Chapter 18

Summary and Synthesis of the ACIA

Lead Author
Gunter Weller

Contributing Authors
Elizabeth Bush, Terry V. Callaghan, Robert Corell, Shari Fox, Christopher Furgal, Alf Håkon Hoel, Henry Huntington, Erland Källén, Vladimir M. Kattsov, David R. Klein, Harald Loeng, Marybeth Long Martello, Michael MacCracken, Mark Nuttall, Terry D. Prowse, Lars-Otto Reiersen, James D. Reist, Aapo Tanskanen, John E. Walsh, Betsy Weatherhead, Frederick J. Wrona

Contents

18.1. Introduction

This chapter provides a brief summary of the main conclusions of the seventeen preceding chapters of the Arctic Climate Impact Assessment (ACIA). The chapter has three main parts. The first part contains the conclusions of the assessment discussed chapter by chapter. Observed climate and ultraviolet (UV) radiation trends (Chapters 2 and 5) are summarized, using both scientific and indigenous (Chapter 3) observations, and information from the latest assessments by the Arctic Monitoring and Assessment Programme (AMAP, 1998) and the Intergovernmental Panel on Climate Change (IPCC, 2001). Projections of climate change over the 21st century, based on emissions scenarios and computer model simulations (Chapter 4) are described, as are the observed and projected changes in stratospheric ozone and UV radiation levels (Chapter 5). Next, the chapter summarizes arctic-wide consequences of climate change, by examining impacts on the environment (Chapters 6, 7, 8, and 9), on people's lives (Chapters 10, 11, 12, 15, and 17), and on economic sectors of importance in the Arctic (Chapters 13, 14, and 16). These impacts cut across the entire Arctic and are generally not dependent on resolving regional details. For example, the timing, intensity, and magnitude of the melting of snow and ice in a warmer climate will have widespread implications for the entire Arctic and the global environment, even if these changes vary regionally.

Projected major large-scale environmental changes in the Arctic are illustrated in Fig. 18.1, which shows the existing and projected boundaries for summer sea-ice extent, permafrost, and the treeline. The likely changes associated with these shifts are many and dramatic, as described in the preceding chapters of this assessment. For example, the map shows that the treeline is projected to reach the Arctic Ocean in most of Asia and western North America by the end of the century. This is likely to lead to a near total loss of tundra vegetation in these areas, with important consequences for many types of wildlife. The consequences of the permafrost thawing and sea-ice reductions shown in Fig. 18.1 are equally dramatic.

The second part of the chapter is a synthesis of impacts on a local and regional basis, providing details on four different regions of the Arctic. A regional emphasis is necessary because the Arctic covers a large area and so experiences significant regional variations in the changes in climate that will lead to different impacts and responses. Different regions also have different social, economic, and political systems, which will each be influenced differently, causing vulnerability and impacts to differ to a large extent on the basis of geopolitical and cultural boundaries. The four regions for which results are presented are:

- Region 1: East Greenland, the North Atlantic, northern Scandinavia, and northwestern Russia;
- Region 2: Siberia;
- Region 3: Chukotka, the Bering Sea, Alaska, and the western Canadian Arctic; and
- Region 4: the central and eastern Canadian Arctic, the Labrador Sea, Davis Strait, and West Greenland.

The rationale for selecting these four broad regions includes climatic, social, and other factors, and is discussed in section 18.3.

The final part of the chapter addresses cross-cutting issues that are important in the Arctic. These are discussed in several chapters of the assessment, although usually in the context of the main topic of the chapter, and include the carbon cycle, biodiversity, and extreme and abrupt climate change.

Changes in climate and UV radiation in the Arctic will not only have far-reaching consequences for the arctic environment and its peoples, but will also affect the rest of the world, including the global climate. The connections include arctic sources of change affecting the globe, e.g., feedback processes affecting the global climate, sea-level rise resulting from melting of arctic glaciers and ice sheets, and arctic-triggered changes in the global thermohaline circulation of the ocean.

The Arctic is also important to the global economy. There are large oil and gas and mineral reserves in many parts of the Arctic, and arctic fisheries are among the most productive in the world, providing food for millions (see section 18.2.2.3). Climate change is likely to benefit north–south connections, including shipping, the global economy, and migratory birds, fish, and mammals that are important conservation species in the south. The Arctic plays a unique role in the global context and climate change in the Arctic has consequences that extend well beyond the Arctic.

