAIW.

Jacka and Budd (1998) found no significant trends in Antarctic sea-ice data over the satellite era (1973–1996). Although the mean trend is zero, the sector from 0° to 40°E has a clear trend toward increased sea ice. This is matched by a larger sector of decreasing extent near the Bellingshausen and Amundsen Seas, from about 65°W to 160°W. Elsewhere, sea-ice extent trends are relatively small (see Figure 16-4)—a finding that also is supported by Cavalieri *et al.* (1997). Analysis of whaling records by de la Mare (1997) suggests that the Antarctic summer sea-ice edge has moved southward by 2.8 degrees of latitude between the mid-1950s and the early-1970s. This suggests a decline in the area covered by sea ice of 25%. It should be noted, however, that the data used in this analysis span two distinct periods, during which differing whale species were harvested. Using atmosphere-ocean sea-ice models, the computations of Wu and Budd (1998) indicate that sea ice was more extensive over the past century, on the annual average by 0.7–1.2 degrees of latitude. It also was thicker by 7–13 cm than at present. Wu *et al.* (1999) conclude that the sea-ice extent reduced by 0.4–1.8 degrees of latitude over the 20th century.

16.1.4. Scenarios of Future Change

The IPCC commissioned a *Special Report on Emissions Scenarios* (SRES). Four "marker scenarios" representing different world storylines are used to estimate emissions and climate change to 2100 (IPCC, 2000). Table 16-1 summarizes these climate projections for the polar regions. In almost all cases, predicted climates are well beyond the range of variability of current climate. However, these estimates cover a very large range of precipitation and temperatures, so future climate remains uncertain except that it will be wetter and warmer. Some of the projected increases in precipitation and temperatures are larger than for any other part of the globe.

Table 16-1*: IPCC SRES climate scenarios for 2080. Values are changes from present climate summarized from Carter et al. (2000), and are scaled output of nine AOGCMs.*

	Summer		**Winter**	
Region	Precipitation (%)	Temperature (°C)	Precipitation (%)	Temperature (°C)
Arctic				
– Land	+10–20[a]	+4.0–7.5	+5–80	+2.5–14.0
– Arctic Ocean	+2–25[b]	+0.5–4.5	+2–45[c]	+3.0–16.0
Antarctica Land	+1–28	+1.0–4.8	+4–32	+1.0–5.0
Southern Ocean	+2–17	+0.0–2.8	+5–20	+0.5–5.0

[a]CSIRO-mk2 model predicts +38%.
[b]CSIRO-mk2 model predicts +42%.
[c]ECHAM4 model predicts +70%.

Models predict that land areas in the Arctic will receive substantially increased snowfall in winter and that the climate will be markedly warmer. Summer could be much warmer and wetter than present. The climate over the Arctic Ocean does not change as dramatically, but it will become warmer and wetter by 2080. For the Antarctic continent, the models tend to predict more snow in winter and summer. Although temperatures are forecast to increase by 0.5°C, there will be little impact on melt because they will remain well below freezing, except in limited coastal localities. The Southern Ocean warms least, especially in summer. Precipitation increases by as much as 20%, so there will be more freshwater input to the ocean surface. This chapter also refers to other climate models. Some are equilibrium models for the atmosphere only; others are transient, coupled atmosphere-ocean models. Some deal with aerosols and other do not. In polar regions there can be large differences in predictions, depending on the model chosen, although most predict large changes in climate over the next 100 years. Assessments of impacts will vary, depending on the climate model chosen. This should be kept in mind in assessing the impacts described in this chapter.

Discrepancies among climate models and problems of downscaling (Shackley *et al.*, 1998) mean that alternative methods of prediction that are based on analysis of empirical climate data (e.g., palaeoclimatic analogs and extrapolation of recent instrumental records) still have value. Anisimov and Poljakov (1999) analyzed modern temperature trends over the northern hemisphere; they suggest that warming in the Arctic will be most pronounced in the continental parts of North America and Eurasia. The potential impacts of continued deepening of the winter polar vortex would include weakening of the wind-driven Beaufort Gyre. This would further reduce the extent and thickness of the Arctic pack ice (McPhee *et al*., 1998) and change ocean temperatures and sea-ice boundaries (Dickson *et al*., 1999).

16.2. Key Regional Concerns

This chapter follows the agreed TAR template for WGII regional assessments. Rather than assessing all possible impacts of climate change, emphasis is placed on eight key regional concerns. These concerns are chosen for the Arctic and the Antarctic on the basis of earlier findings by the IPCC (Everett and Fitzharris, 1998) and on discussions at various workshops of the TAR. They represent what are considered to be the most important impacts of future climate change in the Arctic and Antarctic in the wider global perspective. Although some other impacts (e.g., Arctic glaciers and terrestrial Antarctic biota) may be very important locally, space does not permit a comprehensive review.

16.2.1. Changes in Ice Sheets and Glaciers

Changes in the polar climate will have a direct impact on the great ice sheets, ice caps, and glaciers of the polar regions. How each responds will depend on several climatological parameters; some will grow, whereas others shrink. We have high confidence that their overall contribution to rising sea level will be positive, with glaciers and the Greenland ice sheet shrinking. The contribution from Antarctica, however, is uncertain at present. There is a high likelihood that increasing temperatures over the continent and changing storm tracks will cause increased precipitation and thickening of the ice sheet, but there still exists at low confidence the possibility that the West Antarctic ice sheet will retreat dramatically in coming centuries (Vaughan and Spouge, 2000). Such a change would not result from recent and future climate change (Bentley, 1998) but more probably from continuing readjustment to the end of the last glacial period (Bindschadler, 1998), as a result of internal dynamics of the ice sheet (MacAyeal, 1992), or as a result of ice shelf-ocean interaction. This subject and the general issue of sea-level rise are reviewed more comprehensively in TAR WGI Chapter 11; we include only a summary of the main points here.

The Greenland ice sheet suffers melting in summer at its margin. There is a trend toward an increase in the area and duration of this melt (Abdalati and Steffen, 1997). This trend is likely to continue. Airborne altimetric monitoring has shown that over the period 1993–1998, the Greenland ice sheet was slowly thickening at higher elevations; at lower elevations, thinning (about 1 m yr^{-1}) was underway (Krabill *et al.*, 1999, 2000). If warming continues, the Greenland ice sheet will shrink considerably, as occurred in previous interglacial periods (Cuffey and Marshall, 2000), and if the warming is sustained, the ice sheet will melt completely (see TAR WGI Chapter 11).

Over the Antarctic ice sheet, where only a few limited areas show summer melting (Zwally and Fiegles, 1994), a slight thickening is likely as precipitation rates increase (e.g., Ohmura *et al*., 1996; Smith *et al*., 1998a; Vaughan *et al*., 1999). In the past decade there has been some change in the ice cover in local areas (e.g., on the Antarctic Peninsula; see Section 16.2.2), but the majority of the Antarctic ice sheet appears, from satellite altimetry, to be close to a state of balance (Wingham *et al.*, 1998). Only the Thwaites and Pine Island glacier basins show any spatially coherent trend, but it is not yet known if their thinning is related to a decrease in precipitation or some dynamic change in the ice sheet. Chinn (1998) reports that recession is the dominant change trend of recent decades for glaciers of the Dry Valleys area of Antarctica. The future of glaciers in the Arctic will be primarily one of shrinkage, although it is possible that in a few cases they will grow as a result of increased precipitation.

This report is concerned primarily with the impacts of climate change on particular regions. An important question is: How will changes in glacial ice in the polar regions impact local human populations and ecological systems, and what will be the socioeconomic consequences? The short answer is that impacts on ice systems will be substantial, but because the populations of humans and other biota within polar region are low, impacts may be relatively minor. In Antarctica, the continental human population is only a few thousand. A few localities may undergo changes such as that at Stonington Island on the Antarctic Peninsula (Splettoesser, 1992), where retreat of the ice sheet has left the station stranded on an island. In general, however, changes to ice sheets will directly cause few significant life-threatening problems.

16.2.2. Changes around the Antarctic Peninsula

At least five meteorological records from scientific stations on the Antarctic Peninsula show marked decadal warming trends (King, 1994; Harangozo *et al.*, 1997; King and Harangozo, 1998; Marshall and King, 1998; Skvarca *et al.*, 1998). Although the periods and seasons of observations have been different, the records show consistent warming trends—as much as 0.07°C yr^{-1}, considerably higher than the global mean. This atmospheric warming has caused several notable changes in the ice cover of the Antarctic Peninsula, including changes in snow elevation (Morris and Mulvaney, 1995; Smith *et al.*, 1999a) and the extent of surface snow cover (Fox and Cooper, 1998). The most important change has been the retreat of ice shelves. Seven ice shelves on the Antarctic Peninsula have shown significant, progressive, and continued retreat. On the West Coast, the Wordie Ice Shelf, Müller Ice Shelf, George VI Ice Shelf, and Wilkins Ice Shelf have retreated (Ward, 1995; Vaughan and Doake, 1996; Luchitta and Rosanova, 1998). On the east coast, the ice shelves that occupied Prince Gustav Channel and Larsen Inlet and Larsen Ice Shelf Ahave retreated (Rott *et al.*, 1996; Vaughan and Doake, 1996; Skvarca *et al.*, 1998). Following Mercer (1978), Vaughan and Doake (1996) show that the pattern of retreat could be explained by a southerly movement of the 0°C January isotherm, which appears to define a limit of viability for ice shelves. To date, about 10,000 km^2 of ice shelf have been lost.

Retreat of the ice shelves on the Antarctic Peninsula has attracted considerable media coverage, and environmental campaigns of some nongovernmental organizations (NGOs) have expressed concern that these events presage a more important collapse of the West Antarctic ice sheet. However, few direct impacts result from the loss of these ice shelves. The ice shelves were floating, so their melting does not directly add to sea level, and they usually are replaced by sea-ice cover, so overall albedo changes very little. Because the Antarctic Peninsula is steep and rugged, there is no evidence that removal of ice shelves will cause melting of the glaciers that fed them to accelerate and add to sea-level rise (Vaughan, 1993). Terrestrial ecosystems generally will be unaffected by ice-shelf retreat. Most polar benthic organisms, especially in the Antarctic, grow extremely slowly, so colonization of exposed seabed will be slow.

Because warming on the Antarctic Peninsula exceeds that over much of the rest of the continent (Jacka and Budd, 1998), migration of the limit of viability for ice shelves probably will not affect the Ronne-Filchner or Ross ice shelves in the next 100 years (Vaughan and Doake, 1996). A substantial increase in Antarctic summer temperatures, however, would threaten other large ice shelves beyond the Antarctic Peninsula. The real implications of ice-shelf retreat are that it highlights issues of risk perception and public understanding of climate change, rather than real physical impacts. These issues include questions such as: Does the Antarctic Peninsula warming result from a global effect, or simply from natural regional climate variations? Such problems of attribution of climate change will recur, especially if the costs of adaptation are to be spread across nations. The inherent nonlinearity of natural systems sometimes causes exaggerated local responses to small climate changes. In the present generation of climate models, the Antarctic Peninsula is not well resolved, so local effects on these scales cannot yet be reproduced. Confidence in predicting such changes in the natural ecosystems of the Antarctic Peninsula comes from observed changes on the terrestrial biota of southern ocean islands (Bergstrom and Chown, 1999).

Rapidly increasing temperatures have been directly implicated in colonization by introduced species and displacement of indigenous biota. Thus, the extent of higher terrestrial vegetation on the Antarctic Peninsula currently is increasing (Fowber and Lewis Smith, 1994). In the marine environment, the warming trend on the Antarctic Peninsula has been linked statistically to an associated change in sea ice for this region (Stammerjohn and Smith, 1996). For example, Smith *et al*. (1999b) show that rapid climate warming and associated reduction in sea ice are concurrent with a shift in the population size and distribution of penguin species in the Antarctic Peninsula region.

16.2.3. Changes in the Southern Ocean and Impacts on its Life

16.2.3.1. Overview

The Southern Ocean is an active component of the climate system that causes natural climate variability on time scales from years to centuries. It is a major thermal regulator and has the potential to play an active role in climate change by providing important feedbacks. If climate change is sustained, it is likely to produce long-term and perhaps irreversible changes in the Southern Ocean. These changes will alter the nature and amount of life in the ocean and on surrounding islands, shores, and ice. The impact of climate change is likely to be manifest in the large-scale physical environment and in biological dynamics. There even is the possibility that changes in the Southern Ocean could trigger abrupt and very long-term changes that affect the climate of the entire globe.

16.2.3.2. Role of Ocean Changes

The Southern Ocean is of special significance to climate change because of the variety of water masses produced there and the ability of these waters to spread throughout the global ocean. In particular, shelf waters with temperatures near the freezing point (about -1.9°C) are produced along the margin of the Antarctic continent. They contribute to the formation of Antarctic bottomwater and continuing ventilation of this water in the world's oceans (Whitworth *et al.*, 1998). There already is evidence that climate change has altered SAMW and AAIW (Johnson and Orsi, 1997; Wong *et al*., 1999; Bindoff and McDougall, 2000). Wong *et al*. (1999) compared trans-Pacific sections 20 years apart and found temperature and salinity changes that are consistent with surface warming and freshening in formation regions of the water masses in the Southern Ocean and their subsequent subduction into the ocean.

The main contributions to the production of Antarctic bottomwater come from cooling and transformation of seawater under the floating Filchner-Ronne and Ross ice shelves, as well as from dense water formed as a result of freezing of sea ice. Polynyas also are important. These areas of combined open water and thin sea ice (surrounded by sea ice or land ice) play an important role in ocean-atmosphere heat transfer, ice production, formation of dense shelf water, spring disintegration of sea ice, and sustenance of primary and secondary productivity in polar regions. Their formation is linked to the strength and persistence of cold outflow winds off the Antarctic continent and the position of the polar jet stream and Southern Ocean atmospheric circulation patterns (Bromwich *et al.*, 1998).

Research by Wu *et al*., (1997), Budd and Wu (1998), and Hirst (1999)—using the CSIRO coupled, transient model and IPCC IS92a emissions scenario—suggests that certain aspects of Southern Ocean circulation may be very sensitive to climate change. With an increase in atmospheric equivalent CO_2, there is a substantial increase in the strength of the near-surface halocline and a potential reduction in the formation of Antarctic bottomwater and convection in the Southern Ocean. The decrease in downwelling of cold, dense water, as shown in Figure 16-5, leads to a slowdown in the thermohaline circulation

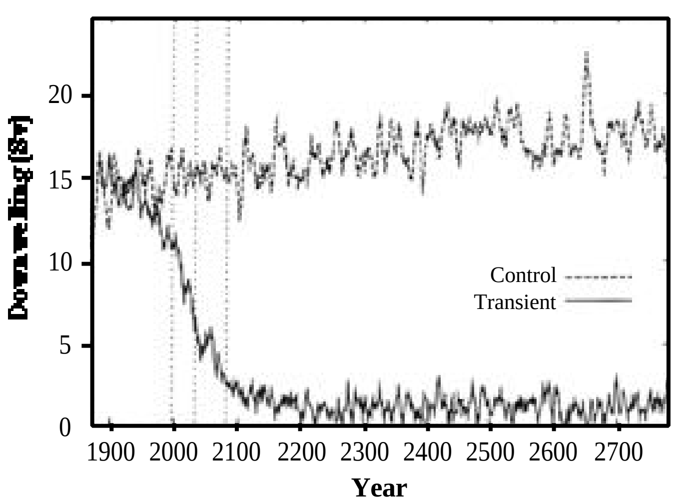

Figure 16-5: Volume transport of Antarctic downwelling past 1,250-m depth level for control and transient climate integrations. Values are in Sverdrups (Sv), filtered using a 7-year running mean, and are for the area of the Southern Ocean between Antarctic coast and 45°S (from Hirst, 1999, Figure 11).

(Broecker *et al*., 1985). A tripling of GHGs is sufficient to induce a shutdown of the thermohaline circulation. Furthermore, this shutdown continues for at least several centuries, to the end of the model integration. The main processes causing a decline in the thermohaline circulation are an increase in precipitation minus evaporation, an increase in glacial melt from the Antarctic, and reduced sea-ice formation, so there is less brine injection into the ocean.

According to this simulation, if concentrations of GHGs continue to grow to the end of the 21st century, there will be significant weakening of the ocean's thermohaline circulation and even potential for its shutdown. These changes might become irreversible in subsequent centuries, despite possible stabilization of GHG concentrations. Modeling by Cai and Baines (1996) indicates that the Antarctic Circumpolar Current is driven at least partly by the thermohaline circulation associated with the formation of Antarctic bottomwater, so this major current of the Southern Ocean also can be expected to slow down. This result is confirmed by Cai and Gordon (1998), who found a clear decreasing trend in the magnitude of the Antarctic Circumpolar Current as CO_2 increases. The foregoing results indicate an ocean circulation that is significantly more sensitive to climate change than that found by Manabe and Stouffer (1994). The possibility remains that certain factors and parameterizations in the Hirst (1999) model could make it overly sensitive and that future changes may not be as dramatic as indicated. For example, in other models the ocean component is much less diffusive, allowing for prolonged maintenance of an enhanced halocline. None of the present generation of climate models can resolve polynyas, where the majority of brine rejection takes place and dense water masses form. These processes need to be better represented in coupled ocean-climate models before the timing of any substantial slowing of Antarctic bottomwater production or of any shutdown of the ocean thermohaline circulation can be predicted confidently. Changes in this circulation also may be driven by variable fluxes at lower latitudes, and results from different ocean models indicate uncertainty about the magnitude and timing of thermohaline slowdown (see TAR WGI Chapter 7 for more detailed discussion of the global thermohaline circulation).

16.2.3.3. *Role of Ice Shelves*

The sensitivity of the Southern Ocean to changes in ice shelves remains uncertain (Williams *et al.*, 1998a,b); it depends on whether there is free access of oceanic water to their underside (Nicholls, 1997). Circulation of meltwater under the ice shelves is complex. Any increase in melting as a result of global warming initially will introduce a fresher layer of water (see Jacobs *et al.*, 1992; Jenkins *et al*., 1997; O'Farrell *et al.*, 1997). This could restrict further melting, unless the current or tides are strong enough to flush the fresher layer away or entrain it into other water masses. Using a three-dimensional model adapted to the underside of the Amery Ice Shelf, Williams *et al.* (1998b) conclude that when the adjacent seas were warmed by 1°C, net melt increased more than three-fold.

Grosfeld and Gerdes (1998) also show increased net melt with warming, but the situation stabilizes if there is less sea-ice formation. In considering the long-term response of the Antarctic ice sheet to global warming of 3°C, Warner and Budd (1998) show that it takes at least several centuries for the ice shelves to disappear in their model.

16.2.3.4. Impacts on Biology of Southern Ocean

No single factor controls overall primary production in the Southern Ocean. The organisms in Antarctic marine communities are similar to the inhabitants of marine systems at lower latitudes, although there is substantial endemism in Antarctica (Knox, 1994). Ice cover and vertical mixing influence algae growth rates by modulating the flux of solar radiation (Priddle *et al.*, 1992). Micronutrients, especially iron, are likely to limit phytoplankton growth in some areas. Experiments involving addition of iron to the ocean show dramatic increases in the biological activity of phytoplankton (de Baar *et al.*, 1995; Coale *et al.*, 1996; Sedwick *et al.*, 1999). Findings by Boyd *et al.* (2000) demonstrate that iron supply controls phytoplankton growth and community composition during the summer, but the fate of algal carbon remains unknown and depends on the interplay between processes that control export, remineralization, and water-mass subduction. Grazing by zooplankton also may be important.

Several of the physical controls on phytoplankton production are sensitive to climate change. Although it is presently impossible to make numerical predictions, these controls have been outlined in a qualitative way by Priddle *et al.* (1992). They consider that projected changes in water temperature and wind-induced mixing of the Southern Ocean will be too small to exert much effect but that changes in sea ice are likely to be more important. Release of low-salinity water from sea ice in spring and summer is responsible for developing the shallow mixed layer in the sea-ice marginal zone—an area of the Southern Ocean that is nearly as productive as the coastal zone (Arrigo *et al.*, 1998)—and plays a major role in supporting other marine life. Projected reductions in the amount of sea ice (Section 16.2.4.2) may limit the development of the sea-ice marginal zone, with a consequential impact on biota there. On the other hand, greater freshening of the mixed ocean layer from increased precipitation, ice-sheet runoff, and ice-shelf melting might have a compensating effect. It seems that the sea-ice marginal zone, under-ice biota, and subsequent spring bloom will continue, but shift to more southern latitudes, as a consequence of the retreat of the ice edge.

Research also demonstrates that the biological production of the Antarctic food web is linked closely to physical aspects of the ocean and ice ecosystem. Matear and Hirst (1999) point out that changes in ocean circulation will impact ocean biological production. They project a reduction in biological export from the upper ocean and an expansion of the ocean's oligotrophic regions. This will alter the structure and composition of the marine ecosystem. For example, interdecadal variations in sponge/predator population and in anchor/platelet ice at depths shallower than 30 m appear to be related to alterations in regional currents and ocean climate shifts (Jacobs and Giulivi, 1998). Changes in ocean currents could bathe new areas of the sea floor in near-freezing water, so that anchor ice and ice crystals will rise through the water column. This will be a liability for some benthic species. On the other hand, there could be a fresher and more stable layer, which could lead to changes in phytoplankton community structure (Arrigo *et al*., 1999), and stronger ocean fronts. Both of these physical changes would be beneficial to many parts of the marine ecosystem. A 20% decline in winter and summer sea ice since 1973 west of the Antarctic Peninsula region (Jacobs and Comiso, 1997) has led to a decline in Adelie penguins, which are obligate inhabitants of pack ice. By contrast, Chinstrap penguins in open water have increased in numbers (Fraser *et al*., 1992; Ainley *et al.*, 1994). Krill recruitment around the Antarctic Peninsula seems to be dependent on the strength of the westerlies and sea-ice cover, with a 1-year lag (Naganobu *et al.*, 2000). Both will decrease in the future, so there will be less krill.

The direct effect of a change in temperature is known for very few Antarctic organisms. Much of the investigation on ecophysiology has concentrated on adaptations to living at low temperature, with relatively little attention devoted to their response to increasing temperatures. Few data are available to assess quantitatively the direct and indirect impacts of climate change. Perhaps the best-studied example of temperature affecting the abundance of marine microorganisms is the increased rate of production of the cyanobacterium *Synechococcus* with increasing temperature, which approximately doubles for an increase in temperature of 2.5°C (Marchant *et al.*, 1987).

The virtual absence of cyanobacteria represents a fundamental difference between the microbial loop in Antarctic waters compared to that in temperate and tropical waters. As discussed by Azam *et al.* (1991), metazoan herbivores apparently cannot directly graze *Synechococcus*; their production must be channelled through heterotrophic protists able to consume this procaryote. Adding another trophic step reduces the energy available to higher trophic levels. Coupled with the direct utilization of nanoplankton by grazers, this may account in part for high levels of tertiary production in the Southern Ocean, despite relatively low levels of primary production (but see Arrigo *et al.*, 1998). Any increase in water temperature will increase the concentration of cyanobacteria and the heterographs that graze them. It is possible that the prey for krill and other grazers also will change, but the ultimate effects are unknown. Changes in the microbial loop may lessen carbon drawdown because of increased respiration by heterotrophs. Furthermore, there is an apparent uncoupling of bacterioplankton and phytoplankton assemblages that contrasts with temperate aquatic ecosystems (Bird and Kalff, 1984; Cole *et al*., 1988; Karl *et al*., 1996). The structure and efficiency of the Antarctic marine food web is temporally variable, and Karl (1993) has suggested that it is reasonable to expect several independent (possibly overlapping in space and time) food webs. There is no consensus with respect to the importance of bacteria and their consumers within this food web or their degree of interaction with photoautotrops. Bird and Karl (1999) have demonstrated, however, that uncoupling of the microbial loop in coastal waters during the spring bloom period was the direct result of protistan grazing. Although underlying mechanisms remain unclear, the distinct difference of the microbial loop in Antarctic waters, compared to more temperate waters, suggests that climate change will have profound effects on the structure and efficiency of the Southern Ocean food web.