18.2. A summary of ACIA conclusions

18.2.1. Changes in climate and UV radiation

18.2.1.1. Observed climate change

The climate of the Arctic has undergone rapid and dramatic shifts in the past and there is no reason that it could not experience similar changes in the future. Past changes show climatic cycles that have occurred regularly on time scales from decades to centuries and longer and are most likely to have been caused by oceanic and atmospheric variability and variations in solar intensity. Examples of long-term cooler and warmer climates were the Little Ice Age and the Medieval Warm Period, respectively, while short-term decadal cycles like the North Atlantic Oscillation and Pacific Decadal Oscillation, among others, have also been found to affect the arctic climate. Since the industrial revolution in the 19th century, anthropogenic greenhouse gas (GHG) emissions have added another major climate driver. In the 1940s, the Arctic experienced a warm period, like the rest of the planet, although it did

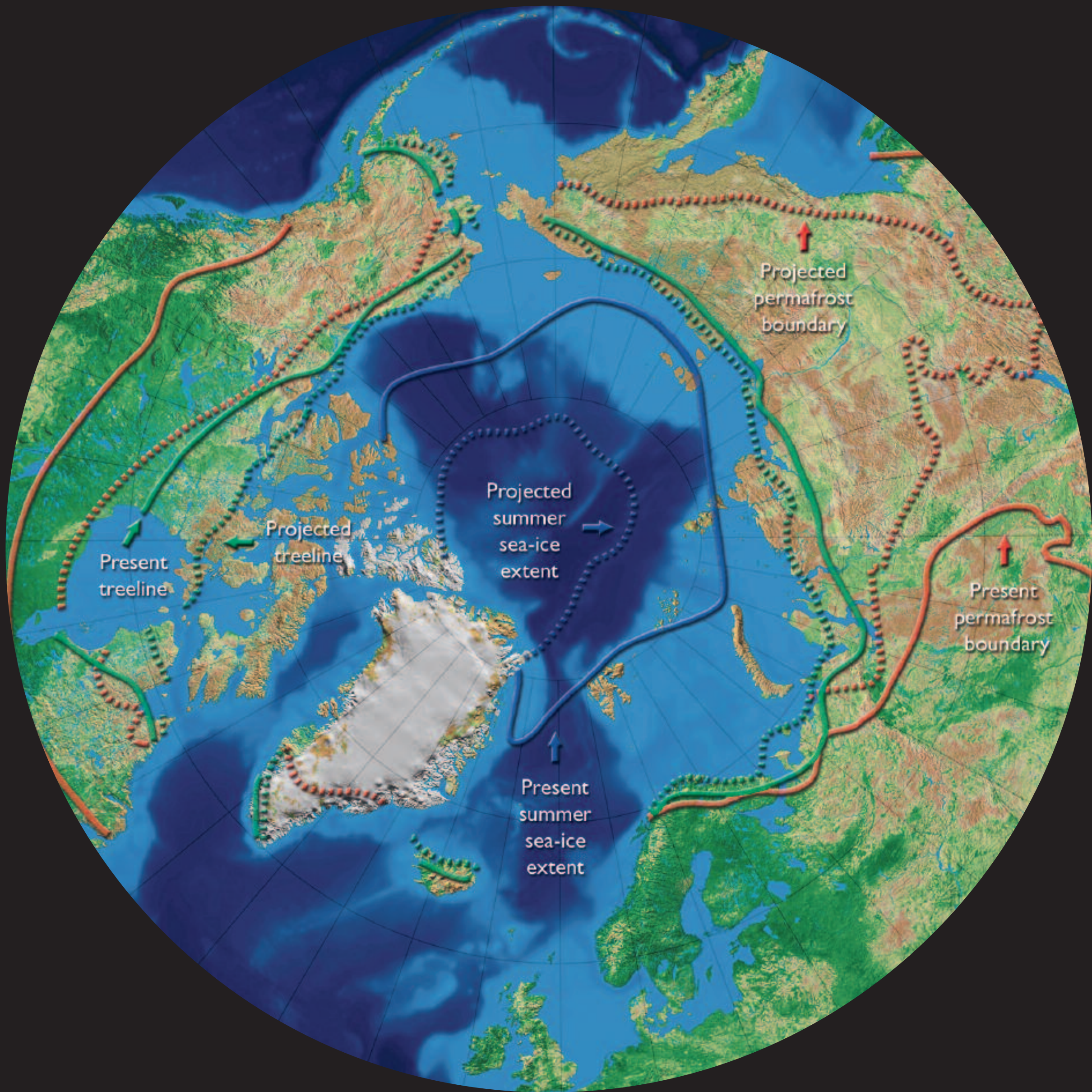

Fig. 18.1. Present and projected boundaries of summer sea-ice extent, permafrost, and the treeline. The changes are projected to occur over different time periods. Changes in summer sea-ice extent will occur by the end of the century, as projected by the five-model composite used by the ACIA (section 6.3, Figs. 6.3b and 6.9c). The projected changes in the treeline by the end of the century are from a vegetation model driven by output from the Hadley Centre model (section 7.1.1, Fig. 7.2 and section 7.5.3.2, Fig. 7.32). The change in the permafrost boundary assumes that the present areas of discontinuous permafrost (section 6.6.1, Fig. 6.21, although published sources differ) will be free of any permafrost in the future; this is likely to occur beyond the 21st century but it is not certain how long it will take.

not reach the level of the warming experienced in the 1990s. The IPCC stated that most of the global warming observed over the last 50 years is attributable to human activities (IPCC, 2001), and there is new and strong evidence that in the Arctic much of the observed warming over this period is also due to human activities.

Chapter 2 discusses the arctic climate system and observed changes in arctic climate over recent decades. Many types of observations indicate that the climate of the Arctic is changing. For example, air temperatures are generally warmer, the extent and duration of snow and sea ice are diminishing, and permafrost is thawing. However, there are also some regions where cooling has occurred, and some areas where precipitation has increased. Reconstruction of the history of arctic climate over thousands to millions of years indicates that there have been very large changes in the past. Based on these indications that the arctic climate is sensitive to changes in natural forcing factors, it is very likely that human-induced factors, for example the rise in GHG concentrations and consequent enhancement of the global greenhouse effect, will lead to very large changes in climate, indeed, changes that will be much greater in the Arctic than at middle and lower latitudes.

The observed temperature changes in the Arctic over the five-decade period from 1954 to 2003 are shown in