An increase in temperature is likely to lead to shifts in species assemblages. Organisms that are unable to tolerate the present low-temperature regime will invade the Southern Ocean. Some that already are there will exhibit increased rates of growth. Predicted reductions in the extent and thickness of sea ice will have ramifications not only for the organisms directly associated with sea ice but also for those that rely on oceanographic processes that are driven by sea-ice production. In the open ocean, there is a correlation between the standing crop and productivity of phytoplankton with wind speed (Dickson *et al.*, 1999). Diatoms—the dominant phytoplanktonic organisms in the Southern Ocean—have high sinking rates and require a turbulent mixed zone to remain in the photic zone. If climate change results in diminution of wind forcing of surface mixing, a reduced biomass of diatoms can be expected. This would lead to less available food for the higher trophic levels and diminution in the vertical flux of carbon and silicon. Together, these effects are likely to have a profound impact on Antarctic organisms at all trophic levels, from algae to the great whales.

Any reduction in sea ice clearly represents a change in habitat for organisms that are dependent on sea ice, such as Crabeater seals and Emperor penguins. Some species of penguins and seals are dependent on krill production. Increased ultraviolet irradiance from ozone depletion is likely to favor the growth of organisms with UV-protecting pigments and/or repair mechanisms (Marchant, 1997; Davidson, 1998). This will lead to a change in species composition and impact trophodynamics and vertical carbon flux. Naganobu *et al.* (2000) show evidence that ozone depletion impacts directly and indirectly on krill density. The growth, survival, and hatching rates of penguin chicks and seal pups are directly influenced by krill abundance in the sea. Animals that migrate great distances, such as the great whales and seabirds, are subject to possible disruptions in the timing and distribution of their food sources. Contraction of sea ice may alter migration patterns but would not be expected to present a major problem to such mobile animals. Other marine mammals (seals, sea lions) have life histories that tie them to specific geographic features such as pupping beaches, ice fields, or sub-Antarctic islands; they may be more severely affected by changes in the availability of necessary habitats and prey species that result from climate change.

Box 16-1. Climate Change and Fisheries

The Southern Ocean has large and productive fisheries that constitute part of the global food reserve. Currently, there are concerns about sustainability, especially with regard to species such as Patagonian toothfish. There are likely to be considerable changes in such fisheries under the combined pressures of exploitation and climate change. Spawning grounds of coldwater fish species are very sensitive to temperature change. Warming and infusion of more freshwater is likely to intensify biological activity and growth rates of fish (Everett and Fitzharris, 1998). Ultimately, this is expected to lead to an increase in the catch of marketable fish and the food reserve. This could be offset in the long term by nutrient loss resulting from reduced deepwater exchange. Fisheries on the margin of profitability could prosper because the retreat of sea ice will provide easier access to southern waters. Everett and Fitzharris (1998) discuss catch-per-unit-effort (CPUE) statistics from the commercial krill fishery operating around South Georgia and demonstrate that there is correlation with ice-edge position. The further south the ice, the lower the CPUE in the following fishing season. Fedoulov *et al.* (1996) report that CPUE also is related to water temperature and atmospheric circulation patterns, and Loeb *et al.* (1997) document the close relationships between seasonal sea-ice cover and dominance of either krill or salps (pelagic tunicates). Ross *et al*. (2000) identify that maximum krill growth rates are possible only during diatom blooms and that production in Antarctic krill is limited by food quantity and quality. Consequently, differences in the composition of the phytoplankton community caused by changes in environmental conditions, including climate change, will be reflected at higher trophic levels in the grazer community and their levels of productivity.

Arctic fisheries are among the most productive in the world. Changes in the velocity and direction of ocean currents affect the availability of nutrients and disposition of larval and juvenile organisms, thereby influencing recruitment, growth, and mortality. Many groundfish stocks also have shown a positive response to recent climate change (NRC, 1996), but Greenland turbot—a species that is more adapted to colder climates—and King crab stocks in the eastern Bering Sea and Kodiak have declined (Weller and Lange, 1999). Projected climate change could halve or double average harvests of any given species; some fisheries may disappear, and other new ones may develop. More warmer water species will migrate poleward and compete for existing niches, and some existing populations may take on a new dominance. These factors may change the population distribution and value of the catch. This could increase or decrease local economies by hundreds of millions of dollars annually.

16.2.4. Changes in Sea Ice

Sea ice is a predominant feature of the polar oceans. Its extent expands and contracts markedly from winter to summer. Sea ice has a dramatic effect on the physical characteristics of the ocean surface. The normal exchange of heat and mass between the atmosphere and ocean is strongly modulated by sea ice, which isolates the sea surface from the usual atmospheric forcing (Williams *et al.*, 1998a). In addition, sea ice affects albedo, the exchange of heat and moisture with the atmosphere, and the habitats of marine life. Finally, sea ice plays a significant role in the thermohaline circulation of the ocean. Changes in air temperature expected with projected climate change are likely to alter the sea-ice regime and hence have impacts on the foregoing mechanisms.

Warming is expected to cause a reduction in the area covered by sea ice, which in turn will allow increased absorption of solar radiation and a further increase in temperature. In some climate models, this sea ice-albedo feedback has led to amplification of projected warming at higher latitudes, more in the Arctic Ocean than in the Southern Ocean. At some point, with prolonged warming a transition to an Arctic Ocean that is ice-free in summer—and perhaps even in the winter—could take place. The possibility of a transition to an ice-free Arctic Ocean that is irreversible also must be considered. Climate models predict a wide range of changes for polar sea ice by the year 2100 (see TAR WGI Chapter 1). Many of the earlier models treated sea ice very simplistically and were not coupled with the ocean, so their results are unlikely to be reliable. More recent climate models include sophisticated sea-ice routines that take into account the dynamics and thermodynamics that control sea-ice formation, transport, and melt (Everett and Fitzharris, 1998). These models, however, still are limited in their ability to reproduce detailed aspects of sea-ice distribution and timing.

Snow on sea ice controls most of the radiative exchange between the ocean and atmosphere, but its exact role in energy transfer is uncertain (Iacozza and Barber, 1999) and difficult to model because of a lack of adequate data (Hanesiak *et al.*, 1999; Wu *et al*., 1999). A further complication is the timing of snowfall in relation to formation of sea ice (Barber and Nghiem, 1999). Accumulation of snow on sea ice also plays a significant role in sub-ice primary production and for habitats of marine mammals (e.g., polar bear and seals).

16.2.4.1. Sea Ice in the Arctic Ocean

Whether the sea ice in the Arctic Ocean will shrink depends on changes in the overall ice and salinity budget, the rate of sea-ice production, the rate of melt, and advection of sea ice into and out of the Arctic Basin. The most important exit route is through Fram Strait (Vinje *et al.*, 1998). The mean annual export of sea ice through Fram Strait was ~2,850 km³ for the period 1990–1996, but there is high interannual variability caused by atmospheric forcing and, to a lesser degree, ice thickness variations. Other important passages are the northern Barents Sea and through the Canadian Arctic Archipelago (Rothrock *et al*., 1999). Analyses by Gordon and O'Farrell (1997), using a dynamic ice routine with a transient coupled atmosphere-ocean climate model (Commonwealth Scientific and Industrial Research Organisation—CSIRO), predict a 60% loss in summer sea ice in the Arctic for a doubling of CO_2. The summer season, during which ice retreats far offshore, increases from 60 to 150 days. The likely distance between northern coasts and Arctic pack ice will increase from the current 150–200 to 500–800 km.

In a more recent study, there is good agreement between Arctic sea-ice trends and those simulated by control and transient integrations from the Geophysical Fluid Dynamics Laboratory (GFDL) and the Hadley Centre (see Figure 16-6). Although the Hadley Centre climate model underestimates sea-ice extent and thickness, the trends of the two models are similar. Both models predict continued decreases in sea-ice thickness and extent (Vinnikov *et al*., 1999), so that by 2050, sea-ice extent is reduced to about 80% of area it covered at the mid-20th century.

GCM simulations for Arctic sea ice predict that warming will cause a decrease in maximum ice thickness of about 0.06 m per °C and an increase in open water duration of about 7.5 days per °C (Flato and Brown, 1996). These projections are somewhat lower than changes observed during the latter part of the 20th century (see Section 16.1.3). Increased snowfall initially causes a decrease in maximum thickness (and corresponding increase in open-water duration), but beyond 4 mm per day (1.33 mm per day water equivalent), formation of "slush ice" by surface

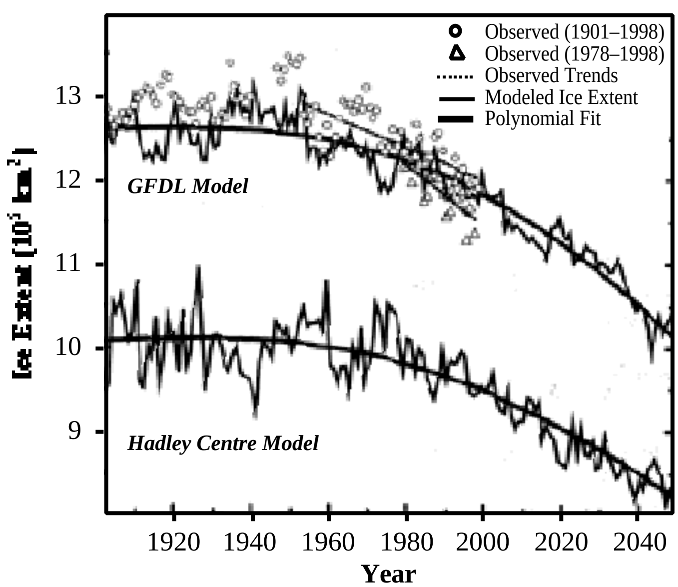

Figure 16-6: Observed and modeled variation of annual averages of Arctic sea-ice extent, based on Vinnikov *et al*. (1999). Observed data are from Chapman and Walsh (1993) and Parkinson *et al*. (1999). Sea-ice curves are produced by GFDL low-resolution R15 climate model and by HADCM2 climate model, both forced by CO_2 and aerosols.

flooding offsets the insulating effect of snow and causes an increase in maximum thickness and a decrease in the duration of open water.

Without sea ice, wave heights will increase, and the Arctic coast will be more exposed to severe weather events such as storm surges that cause increased coastal erosion, inundation, and threat to structures. Areas of ice-rich permafrost are particularly vulnerable to coastal erosion (Nairn *et al.*, 1998; Wolfe *et al.*, 1998). A portent of the future is severe coastal erosion—as much as 40 m yr^{-1}—along the Siberian coast. Deposited organic material changes the entire biogeochemistry of the nearshore waters (Weller and Lange, 1999).More open water may lead to increased precipitation and further amelioration of temperatures. Projected losses in sea ice are likely to have considerable impacts on Arctic biology through the entire food chain, from algae to higher predators (e.g., polar bears and seals). Loss of sea ice also will affect indigenous peoples and their traditional ways of life. A more open ocean will favor increased shipping along high-latitude routes and could lead to faster and cheaper ship transport between eastern Asia, Europe, and eastern North Amercia.

16.2.4.2. Sea Ice in the Southern Ocean

Antarctic sea ice is not confined by land margins but is open to the Southern Ocean. Sea-ice extent contracts and expands on an annual cycle in a roughly concentric zone around Antarctica. The ultimate extent is controlled by a balance of air temperature, leads, wind direction, upper ocean structure, and pycnocline depth. Some of these parameters are controlled in the atmosphere by the relative position of the subpolar trough with respect to the sea ice. In the ocean, variations in the Antarctic Circumpolar Current are important. The extent and thickness of Antarctic sea ice are sensitive to the depth and thermal properties of overlying snow, about which relatively little is known.

A reduction in Antarctic sea ice volume of about 25–45% is predicted for a doubling of CO_2, with sea ice retreating fairly evenly around the continent (Gordon and O'Farrell, 1997). This CSIRO model assumes a 1% yr^{-1} compounding increase of CO_2, corresponding to global warming of 2.1°C. Using a similar but modified model that has a higher albedo feedback and predicted global warming of 2.8°C, Wu *et al*. (1999) calculate a reduction in mean sea-ice extent of nearly two degrees of latitude, corresponding to 45% of sea-ice volume. These estimates do not represent the equilibrium state, and sea ice can be expected to shrink further, even if GHGs are stabilized. Changes in Antarctic sea ice will have little impact on human activity except where they allow shipping (mostly research, fishing, and tourist vessels) to get closer to the Antarctic continent. However, there are important biological and oceanographic impacts derived from reductions in sea ice, as well as significant ecological consequences attributable to changes in the magnitude and timing of seasonal sea-ice advance and retreat (Smith *et al*., 1999b).

16.2.5. Permafrost

The term *permafrost* refers to layers of earth materials at relatively shallow depth that remain below 0°C throughout 2 or more consecutive years, independent of material composition or ice content. The role of permafrost in the context of global change is three-fold (Nelson *et al*., 1993): It records temperature changes (Lachenbruch and Marshall, 1986), translates changes to other components of the environment (Osterkamp *et al.*, 2000), and facilitates further climatic changes through release of trace gases (Rivkin, 1998; Robinson and Moore, 1999). Permafrost is highly susceptible to long-term warming. Although it is an important factor in ice-free parts of Antarctica (Bockheim, 1995), permafrost is far more extensive in the continental areas of the subarctic and Arctic (Brown *et al.,* 1997; Zhang *et al*., 1999), and changes there have great potential to affect human activities adversely. Accordingly, frozen ground activity has been designated as a "geoindicator" for monitoring and assessing environmental change (Berger and Iams, 1996).

Most biological and hydrological processes in permafrost terrain are confined to the active (seasonally thawed) layer, which forms a boundary across which exchanges of heat, moisture, and gases occur between the atmospheric and terrestrial systems. Its thickness is a response to a complex interplay among several factors, including aboveground climate, vegetation type and density, snow-cover properties, thermal properties of the substrate, and moisture content. If other conditions remain constant, the thickness of the active layer could be expected to increase in response to climate warming. Long-term records of active-layer thickness are rare; those that do exist, however, indicate that variations occur at multiple temporal scales and are determined by climatic trends and local conditions at the surface and in the substrate (Nelson *et al*., 1998b).

16.2.5.1. Temperature Archive

Because heat transfer within thick permafrost occurs primarily by conduction, the shallow earth acts as a low-pass filter and "remembers" past temperatures. Temperature trends are recorded in the temperature-depth profile over time scales of a century or more (e.g., Lachenbruch and Marshall, 1986; Clow *et al*., 1998; Osterkamp *et al*., 1998; Taylor and Burgess, 1998). Permafrost is affected primarily by long-term temperature changes and thus contains a valuable archive of climate change (Lachenbruch and Marshall, 1986), although changes in snow cover must be taken into account. In contrast, the temperature regime of the overlying seasonally thawed active layer is highly complex, owing to nonconductive heat-transfer processes that operate much of the year (Hinkel *et al*., 1997).

Multi-decadal increases in permafrost temperature have been reported from many locations in the Arctic, including northern and central Alaska (Lachenbruch and Marshall, 1986; Osterkamp and Romanovsky, 1999), northwestern Canada (Majoriwicz and Skinner, 1997), and Siberia (Pavlov, 1996). Temperature increases are not uniform, however, and recent cooling of permafrost has been reported in northern Quebec (Wang and Allard, 1995). To obtain a more comprehensive picture of the spatial structure and variability of long-term changes in permafrost, the Global Terrestrial Network for Permafrost or (GTNet-P) (Brown *et al*., 2000; Burgess *et al*., 2000b) was developed in the 1990s. The program has two components: long-term monitoring of the thermal state of permafrost in a network of boreholes, and monitoring of active-layer thickness and processes at representative locations. The latter network—the Circumpolar Active Layer Monitoring (CALM) program (Nelson and Brown, 1997)—has been in operation since the mid-1990s and incorporates more than 80 stations in the Arctic and Antarctic. The CALM network includes components in which regional mapping (Nelson *et al*., 1999) and spatial time series analysis of active-layer thickness (Nelson *et al*., 1998a) are performed.

16.2.5.2. Predicted Changes in Permafrost

Figure 16-1 illustrates the geographic distribution of permafrost and ground ice in the northern hemisphere. Computations based on a digital version of the map by Brown *et al*. (1997) indicate that permafrost currently underlies 24.5% of the exposed land area of the northern hemisphere (Zhang *et al*., 1999). Under climatic warming, much of this terrain would be vulnerable to subsidence, particularly in areas of relatively warm, discontinuous permafrost (Osterkamp *et al.*, 2000). Anisimov and Nelson (1997) conducted experiments with a simple model of permafrost distribution driven by three transient GCMs (as reported by Greco *et al*., 1994). Figure 16-7 shows the mid-range result from this study; the area of the northern hemisphere occupied by permafrost eventually could be reduced by 12–22% of its current extent. Experiments by Smith and Burgess (1999) with a $2xCO_2$ GCM indicated that permafrost eventually could disappear from half of the present-day Canadian permafrost region. Thawing of ice-rich permafrost is subject, however, to considerable lag resulting from the large latent heat of fusion of ice. Simulations by Riseborough and Smith (1993), for example, indicate that areas of 5 m thick ice-rich permafrost near the southern limit of the discontinuous zone in subarctic Canada could thaw in less than 70 years. Where permafrost currently is thick, it could persist in relict form for centuries or millennia. Figure 16-7 therefore is best regarded as indicating areas in which considerable potential exists for changes in permafrost distribution. Nonetheless, pronounced changes in permafrost temperature, surface morphology, and distribution are expected (Smith and Burgess, 1998, 1999; Osterkamp and Romanovsky, 1999).

16.2.5.3. Environmental Impacts

The geological record of the Arctic shows abundant evidence for regional-scale deterioration of permafrost in response to climatic change. Thawing of ice-rich permafrost can result in subsidence of the ground surface and development of uneven and frequently unstable topography known as thermokarst terrain. In unglaciated parts of Siberia, alases (coalescing thaw depressions) formed during Holocene warm intervals occupy areas as large as 25 km^2. Cryostratigraphic studies in northwestern Canada have documented thaw unconformities in the form of truncated ice wedges associated with climatic warming during the early Holocene (Burn, 1997, 1998). Warming of permafrost and thaw subsidence has been reported widely from subarctic regions in recent years (Fedorov, 1996; Osterkamp and Romanovsky, 1999; Osterkamp *et al.*, 2000; Wolfe *et al.*, 2000; Zuidhoff and Kolstrup, 2000).

Changes in active-layer thickness could have marked impacts on local environments (Anisimov *et al*., 1997; Burgess *et al*., 2000a; Dyke, 2000). Thawing of perennially frozen subsurface materials will create few problems where permafrost is “dry” (Bockheim and Tarnocai, 1998). However, thawing of ice-rich permafrost can be accompanied by mass movements and subsidence of the surface, possibly increasing delivery of sediment to watercourses and causing damage to infrastructure in developed regions. Many recent examples of such phenomena already have been reported, and a poll conducted for the Canadian Climate Centre showed that most of the engineers interviewed think that climate warming is a very important factor for the stability of structures in permafrost regions (Williams, 1995; Vyalov *et al*., 1998; Weller and Anderson, 1999). Weller and Lange (1999) note that the bearing capacity of permafrost has decreased with warming, resulting in failure of pilings for buildings and pipelines, as well as roadbeds. Accelerated permafrost thawing has led to costly increases in road damage and maintenance. In Alaska, for example, it costs as much as US$1.5 million to replace 1 km of road system. However, eventual disappearance of permafrost reduces construction problems.

Degradation of permafrost, which depends on the precipitation regime and drainage conditions, poses a serious threat to Arctic biota through oversaturation or desiccation of the surface (Callaghan and Jonasson, 1995). Changes in permafrost and active-layer thickness will produce a complicated response. Development of thermokarst in relatively warm, discontinuous permafrost in central Alaska has transformed some upland forests into extensive wetlands (Osterkamp *et al*., 2000). In contrast, climatic warming in the northern foothills of the Brooks Range could lead to increasing plant density, resulting in evolutionary transitions from nonacidic to acidic tundra or shrub tundra. Despite increasing air temperature, such changes could prevent increases in active-layer thickness (Walker *et al.*, 1998).

16.2.6. Arctic Hydrology

The hydrological regime of the Arctic is particularly susceptible to predicted climate change because of the dominance of the thermally sensitive cryosphere and its controlling influence on the water cycle. Virtually all major hydrological processes and related aquatic ecosystems are affected by snow and ice processes, including the major Arctic rivers. Although these rivers originate in more temperate southern latitudes, they pass

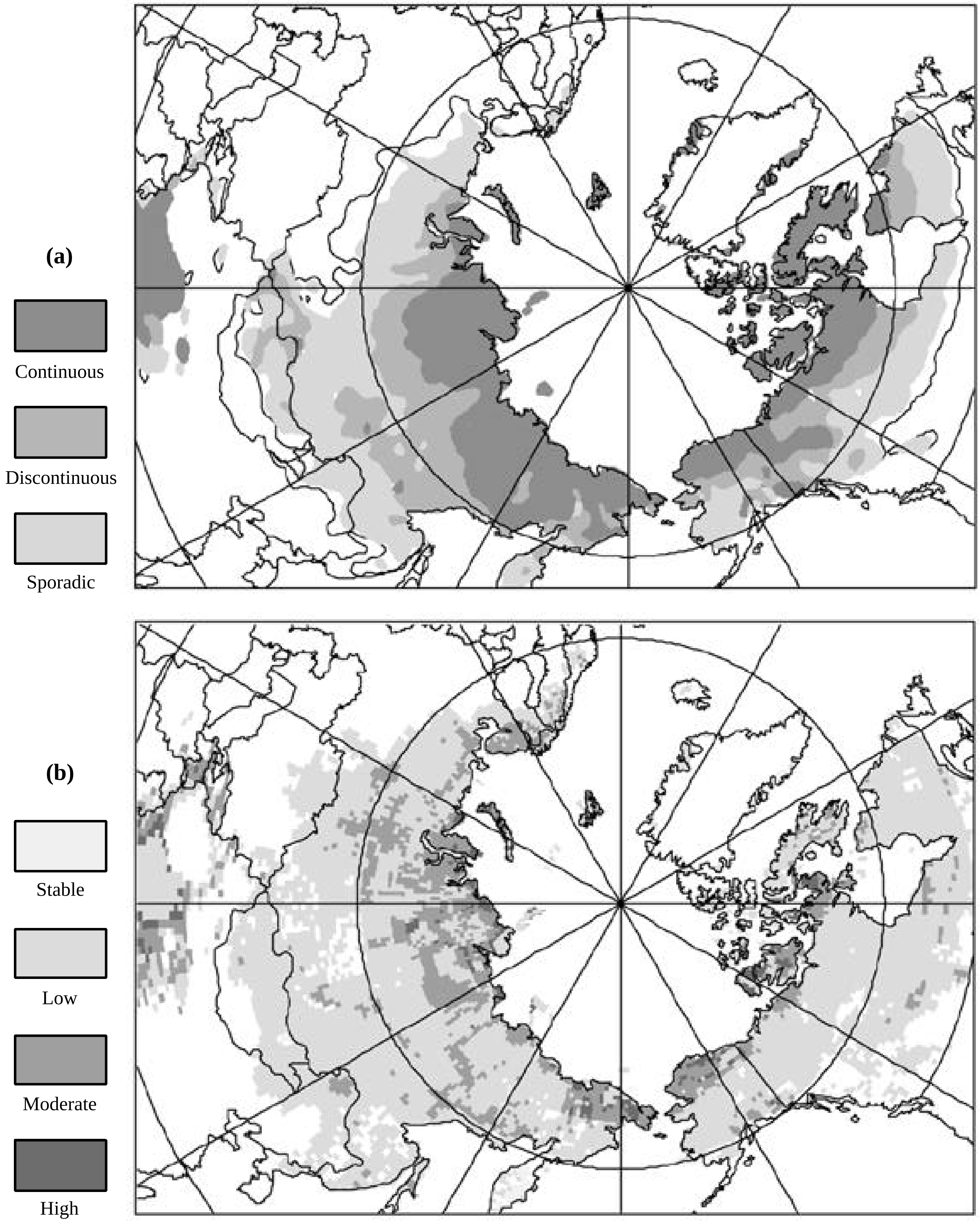

Figure 16-7: (a) Zonation of permafrost in the northern hemisphere under climate scenario predicted by ECHAM1-AGCM (Cubasch *et al*., 1992). (b) Hazard potential associated with degradation of permafrost under ECHAM1-A climate change scenario. Map represents areas of stable permafrost and low, moderate, and high susceptibility to subsidence. Classification is based on a "thaw-settlement index" calculated as the product of existing ground-ice content (Brown *et al*., 1997) and predicted increases in depth of thaw (Anisimov *et al*., 1997). Hazard-zone intervals were derived through division of resulting frequency distribution, using a nested-means procedure (Scripter, 1970).

through cold regions before reaching the Arctic Ocean. Changes in precipitation also have great potential for modifying the hydrology and sediment load in rivers, which could affect aquatic life (Michel and van Everdingen, 1994).