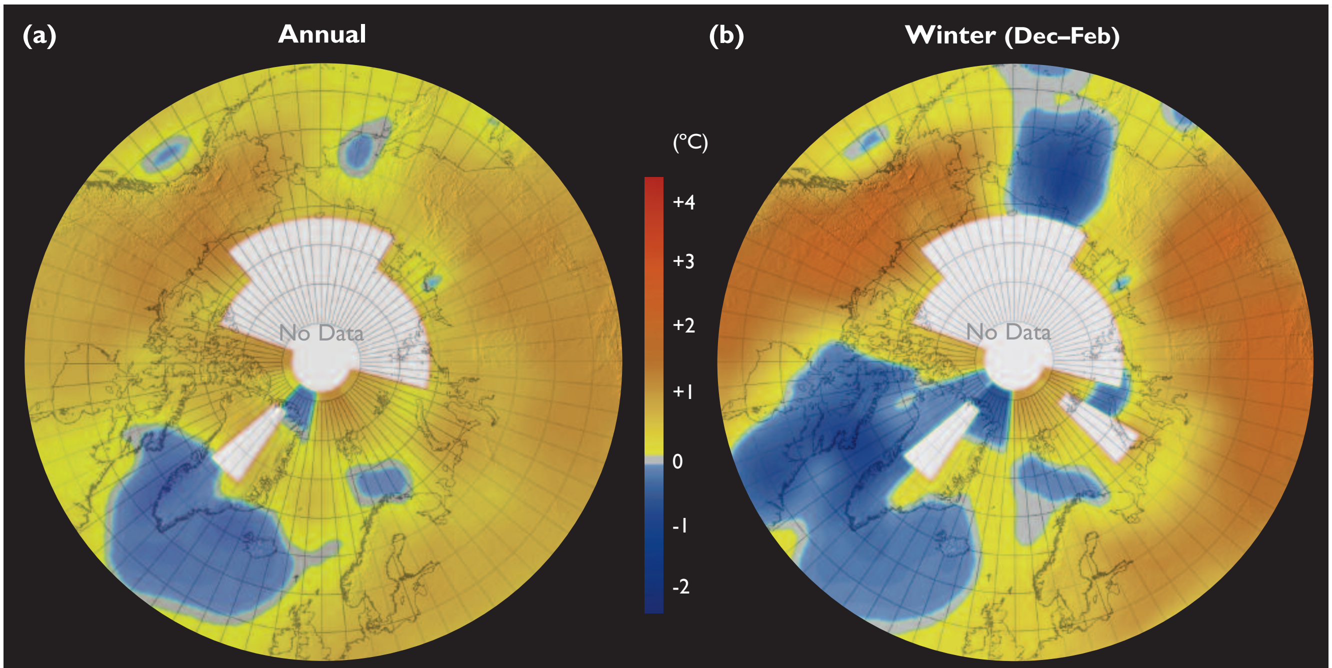

Fig. 18.2. Change in observed surface air temperature between 1954 and 2003: (a) annual mean; (b) winter (Chapman and Walsh, 2003, using data from the Climatic Research Unit, University of East Anglia, www.cru.uea.ac.uk/temperature).

Fig. 18.2. Owing to natural variations and the complex interactions of the climate system, the observed trends show variations within each region. Mean annual atmospheric surface temperature changes range from a 2 to 3 °C warming in Alaska and Siberia to a cooling of up to 1 °C in southern Greenland. Winter temperatures are up to 4 °C warmer in Siberia and in the western Canadian Arctic.

Although some regions have cooled slightly the overall trend for the Arctic is a substantial warming over the last few decades. For the Arctic as a whole, the 20th century can be divided into two warming periods, bracketing a 20-year cooling period (approximately 1945 to 1966) in the middle of the century. This pattern is less evident in northern Canada than in some other areas of the Arctic. The Canadian Archipelago and West Greenland did experience some cooling mid-century, although even then, there was substantial winter warming. The warming has been significant over the past few decades (1966 to 2003), particularly in the Northwest Territories – continuing the band of substantial warming across northwest North America that also covers Alaska and the Yukon – reaching an increase of 2 °C per decade. This warming is most evident in winter and spring. A more detailed description of observed climate change is given in Chapter 2. The climate change for each of the four ACIA regions is summarized in section 18.3.

Observations of arctic precipitation are restricted to a limited network of stations and are often unreliable since winter snowfall is not accurately measured by existing gauges, due to drifting snow. Available records indicate 20th-century increases in precipitation at high latitudes on the North American continent but little if any change in precipitation in the watersheds of the large Siberian rivers.

Rapid changes in regional climates (so-called regime shifts) are also evident in the climatic record. For example, in 1976 in the Bering Sea region there was a relatively sudden shift in prevailing climatic patterns, which included rapid warming and reduction in sea-ice extent. Such shifts have led to numerous, nearly instantaneous impacts on biota and ecosystems, as well as impacts on human communities and their interactions with the environment. Although such fluctuations are not fully understood and are therefore difficult to predict, regime shifts can be expected to continue to occur in the future, even as the baseline climate is also changing as a result of global warming (see section 18.4.3).

18.2.1.2. Indigenous observations of recent changes in climate

Indigenous observations of climate change, as discussed in Chapters 3 and 12, contribute to understanding of climate change and associated changes in the behavior and movement of animals. Through their various activities, which are closely linked to their surroundings, the indigenous peoples of the Arctic experience the climate in a very personal way. Over many generations and based on direct, everyday experience of living in the Arctic, they have developed specific ways of observing, interpreting, and adjusting to weather and climate changes. Based on careful observations, on which they often base life and death decisions and set priorities, indigenous peoples have come to possess a rich body of knowledge about their surroundings. Researchers are now working with indigenous peoples to learn from their observations and perspectives about the influences of climate change and weather events on the arctic environment and on their own lives and cultures. These studies are finding that the climate variations observed by indigenous people and by scientific observation are, for the most part, in good accord and often provide mutually reinforcing information.