16.2.6.1. Changes in Precipitation, Snow Accumulation, and Spring Melt

Almost all climate models forecast increases in precipitation; but estimates vary widely and are complicated by many other factors, such as clouds (Stewart, 2000). Combined changes in temperature and precipitation will produce changes in the pattern of snow storage and, ultimately, Arctic hydrology. Warmer conditions generally will reduce the length of winter. Seasonal snow accumulation could increase in higher elevation zones, especially above the freezing level, where there would be little summer melt. Increased summer storminess will reduce melt at intermediate elevations as a result of increased cloud and summer snowfall, so many existing semi-permanent snowpacks will continue to exist (Woo, 1996). At lower elevations, particularly in the more temperate maritime zones, rainfall and rain-on-snow melt events probably will increase.

An earlier transition from winter to spring will mean that snowmelt will be more protracted, with less intense runoff. This will be accentuated where increased active-layer thickness and loss of permafrost increases the water storage capacity of the ground, leading to a decrease in runoff. Summer base flow will increase. Overall, this means that there will be less seasonal fluctuation in runoff through the year (Rouse *et al.*, 1997).

16.2.6.2. Surface Water Budgets and Wetlands

Predicted climate change will lead to greater evaporation and transpiration. Transpiration should increase as nontranspiring lichens and mosses that currently dominate the tundra regions are replaced by a denser cover of vascular plants (Rouse *et al.*, 1997). These changes are likely to reduce the amount of ponded water and runoff. The unglaciated lowlands of many Arctic islands, where special ecological niches occur, are likely to be especially sensitive. For coastal areas, changes to local micro-climates may occur because longer open-water seasons in the adjacent sea will lead to more frequent fog and low clouds, as well as reduced incident solar radiation. These changes may limit the expected increase in evaporation and transpiration (Rouse *et al.*, 1997).

The ability of Arctic wetlands to act as a source or sink of organic carbon and CH_4 depends on the position of the water. Analysis of subarctic sedge fens to increases in temperature of 4°C suggests reduced water storage of 10–20 cm over the summer in northern peatlands, even with a small increase in precipitation (Rouse, 1998). This is significant, given that Moore and Roulet (1993) suggest that a reduction of 0.1 m in water storage in northern forested peatland is sufficient to convert these areas from a source to a sink of atmospheric CH_4. Wider questions concerning the carbon budget, including the level of uncertainty, are discussed in TAR WGI Chapter 3. Further predictions based on $2xCO_2$ changes indicate a 200–300 km retreat of the southern boundary of peatlands in Canada toward the Arctic coast and significant changes in their structure (Gignac and Vitt, 1994). Degradation of permafrost, which currently forms an impermeable layer, will couple many ponds with the groundwater system and lead to their eventual drainage. Areas of special sensitivity include patchy Arctic wetlands on continuous permafrost and those along the southern limit of permafrost (Woo and Young, 1998). In contrast, warming of surface permafrost also could lead to formation of new wetlands, ponds, and drainage networks through the process of thermokarst development, especially in areas with high concentrations of ground ice.

16.2.6.3. Ecological Impact of Changing Runoff Regimes

A warmer climate will create a more pluvial runoff regime as a greater proportion of the annual precipitation is delivered by rain rather than snow and a flattening of the seasonal runoff cycle occurs. Enhancement of winter flow will mean streams that currently freeze to their beds will retain a layer of water beneath the ice. This will be beneficial to invertebrates and fish populations. However, such rivers will then be prone to ice jamming and hence larger annual flood peaks. Warming will lead to a shortened ice season and thinner ice cover. For large northward-flowing rivers, this could reduce the severity of ice jamming in spring, especially if the magnitude of the peak snowmelt that drives breakup also is reduced (Beltaos and Prowse, 2000). Decreased ice-jam flooding will benefit many northern communities located near river floodplains. In contrast, reductions in the frequency and severity of ice-jam flooding would have a serious impact on northern riparian ecosystems, particularly the highly productive river deltas, where periodic flooding has been shown to be critical to the survival of adjacent lakes and ponds (Marsh and Hey, 1989; Prowse and Conly, 1998).

Decreases in winter snowpack and subsequent spring runoff from upstream tributaries has led to reduced frequency and severity of ice jams affecting the very large Peace-Athabasca Delta (Prowse *et al.*, 1996). These changes are analogous to those expected with predicted climate warming. Ice breakup is a major control over aquatic ecology, affecting numerous physical and biochemical processes and the biodiversity and productivity of such northern rivers (Prowse, 1994; Scrimgeour *et al.*, 1994). Major adjustments in their ecology are expected in the future. A similar situation exists for northern ponds and lakes, where ice cover will be thinner, form later, and break up earlier—with consequent limnological changes. Total primary production should increase in all Arctic lakes and ponds with an extended and warmer ice-free season (Douglas *et al.*, 1994). Primary productivity of Arctic aquatic systems also should be boosted by a greater supply of organic matter and nutrients draining from a more biologically productive terrestrial landscape (Schindler, 1997; Hobbie *et al.*, 1999). Thinner ice cover will increase the solar radiation penetrating to the underlying water, thereby increasing photosythnetic production of oxygen and reducing the potential for winter fish kills. However, a longer ice-free season will increase the depth of mixing and lead to lower oxygen concentrations and increased stress on coldwater organisms (Rouse *et al.*, 1997).

16.2.6.4. Sensitivity of Arctic Ocean to River Flow

Increased future melting from the Greenland ice sheet and Arctic glaciers and ice caps has potential to increase significantly freshwater runoff to the northern circumpolar seas on time scales as short as decades. Combined with changes in Arctic runoff, there will be an effect on Arctic sea ice. Freshwater input to the Arctic Ocean is important for growth, duration, and melt of sea ice, particularly on the large, shallow continental shelf areas that constitute 30% of the area of the Arctic basin. Spreading over the ocean of lower density freshwater from summer runoff, together with sinking of denser brine rejected during autumn and winter sea-ice production, maintain characteristic salinity and temperature layering. This leads to the Arctic halocline—a cold, salt-stratified layer that separates the upper mixed layer from underlying warm saline waters. The strength and position of surface and deep currents in the slope water south of Newfoundland are thought to vary as a coupled system in relation to the dipole in atmospheric sea-level pressure known as the NAO (Keigwin and Pickart, 1999).

Overall, runoff to the Arctic Ocean is approximately 3–4 x 10^3 km^3 yr^{-1} (Prowse and Flegg, 2000)—twice that produced by precipitation minus evaporation for the Arctic Ocean or the influx of low-salinity ocean water (Barry and Serreze, 2000). Export of freshwater (as low-salinity water and sea ice) from the Arctic Ocean into the North Atlantic couples northern latitudes to the world thermohaline circulation.

Almost 70% of the total runoff to the Arctic Ocean is provided by four rivers: the Ob, Yenisey, and Lena in Russia and the Mackenzie in Canada. The three Russian rivers have flow measurements dating back to the 1930s, whereas the Mackenzie record begins only in 1972. Although there is no significant long-term trend in flow for these rivers, there has been a slight increase in runoff beginning in the late-1970s for other rivers in European Russia and western Siberia, with some dependence on season (Georgievskii *et al.*, 1996; Georgievskii, 1998; Grabs *et al*., 2000; Shiklomanov *et al*., 2000). Shiklomanov *et al*. (2000) found that historical temperature shifts of -0.5 to +1.0°C had little effect on river inflows to the Arctic Ocean, which remained within 3–5% of their long-term average.

For a range of future climate scenarios, results from hydrological routines embedded in climate models and from independent hydrological models that are driven by climate model output indicate that discharge from the major Arctic rivers will increase significantly (Miller and Russell, 1992; Shiklomanov, 1994; van Blarcum *et al.*, 1995; Shiklomanov, 1997; Hagemann and Dümenil, 1998; Lewis *et al*., 2000). Mackenzie basin studies, however, have projected some reduction in streamflow as a result of expected climate warming (MBIS, 1997). Summarizing the general results, Shiklomanov *et al*. (2000) note that with an atmospheric CO_2 doubling, total annual inflow to the Arctic Ocean will increase by 10–20%, with a 1.5- to 2.0-fold increase during winter, although most of the flow still will occur in summer. Such predictions must be treated cautiously, however, because most climate models have been found to overestimate Arctic precipitation and simulate soil moisture and evaporation poorly (Robock *et al*., 1998; Walsh *et al*., 1998). Uncertainty in hydrological modeling of high-latitude river systems must be resolved before the risk of changes to the Arctic Ocean freshwater budget and thermohaline circulation can be quantified accurately (Carmack, 2000; Prowse and Flegg, 2000).

16.2.7. Changes in Arctic Biota

16.2.7.1. Impacts of Climate Change on Arctic Terrestrial Environments

Northern environments are thought to be particularly sensitive to climate warming, owing to changes in surface albedo degradation of permafrost, increased active-layer thickness, and earlier snowmelt. Recent warming reflects partial replacement of dry Arctic air masses by wetter Atlantic, Pacific, and southerly air masses, particularly in the subarctic and southern Arctic (Rouse *et al.*, 1997). Most of the increase is related to higher late-winter and early-spring air temperatures (+4.5°C), whereas summer temperatures in the region have increased by only about 2°C (Chapman and Walsh, 1993). In parts of Alaska, growing-season length has increased over the past 65 years as a result of reductions in snow and ice cover (Sharratt, 1992; Groisman *et al.*, 1994). The annual amplitude of the seasonal CO_2 cycle also has increased recently by as much as 40% (Keeling *et al.*, 1996). There has been an accompanying advance in the timing of spring by about 7 days and a delay in autumn by the same period, leading to an expected lengthening of the growing season (Keeling *et al.*, 1996). Such trends are likely to continue with projected climate change.

Precipitation will increase during the summer months, but evaporation and transpiration rates also are predicted to increase; this, together with earlier snowmelt, will lead to soil moisture deficits later in the summer (Oechel *et al.*, 1997). These changes in moisture and the thermal regimes of arctic soils ultimately will determine the fate of soil carbon stored in permafrost and the active layer (Miller *et al.*, 1983, Billings, 1987; Gorham, 1991; Schlesinger, 1991). Any change in physical properties in the active layer will have an impact on organisms and abiotic variables (Gates *et al.*, 1992; Kane *et al.*, 1992; Waelbroeck, 1993; Groisman *et al.*, 1994). The effects of changed drainage patterns and active-layer detachments (Dyke, 2000)—increasing sediment-nutrient loads in lakes and rivers—will alter biological productivity in aquatic ecosystems considerably (McDonald *et al.*, 1996).

Changes in the relative abundance of soil biota are predicted to affect soil processes, but only in a modest way. The rate of decomposition of organic matter is expected to rise with an increase in soil temperature and a longer growing season. This is likely to lead to enhanced rates of gross mineralization. However, the high carbon-to-nitrogen ratio of organic soils may still limit the availability of nitrogen to plants. If the thickened active layer extends into mineral layers, the release of mineral nutrients may be increased greatly, causing the upper organic layer to become more alkaline (Heal, 1998).

In summary, climate change probably will release more soil nutrients to biota, but nutrient limitations—especially of nitrogen and phosphorus—still are likely to occur. Studies have identified that the combination of nutrient and temperature increases results in the increasing importance of dominant plant species and suppression of subordinate ones. Species richness increased in an Arctic site, as a result of invasion of nitrophilous species, but decreased in a subarctic site. The impact of higher nutrient supplies and temperatures are likely to exceed those of elevated CO_2 and UV-B as measured in a related experiment (Press *et al*., 1998). Because little is known about interactions between species within the soil and hence overall community response, the effect of climate change on rates of tundra soil decomposition and carbon loss is hard to predict (Smith *et al*., 1998b).

16.2.7.2. Response of Arctic Plant Communities

There are a wide range of physiological responses of Arctic plants to climate change. Evidence indicates that changes will be at the level of individual species rather than groups of species (Chapin *et al.*, 1997; Callaghan *et al.*, 1998). Some responses to increased nutrient supply are specific to particular growth forms, such as the positive response of forbs, graminoids, and deciduous shrubs and the negative responses of mosses, lichens, and evergreen shrubs (Jonasson, 1992; Chapin *et al.*, 1995, 1996; Callaghan *et al*., 1998; Shaver and Jonasson, 1999). The direct growth responses of evergreen dwarf shrubs to increased temperatures are small (Havström *et al.*, 1993; Wookey *et al.*, 1993; Chapin *et al.*, 1995, 1996). This is in contrast to the growth rates of graminoids, forbs, and deciduous dwarf shrubs (Wookey *et al.*, 1994; Henry and Molau, 1997; Arft *et al*., 1999). In the Arctic, where these growth forms are abundant, there is a significant increase in plant biomass in response to increased temperatures in summer (Henry and Molau, 1997). The response of reproductive and vegetative structures to warming will vary, depending on abiotic constraints (Wookey *et al.*, 1994; Arft *et al.*, 1999). Warming in the winter and spring may encourage premature growth, so subsequent frost can lead to damage in plants (e.g., as discussed for *Vaccinium myrtillus* by Laine *et al.*, 1995, and for *Diapensia lapponica* by Molau, 1996). In northern Europe, processes that control the transition from boreal forest to tundra are more complicated than in North America because of infrequent large-scale defoliation of birch forest by geometrid moths. The eggs of the moths, which are killed at low temperatures, are likely to survive if winter temperatures increase (Neuvonen *et al*., 1999).

Increased CO_2 concentrations in the atmosphere also could directly affect photosynthesis and growth rates of Arctic plants, but the effects are not easily predictable. For example, a rise in CO_2 concentration in the air leads to an initial increase in photosynthesis in individual tussocks of *Eriophorum vaginatum.* However, this effect can disappear in as little as 3 weeks as a result of homeostatic adjustment, indicating a loss of photosynthetic potential has occurred (Oechel *et al.*, 1997). Such short-lived responses are thought to be caused by limitations in nutrient (especially nitrogen) availability (Chapin and Shaver, 1985; Oechel *et al.*, 1997). At the ecosystem level in tussock tundra plots, the homeostatic adjustment took 3 years—by which time enhanced rates of net CO_2 uptake had disappeared entirely, in spite of substantial photosynthetic carbon gain during the period (Oechel *et al*., 1994). Adjustment of the photosynthetic rate was thought to be caused by nutrient limitation. Körner *et al*. (1996) also have reported an increase in net CO_2 accumulation of 41% in *Carex curvula* after 2 years of exposure to elevated CO_2, but plant growth changes were minimal. Exposure of plants to increased temperatures and levels of CO_2 indicated that the initial stimulation in net CO_2 flux persisted, for reasons that are not entirely clear, although it may be linked to increased nutrient availability (Oechel and Vourlitis, 1994; Oechel *et al*., 1994, 1997).

Results from plants of *Nardus stricta* growing adjacent to springs in Iceland indicate that they have been exposed to elevated levels of CO_2 for at least 150 years. There was a reduction in photosynthetic capacity of high-CO_2 grown plants of this grass from the vicinity of the spring, compared with plants grown at ambient CO_2 concentations—again linked to reduction in Rubisco content and the availability of nutrients (Oechel *et al*., 1997). Collectively, these results indicate that it is unlikely that carbon accumulation will increase markedly over the long term as a result of the direct effects of CO_2 alone (Oechel *et al*., 1997). A return to summer sink activity has occurred during the warmest and driest period in the past 4 decades in Alaskan arctic ecosystems, thereby eliminating a net summer CO_2 flux to the atmosphere that was characteristic of the early 1980s. The mechanisms are likely to include nutrient cycling, physiological acclimatization, and reorganization of populations and communities (Oechel *et al*., 2000), but these systems are still net sources of CO_2.

A compounding consideration for Arctic plants is the impact of increased UV-B radiation. In Arctic regions, UV-B radiation is low, but the relative increase from ozone depletion is large, although the ancestors of present-day Arctic plants were growing at lower latitudes with higher UV-B exposure. Over the past 20 years, there has been a trend of decreasing stratospheric ozone of approximately 10–15% in northern polar regions (Thompson and Wallace, 2000). As a first approximation, a 1% decrease in ozone results in a 1.5–2% increase in UV-B radiation. Damage processes to organisms are temperature-independent, whereas repair processes are slowed at low temperatures. Hence, it is predicted that Arctic plants may be sensitive to increased UV-B radiation, especially because many individuals are long-lived and the effects are cumulative. In a study of responses by *Ericaceous* plants to UV-B radiation, responses varied from species to species and were more evident in the second year of exposure (Bjorn *et al.*, 1997; Callaghan *et al.*, 1998). For unknown reasons, however, the growth of the moss *Hylocomium splendens* is strongly stimulated by increased UV-B, provided adequate moisture is available (Gehrke *et al.*, 1996). Increased UV-B radiation also may alter plant chemistry that could reduce decomposition rates and nutrient availability (Bjorn *et al.*, 1997, 1999). Soil fungi differ with regard to their sensitivity to UV-B radiation, and their response also will affect the processes of decomposition (Gehrke *et al.*, 1995).

Climate change is likely to result in alterations to major biomes in the Arctic. Ecosystem models suggest that the tundra will decrease by as much as two-thirds of its present size (Everett and Fitzharris, 1998). On a broad scale—and subject to suitable edaphic conditions—there will be northward expansion of boreal forest into the tundra region, such that it may eventually cover more than 1.6 million km^2 of the Arctic. In northern Europe, vegetation change is likely to be more complicated. This is because of the influence of the geometrid moths, *Epirrita autumnata* and *Operophtera spp*., which can cause large-scale defoliation of boreal forests when winter temperatures are above 3.6°C (Neuvonen *et al*., 1999). Boreal forests are protected from geometrid moths only during cold winters. Empirical models estimate that by 2050, only one-third of the boreal forests of northern Europe will be protected by low winter temperatures in comparsion to the proportion protected during the period 1961–1991 (Virtanen *et al*., 1998). However, the northward movement of forest may lag changes in temperature by decades to centuries (Starfield and Chapin, 1996; Chapin and Starfield, 1997), as occurred for migration of different tree species after the last glaciation (Delcourt and Delcourt, 1987). The species composition of forests is likely to change, entire forest types may disappear, and new assemblages of species may be established. Significant land areas in the Arctic could have entirely different ecosystems with predicted climate changes (Everett and Fitzharris, 1998). However, note that locally, climate change may affect boreal forest through decreases in effective soil moisture (Weller and Lange, 1999), tree mortality from insect outbreaks (Fleming and Volney, 1995; Juday, 1996), probability of an increase of large fires, and changes caused by thawing of permafrost.

16.2.7.3. Changes in Arctic Animals

In the immediate future, the greatest environmental change for some parts of the Arctic is likely to result from increased herding of reindeer rather than climate change (Crete and Huot, 1993; Manseau *et al*., 1996; Callaghan *et al*., 1998). Winter lichen pastures are particularly susceptible to grazing and trampling, and recovery is slow, although summer pastures in tundra meadows and shrub-forb assemblages are less vulnerable (Vilchek, 1997). The overall impact of climatic warming on the population dynamics of reindeer and caribou ungulates is controversial. One view is that there will a decline in caribou and muskoxen, particularly if the climate becomes more variable (Gunn, 1995; Gunn and Skogland, 1997). An alternative view is that because caribou are generalist feeders and appear to be highly resilient, they should be able to tolerate climate change (Callaghan *et al*., 1998). Arctic island caribou migrate seasonally across the sea ice between Arctic islands in late spring and autumn. Less sea ice could disrupt these migrations, with unforeseen consequences for species survival and gene flow.

The decrease in the extent and thickness of Arctic sea ice in recent decades may lead to changes in the distribution, age structure, and size of populations of marine mammals. Seal species that use ice for resting, pup-rearing, and molting, as well as polar bears that feed on seals, are particularly at risk (Tynan and DeMaster, 1997). If break-up of annual ice occurs too early, seal pups are less accessible to polar bears (Stirling and Lunn, 1997; Stirling *et al*., 1999). According to observational data, recent decreases in sea ice are more extensive in the Siberian Arctic than in the Beaufort Sea, and marine mammal populations there may be the first to experience climate-induced geographic shifts or altered reproductive capacity (Tynan and DeMaster, 1997).

Ice edges are biologically productive systems, with diatoms and other algae forming a dense layer on the surface that sustains secondary production. Of concern as ice melts is the loss of prey species of marine mammals, such as Arctic cod (*Boreogadus saida)* and amphipods, that are associated with ice edges (Tynan and DeMaster, 1997). The degree of plasticity within and between species to adapt to these possible long-term changes in ice conditions and prey availability is poorly known and requires study. Regime shifts in the ocean will impact the distribution of commercially important fish stocks. Recruitment seems to be significantly better in warm years than in cold years, and the same is valid for growth (Loeng, 1989). The distribution of fish stocks and their migration routes also could vary considerably (Buch *et al*., 1994; Vilhjalmsson, 1997).

For other species, such as the lesser snow goose, reproductive success seems to be dependent on early-season climatic variables, especially early snowmelt (Skinner *et al.*, 1998). Insects will benefit from temperature increases in the Arctic (Danks, 1992; Ring, 1994). Many insects are constrained from expanding northward by cold temperatures, and they may quickly take advantage of a temperature increase by expanding their range (Parmesan, 1998).

16.2.8. Impact on Human Communities in the Arctic

16.2.8.1. Impacts on Indigenous Peoples

Historically, most indigenous groups have shown resilience and ability to survive changes in resource availability (e.g., the transition from Dorset to Thule cultures), but they may be less well equipped to cope with the combined impacts of climate change and globalization (Peterson and Johnson, 1995). Indigenous peoples, who number 1.5 million of a total Arctic population of 10 million, have a mixture of formal economies (e.g., commercial harvesting of fish, oil and mineral extraction, forestry, and tourism) and informal economies (e.g., harvesting of natural renewable resources). Increasingly, the overall economy is tied to distant markets. For example, in Alaska, gross income from tourism is US$1.4 billion, and in Russia 92% of exported oil is extracted from wells north of the Arctic Circle (Nuttall, 1998). The distinction between formal and informal economies becomes blurred by transfer payments and income derived from commercial ventures. The value of native harvests of renewable resources has been estimated to be 33–57% of the total economy of some northern communities (Quigley and McBridge, 1987; Brody, 1991). However, harvesting of renewable resources also must be considered in terms of maintaining cultural activities (Duerden, 1992). Harvesting contributes to community cohesion and self-esteem, and knowledge of wildlife and the environment strengthens social relationships (Warren *et al.*, 1995; Berkes, 1998). For example, hunting of wildlife is an essential part of Inuit tradition (Wenzel, 1995).

Climate change and economic development associated with oil extraction, mining, and fish farming will result in changes in diet and nutritional health and exposure to air-, water-, and food-borne contaminants in northern people (Bernes, 1996; Rees and Williams, 1997; Vilchek and Tishkov, 1997; AMAP, 1998; Weller and Lange, 1999; Freese, 2000). People who rely on marine systems for food resources are particularly at risk because Arctic marine food chains are long (Welch, 1995; AMAP, 1997). Low-lying Arctic coasts of western Canada, Alaska, and the Russian Far East are particularly sensitive to sea-level rise. Coastal erosion and retreat as a result of thawing of ice-rich permafrost already are threatening communities, heritage sites, and oil and gas facilities (Forbes and Taylor, 1994; Dallimore *et al*., 1996; Cohen, 1997a,b; Shaw *et al.*, 1998; Wolfe *et al*., 1998; Are, 1999).

Along the Bering and Chukchi Sea coasts, indigenous peoples report thinning and retreating sea ice, drying tundra, increased storms, reduced summer rainfall, warmer winters, and changes in the distribution, migration patterns, and numbers of some wildlife species. These peoples testify that they already are feeling some of the impacts of a changing, warming climate (Mulvaney, 1998). For example, when sea ice is late in forming, certain forms of hunting are delayed or may not take place at all. When sea ice in the spring melts or deteriorates too rapidly, it greatly decreases the length of the hunting season. Many traditional foods are dried (e.g., walrus, whale, seal, fish, and birds) in the spring and summer to preserve them for consumption over the long winter months. When the air is too damp and wet during the "drying" seasons, food becomes moldy and sour. The length of the wet season also affects the ability to gather greens such as willow leaves, beach greens, dock, and wild celery. These testimonies reflect the kinds of changes that could be expected as global warming affects the Arctic (Mulvaney, 1998). As climate continues to change, there will be significant impacts on the availability of key subsistence marine and terrestrial species. At a minimum, salmon, herring, walrus, seals, whales, caribou, moose, and various species of waterfowl are likely to undergo shifts in range and abundance. This will entail local adjustments in harvest strategies as well as in allocations of labor and resources (e.g., boats, snowmobiles, weapons). As the climate changes, community involvement in decisionmaking has the potential to promote sustainable harvesting of renewable resources, thereby avoiding deterioration of common property. However, factors that are beyond the control of the local community may frustrate this ideal. For example, many migratory animals are beyond the hunters' geographical range for much of the year—and thus beyond the management of small, isolated communities. Traditional subsistence activities are being progressively marginalized by increasing populations and by transnational commercial activities (Sklair, 1991; Nuttall, 1998).

In the past, when population densities of indigenous people were lower and economic and social structures were linked only weakly to those in the south, northern peoples showed significant flexibility in coping with climate variability (Sabo, 1991; Odner, 1992). Now, commercial, local, and conservation interests have reduced their options. Predicted climate change is likely to have impacts on marine and terrestrial animal populations; changes in population size, structure, and migration routes also are probable (Beamish, 1995; Gunn, 1995; Ono, 1995). Careful management of these resources will be required within a properly consultative framework, similar to recent agreements that are wide-ranging and endeavor to underpin the culture and economy of indigenous peoples (Nuttall, 1998). Langdon (1995) claims that "the combination of alternative cultural lifestyles and altered subsistence opportunities resulting from a warmer climate may pose the greatest threat of all to the continuity of indigenous cultures in northern North America." An alternative view is that northern people live with uncertainty and learn to cope with it; this view suggests that "for indigenous people, climate change is often not a top priority, but a luxury, and Western scientists may well be indoctrinating Natives with their own terminology and agenda on climate change" (BESIS, 1999).

16.2.8.2. Impacts on Economic Activity

The following subsections summarize the impacts of climate change and adaptive responses for different economic sectors that are relevant to the Arctic. Within different regions of the Arctic, important economic sectors differ substantially; some sectors are underrepresented, and others are just developing in certain regions (e.g., tourism). This latter topic (like agriculture and forestry) receives little or no comment in this section because there is insufficient literature to address the effects of climate change from a polar perspective.

16.2.8.2.1. Oil and gas extraction

Exploration, production, transportation, and associated construction of processing facilities are likely to be affected by climatic change (Maxwell, 1997). Changes in a large number of climate and related variables will affect on- and offshore oil and gas operations. Use of oil drilling structures or ice-strengthened drillships designed to resist ice, use of the ice itself as a drilling platform, and construction of artificial islands are likely to give way to more conventional drilling techniques employed in ice-free waters (Maxwell, 1997). These likely changes are not without concerns. Although the use of regular drillships may reduce operating costs by as much as 50% (Croasdale, 1993), increased wave action, storm surges, and coastal erosion may necessitate design changes to conventional offshore and coastal facilities (McGillivray *et al.*, 1993; Anderson and DiFrancesco, 1997). This may increase the costs of pipeline construction because extensive trenching may be needed to combat the effects of coastal instability and erosion, especially that caused by permafrost melting (Croasdale, 1993; Maxwell, 1997). Design needs for onshore oil and gas facilities and winter roads are strongly linked to accelerated permafrost instability and flooding. The impact of climate change is likely to lead to increased costs in the industry associated with design and operational changes (Maxwell, 1997).

16.2.8.2.2. Buildings and industrial facilities

The capacity of permafrost to support buildings, pipelines, and roads has decreased with atmospheric warming, so pilings fail to support even insulated structures (Weller and Lange, 1999). The problem is particularly severe in the Russian Federation, where a large number of five-story buildings constructed in the permanent permafrost zone between 1950 and 1990 already are weakened or damaged, probably as a result of climate change (Khroustalev, 1999). For example, a 2°C rise in soil temperature in the Yakutsk region has led to a decrease of 50% in the bearing capacity of frozen ground under buildings. Khroustalev (1999) has predicted that by 2030, most buildings in cities such as Tiksi and Yakutsk will be lost, unless protective measures are taken. The impact of warming is likely to lead to increased building costs, at least in the short term, as new designs are produced that cope with permafrost instability. Snow loads and wind strengths may increase, which also would require modifications to existing building codes (Maxwell, 1997). There will be reduced demand for heating energy with warmer climate (Anisimov, 1999).

16.2.8.2.3. Transportation and communications

The impact of climate warming on transportation and communications in Arctic regions is likely to be considerable. Within and between most polar countries, air transport by major commercial carriers is widely used to move people and freight. Irrespective of climate warming, the number of scheduled flights in polar regions is likely to increase. This will require an adequate infrastructure over designated routes, including establishment of suitable runways, roads, buildings, and weather stations. These installations will require improved engineering designs to cope with permafrost instability. Because paved and snow-plowed roads and airfield runways tend to absorb heat, the mean annual surface temperature may rise by 1–6°C, and this warming may exacerbate climate-driven permafrost instability (Maxwell, 1997). Cloud cover, wind speeds and direction, and patterns of precipitation may be expected to change at the regional level in response to global warming. At present, the density of weather stations is relatively low in Arctic regions. Increased air (and shipping) travel under a changing climate will require a more extensive weather recording network and navigational aids than now exists.

The impact of climate warming on marine systems is predicted to lead to loss of sea ice and opening of sea routes such as the Northeast and Northwest passages. Ships will be able to use these routes without strengthened hulls. There will be new opportunities for shipping associated with movement of resources (oil, gas, minerals, timber), freight, and people (tourists). However, improved navigational aids will be needed, and harbor facilities probably will have to be developed. The increase in shipping raises questions of maritime law that will need to be resolved quickly. These issues include accident and collision insurance, which authority is responsible for removal of oil or toxic material in the event of a spill, and which authority or agency pays expenses incurred in an environmental cleanup. These questions are important because sovereignty over Arctic waters is disputed among polar nations, and increased ship access could raise many destabilizing international issues. Increased storm surges are predicted that will affect transport schedules.

16.2.8.2.4. Pollution associated with increased economic activity

There already are a large number of case studies in the Arctic that indicate the effects of different pollutants on terrestrial, freshwater, and marine ecosystems (Crawford, 1997). In the event of increased industrial activity (e.g., mining, oil and gas extraction) under climate warming, new codes will be needed for retention of toxic wastes and to limit emissions of pollutants from processing plants. In the oil industry, considerable progress has been made in revegetating disturbed and polluted sites (McKendrick, 1997), often with plant species that can survive at northern sites under climatic warming. Changes in hydrology, possible increases in catchment rates, and melting of ice may result in wider dispersion of pollutants from accidents. Current ice cover and the low productivity of Arctic lakes restrict sequestration of contaminants (Barrie *et al.*, 1997; Gregor *et al.*, 1998). Projected changes to ice cover and the hydrology of these lakes may cause them to become greater sinks for river-borne contaminants, similar to those in more temperate regions. In the Arctic Ocean, many persistent organic pollutants (e.g., hexachlorocyclohexane) are trapped under ice as "ghosts of the past" (de March *et al*., 1998). Reductions in sea-ice cover may speed their introduction to the Arctic food chain and pose risks for the human population. Long-lived apex consumers with high lipid content have a high potential for long-term accumulation of contaminants (Alexander, 1995;

Tynan and DeMaster, 1997), and not all of these pollutants are derived within the Arctic. Development of Arctic haze is thought to result from aerosol loading (primarily sulfate particles) of the atmosphere in mid-latitude regions. These particles are then carried northward to the Arctic. The haze is most pronounced in the winter because the particles have a longer residence time in the stable Arctic air masses at that time of year. The increased presence of sulfate particles in the atmosphere is of concern because of their ability to reduce the flow of energy through the atmosphere to the Earth's surface (Shaw, 1987).

16.2.8.2.5. Fisheries

High-latitude marine fisheries are very productive. For example, those in the northern Pacific Ocean and the Bering Sea contribute more than 28% to total world landings of fish, mollusks, and crustaceans. In some northern countries, fisheries and fish products account for a large proportion of gross domestic product. In Greenland, the shrimp industry contributed more than 30% to GDPin 1986. Landings of fish in the Northwest Territories and in Nunavut, in the commercial and the subsistence sectors of the economy, are valued at CDN$12 million.

Shifts in oceanic circulation associated with global warming are likely to affect the distribution of commercially important fish and their migration routes (Buch *et al*., 1994; Vilhjalmsson, 1997). For example, the first catches of two species of Pacific salmon *(Oncorhnchus nerka, O. gorbuscha*) recently have been made in estuaries on Banks Island, Canada. These locations are well outside the known range for these Pacific species (Babaluk *et al*., 2000*)*.Changes in ocean currents, nutrient availability, salinity, and the temperature of ocean waters can be expected to influence the disposition of larval and juvenile organisms, the growth rates of individuals, and the population structure of different fish species (Otterson and Loeng, 2000). For example, recruitment appears to be significantly better in warm years (Loeng, 1989), an example of which is increased landings of cod (*Gadus morhua*) associated with warmer air and surface water temperatures (Brander, 1996). During a warm phase between the 1920s and the 1960s, Norwegian herring fed in Icelandic waters but disappeared when the water temperature cooled by 1°C (Vilhjalmsson, 1997). Quinn and Marshall (1989) report positive correlations between salmon returns and reduced sea ice. However, species that are adapted to cold water, such as the Greenland turbot and the Alaskan King crab, declined in numbers during these warm phases, although other factors also contributed to the decline of crab stocks (Weller and Lange, 1999). However, the underlying mechanisms that account for changes in population sizes are poorly understood. This topic is a high research priority, particularly because plankton production and trophic interactions may be significantly altered by changes in climate. Research and management advice for fish stocks is provided by the International Council for the Exploration of the Seas (ICES). This authority and others face formidable challenges if the distributions of fish populations change in response to global warming (Hønneland *et al*., 1999; Freese, 2000).

16.2.8.2.6. Reindeer husbandry

Husbandry of different subspecies of *Rangifer tarandus* is widely practiced in different regions of the Arctic, particularly in Eurasia. Between 1991 and 1997, Russia's domestic reindeer stock declined from 2.3 million to 1.6 million animals. Whether climate change contributed to this decline is uncertain (Weller and Lange, 1999), but climate warming is likely to alter husdandry practices. Concerns include the presence of deep snow with an ice surface that stops animals from obtaining forage, lichens and graminoids that are ice-covered, destruction of vegetation as a result of "overgrazing," exposure of soil that encourages establishment of southerly weedy species under a warmer climate (Vilchek, 1997), and an increased likelihood of damage from more frequent tundra fires.

16.3. Synthesis

16.3.1. Feedbacks and Interactions—Polar Drivers

Climate change will affect some key polar drivers, creating impacts in the wider global arena. Many of these impacts will be self-amplifying and, once triggered, will affect other regions of the world for centuries to come. These impacts relate to probable changes in the cryosphere, sea level, thermohaline circulation and ocean ventilation, exchange of GHGs, and cloudiness:

- *Snow/ice–albedo feedback:* The amount of absorbed solar radiation, and thus surface heating, depends on surface albedo, which is very high for snow or ice surfaces and much lower in the absence of snow and ice. Thus, absorbed shortwave radiation over the vast areas of snow and ice in polar regions is about three times lower than over non-snow-covered surfaces. Warming will shrink the cryosphere, particularly in the Arctic, causing additional heating of the surface, which in turn will further reduce ice and snow cover. Thus, any significant alteration in albedo over large areas will have the potential to produce a nonlinear, accelerated change.
- *Sea-level rise:* Projected climate change in polar regions will have a critical impact on global sea levels. Expected sea-level rise is in the range 0.09–0.88 m by 2100, using the SRES scenarios (TAR WGI Chapter 11). Increased melting of the Greenland ice sheet and Arctic glaciers, as well as possible thinning of the West Antarctic ice sheet, is expected to make important contributions. However, increased snow accumulation on the East and West Antarctic ice sheets is a major process that can offset sea-level rise. Sea level will continue to rise long after atmospheric GHGs are stabilized, primarily because of the large heat capacity of the ocean and the slow response of glaciers and ice sheets. The rate of downwelling of cold, dense waters in polar regions is a major control on thermal expansion of the ocean and hence the rate of sea-level rise over the next centuries.

Feedbacks that link sea-level rise to the size and health the West Antarctic ice sheet remain the subject of research and debate and are discussed in more depth in TAR WGI Chapter 11.

- *Ocean circulation:* Ocean-climate models predict increased stability of the surface mixed layer, reduction in salt flux, less ocean convection, and less deepwater formation. This could lead to a prolonged, major reduction in thermohaline circulation and ocean ventilation (O'Farrell *et al*., 1997; Budd and Wu, 1998; Hirst, 1999). Such changes will affect surface ocean currents and climates of Europe and mid-latitude landmasses in the southern hemisphere, where it could slow warming in some regions (Murphy and Mitchell, 1995; Whetton *et al*., 1996) but amplify it in others. Changes in runoff from large Arctic rivers (especially in Siberia) and increased melt from the Greenland ice sheet and glaciers will to lead to more freshwater in the Arctic Ocean. This may further weaken the thermohaline circulation in the North Atlantic. With less overturning in the ocean, there will be a reduction of upwelling in temperate and subtropical latitudes. Wood *et al*. (1999) present simulations of present-day thermohaline circulation, using a coupled ocean-atmosphere climate model without flux adjustments. The model responds to forcing with increasing atmospheric concentrations of GHGs with a collapse of circulation and convection in the Labrador Sea. These changes are similar in two separate simulations with different rates of increase of CO_2 concentrations. Although various models give differing results, any changes in the thermohaline circulation will have profound consequences for marine biology and fisheries because of inevitable changes in habitat and nutrient supply. Perturbations caused by projected climate change, such as a marked increase in freshwater inputs in polar regions, may cause reorganization of the global ocean thermohaline circulation, leading to abrupt climate change (e.g., Manabe and Stouffer, 1993; Wright and Stocker, 1993; Stocker and Schmittner, 1997). Palaeoclimatic effects of past large freshwater inputs are widely discussed for the Atlantic (e.g., Broecker *et al*., 1990; Rasmussen *et al*., 1996; Bianchi and McCave, 1999) and for extra melt from the Antarctic ice sheet (Mikolajewicz, 1998). These studies show that with past climate changes, shifts from one circulation mode to another have caused large, and sometimes abrupt, regional climate changes. Although there is low confidence that such events will occur, the associated impacts would be substantial.
- *Greenhouse gases—reduced uptake by the Southern Ocean:* Projected climate change will alter vast areas of oceans, wetlands, and permafrost in the polar regions that act as major sources and sinks for atmospheric CO_2 and CH_4. Projected climate change will alter these features, thereby altering the exchange of these gases. Model results (Sarmiento and Le Quere, 1996) show that of all oceans, the Southern Ocean is likely to experience the greatest slowing in CO_2 uptake with climate change. Reduced downwelling also will limit the ability of the ocean to sequester anthropogenic CO_2 (Sarmiento *et al*., 1998). Changing marine biology also must be considered. Using coupled climate model output under the IPCC IS92a GHG scenario, Matear and Hirst (1999) calculate that by the year 2100, there could be a reduction in cumulative oceanic uptake of carbon of 56 Gt. This reduced uptake is equivalent to a 4% yr^{-1} increase in CO_2 emissions for 1995–2100.
- *Greenhouse gases—emission by Arctic landscapes:* Whether the Arctic will be a net sink or a net source of CO_2 will depend largely on the magnitude and direction of hydrological changes and the rate of decomposition of exposed peat in response to temperature rise (Oechel *et al*., 1993; McKane *et al*., 1997a,b). Tundra ecosystems have large stores of nutrients and carbon bound in permafrost, soil, and microbial biomass and have low rates of CO_2 uptake as a result of low net primary production (Callaghan and Jonasson, 1995). The 25-year pattern of net CO_2 flux indicates that tundra in Alaska was a net sink during the cool, wet years of the 1970s; a net source of CO_2 during the warm, dry 1980s; and a net sink during the warm but less dry 1990s (Vourlitis and Oechel, 1999). These responses also may reflect a decrease in the rate of decomposition of soil organic matter because decay potential decreases with depth, as older, more recalcitrant carbon is exposed in soil profiles (Christensen *et al*., 1998, 1999a,b). Sink activity will be altered by changes in soil water content, temperature, or longer term adjustment of biotic processes (Oechel and Billings, 1992; Shaver *et al*., 1992; Oechel and Vourlitis, 1994; Chapin *et al*., 1995; Jonasson, 1996; Nadelhoffer *et al*., 1996; Rastetter *et al*., 1996; Waelbroeck *et al*., 1997). Increased frequency of disturbances such as fire in boreal forest also could contribute to increased seasonal amplitude of atmospheric CO_2 (Zimov *et al*., 1999). CH_4 production also is related to the position of the water table in the active layer (Torn and Chapin, 1993; Vourlitis *et al*., 1993; Johnson *et al*., 1996). The gas is oxidized in unsaturated soils and in the uppermost layer of the soil water column (Gilmanov and Oechel, 1995; Rouse *et al*., 1995; Tenhunen, 1996). Hence, the future magnitude of soil emissions of CH_4 and CO_2 will reflect the net outcome of anaerobic and aerobic processes. Thawing of permafrost has the potential to release considerable quantities of CH_4 and CO_2 (Fukuda, 1994; Michaelson *et al*., 1996; Anisimov *et al*., 1997; Goulden *et al*., 1998; Bockheim *et al*., 1999). Considering all of these effects, future warming is likely to further increase natural GHG emissions. Fluxes of these gases eventually may revert, however, to current levels after an initial pulse (Waelbroeck *et al*., 1997).
- *Hydrates of greenhouse gases:* Substantial amounts of natural gas may be released to the atmosphere as a result of climate-induced destabilization of gas hydrates beneath the surface of the Earth. On the continents, stable gas hydrates can be found only at depths of several hundreds of meters, making it unlikely that they will be

released by climate change in the coming centuries. In the northern seas, gas hydrates may be deposited in the near-bottom zone, and their decomposition is likely to occur if deepwater temperature rises by even a few degrees. Because there are large uncertanties in the estimated amounts of the near-bottom gas hydrates, their role in providing positive feedback to the climate system cannot be evaluated with reasonable accuracy. There is evidence of methane hydrate destabilization and release with warming of coastal ocean bottomwater from other parts of the world (Kennett *et al*., 2000).

16.3.2 Adaptation Potential and Vulnerability

Parts of the Arctic and Antarctic where water is close to its melting point are highly sensitive to climate change, rendering their biota and socioeconomic life particularly vulnerable. Adaptation to climate change will occur in natural polar ecosystems mainly through migration and changing mixes of species. This may cause some species to become threatened (e.g., walrus, seals, polar bears), whereas others may flourish (e.g., fish, penguins). Although such changes may be disruptive to many local ecological systems and particular species, the possibility remains that predicted climate change eventually will increase the overall productivity of natural systems in polar regions.

For people, successful future adaptation to change depends on technological advances, institutional arrangements, availability of financing, and information exchange. Stakeholders must be involved in studies from the beginning as well as in discussions of any adaptive and mitigative measures (Weller and Lange, 1999). For indigenous communities following traditional lifestyles, opportunities for adaptation to climate change appear to be limited. Long-term climate change, combined with other stresses, may cause the decline and eventual disappearance of communities. Technologically developed communities are likely to adapt quite readily to climate change by adopting altered modes of transport and by increased investment to take advantage of new commercial and trade opportunities.

Except in the Antarctic Peninsula, the Antarctic and the Southern Ocean probably will respond slowly to climate change; consequently, there will be less obvious impact in this region by 2100. Nevertheless, these areas are vulnerable because climate change could initiate millennial-scale processes with the potential to cause irreversible impacts on ice sheets, global ocean circulation, and sea-level rise. Antarctic drivers of sea-level rise, slowdown of the ocean thermohaline circulation, and changes in marine ecological habitats will continue for several centuries, long after GHG emissions are stabilized.

16.3.3. Development, Sustainability, and Equity

Distinctive patterns of development in the Arctic arise from the special nature of northern communities. The region is marked by decentralized administration and the presence of relict military establishments. The main forms of resource use are oil, gas, and mineral mining (e.g., lead, zinc, gold, diamonds), ecotourism, fishing, and traditional hunting and gathering by indigenous peoples. Further development of these resources is likely. Maintenance of existing infrastructure is likely to be more costly. Transportation may be affected as permafrost thaws and ice disappears. Waste disposal strategies also will have to change. Reduced sea ice will change strategic defense situations, especially for navies of the large powers flanking the Arctic. Sovereignty issues are of concern because of confusion over northern boundaries, the increased likelihood of territorial disputes as ice gives way to open water, and new northern sea routes create new trade patterns. Changes in sea ice and easier navigation may bring new policy initiatives, and improved sea access will greatly increase ecotourism. Overall, there will be increased human activity in the Arctic.

There are large regional differences across the Arctic in development, infrastructure, and ability of people to cope with climate change. Increasingly, Arctic communities are sustainable only with support from the south. Indigenous peoples are more sensitive to climate change than nonindigenous peoples. Their homelands and hunting habitats will be directly affected, and they cannot easily retreat to less affected areas. Some native peoples may be able to adapt, but probably at the expense of traditional lifestyles. Nonindigenous peoples also are vulnerable where links with the south are broken by changes in the physical environment and altered political circumstances. Their lifestyles require high capital investment, which will have to be maintained or even increased for them to be adaptable to climate change. With climate change, economies that rely on support from the south may become more expensive because of disrupted land-based transport, and this may not be sustainable. However, new transport opportunities, growing communities, and easier mining will create new wealth—but only for those who move away from traditional lifestyles.

In Antarctica, future use of the continent is governed by the Antarctic Treaty, and there are no permanent residents. With regard to policy issues, changes in the climate may mean less sea ice, easier access for ecotourism, and increased pressure on the environment. Sustaining the Antarctic's pristine nature may become more difficult.

16.3.4. Uncertainties and Risks

The polar regions will play a substantial role in driving global climate change through positive feedbacks to global warming. They also provide us with unparalleled records of that change. The most important uncertainties, risks, and thus targets for research are as follows:

- *Ocean thermohaline circulation:* Will downwelling in the North Atlantic and the Southern Ocean cease, causing a shutdown of the circulation of the global ocean? Or will this downwelling simply reduce and eventually recover with stabilization of GHGs? What is the role of changing input of freshwater from Arctic rivers?

- *Antarctic ice sheet:* What will be the contribution of the Antarctic ice sheets to global sea-level rise over the coming centuries? Although it is likely that the Antarctic ice sheet will provide some degree of mitigation of predicted sea-level rise, there is a small risk that the West Antarctic ice sheet (or portions of it) may retreat rapidly, causing a greater than predicted rise.
- *Marine biology:* What will be the response to predicted climate change of the structure of marine communities and the overall productivity of polar oceans? Uncertainty arises because existing biological models are not yet sufficiently developed to provide authoritative and quantitative estimates. There is some risk of unforeseen collapse of parts of the marine biological system, with consequent global effects—particularly on fisheries.
- *Arctic ice sheets, glaciers, and ice caps:* What is the current and future magnitude of freshwater input to the oceans from ice masses? What is the impact on global sea level and the thermohaline circulation on decadal to century time scales, and how can uncertainties in estimates be reduced?
- *Permafrost:* As ice-rich permafrost degrades, what will be the magnitude, spatial extent, and variability of its impacts? Will increases in the thickness of the active layer in currently cold, continuous permafrost be sufficient to cause widespread damage to human infrastructure? How important is soil organic carbon sequestered in the upper layer of permafrost in the context of the world carbon balance?
- *Arctic hydrology:* Will the balance between increased precipitation and evapotranspiration lead to a drier or wetter Arctic landscape? What will be the water balances of the large river basins that generate freshwater inflow to the Arctic Ocean?
- *Arctic sea ice:* Is it possible that with increased open water in the Arctic Ocean, summer sea ice in the Arctic eventually could disappear completely? The risk is that substantially more open water could generate large changes in regional climate for countries on the Arctic rim.
- *Fluxes of greenhouse gases:* What are the current and future fluxes of GHGs from polar oceans and landscapes? In particular, what is the likely future role of gas hydrates?
- *Stresses on human communities in the Arctic:* Can Arctic communities survive the combined stresses of globalization and marked changes in their local environments that may result from climate change? Traditional lifestyles will be threatened, but the communities that practice these lifestyles may be sufficiently resilient to cope with these changes, as they have in the recent and distant past.

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