The presently observed climate change is increasingly beyond the range experienced by the indigenous peoples in the past. These new conditions pose new risks to the lifestyles of the indigenous populations, as described in section 18.2.2. The magnitude of these threats is critically dependent on the rate at which change occurs. If change is slow, adaptation may be possible; if however, change is rapid, adaptation is very likely to be considerably more difficult, if possible at all in response to some types of impacts.

Recent observations by the indigenous peoples of the Arctic of major changes in the climate and associated impacts are summarized in Table 18.1. Taken together, the body of observations from people residing across the Arctic presents a compelling account of changes that are increasingly beyond what their experience tells them about the past.

Indigenous observations of climate and related environmental changes include many other effects on plants and animals that are important to them (Chapter 7). These observations provide evidence of nutritional stresses on many animals that are indicative of a changing environment and changes in food availability. New species, never before recorded in the Arctic, have also been observed. The distribution ranges of some species of birds, fish, and mammals now extend further to the north than in the past. These observations are significant for indigenous communities since changes likely to occur in traditional food resources will have both negative and positive impacts on the culture and economy of arctic peoples.

18.2.1.3. Projections of future climate

In projections of future climate, uncertainties of many types can arise, especially for as complex a challenge as projecting ahead 100 years. The ACIA adopted a lexicon of terms (section 1.3.3) describing the likelihood of expected change (Fig. 18.3). These terms are used throughout this chapter, and in all ACIA documents.

Chapter 4 presents the ACIA projections of future changes in arctic climate. These projections extend the IPCC assessment (IPCC, 2001) by presenting regional (north of 60º N) climate parameters, derived from global model outputs. The ACIA used five different global climate models (CGCM2, Canadian Centre for Climate Modelling and Analysis; CSM_1.4, National Center for Atmospheric Research, United States; ECHAM4/OPYC3, Max Planck Institute for Meteorology, Germany; GFDL-R30_c, Geophysical Fluid Dynamics Laboratory, United States; and HadCM3, Hadley Centre for Climate Prediction and Research, United Kingdom) forced with two different emissions (GHG and aerosol) scenarios. The emissions scenarios are the B2 and A2 scenarios drawn from the IPCC Special Report on Emissions Scenarios (Nakićenović and Swart, 2000). The A2 emissions scenario assumes global emphasis on sustained economic development while the B2 emissions scenario reflects a world that promotes environmental sustainability. Neither scenario is considered an upper or lower

Table 18.1. Examples of indigenous observations of environmental change in the Arctic. This table is mainly based on Chapters 3 and 12.

	European Arctic	Canada and Greenland	Alaska
Atmosphere/ weather/winds	Weather patterns are changing so fast that traditional methods of prediction are no longer applicable. Winters are warmer. Seasonal patterns have changed.	Weather patterns are changing so fast that traditional methods of prediction are no longer applicable. Winters are warmer. There has been cooling in Hudson Strait/Baffin Island area, but greater variability.	Weather patterns are changing so fast that traditional methods of prediction are no longer applicable. There are more storms and fewer calm days. Winters are shorter and warmer, summers longer and hotter.
Rain/snow	Rain is more frequent in winter than before. There are more freeze–thaw cycles, thus more trouble for reindeer grazing in winter.	Snow is melting earlier and some permanent snow patches disappear. There is less snow and more wind, producing snow conditions that do not allow igloo building.	There is less snow.
Ocean/sea ice		Later freeze-up and earlier breakup of sea ice. Shore-fast ice is melting faster, creating large areas of open water earlier in summer.	Sea ice is thinner and is forming later. There is increased coastal erosion due to storms and lack of ice to protect the shoreline from waves.
Lakes/rivers/ permafrost	Ice on lakes and rivers is thinner.	Water levels in lakes and rivers are falling on the Canadian mainland. Thinner river ice affects caribou on migration (they fall through). Permafrost is thawing, slumping soil into rivers and draining lakes.	Lakes and wetlands are drying out. Permafrost thawing is affecting village water supply, sewage systems, and infrastructure.
Plants and animals	New species are moving into the region.	Caribou suffer from more insects; body condition has declined. Caribou migration routes have changed.	Trees and shrubs are advancing into tundra. There are die-offs of seabirds and marine mammals due to poor body condition. New species of insects are observed.

Fig. 18.3. Five-tier lexicon describing the likelihood of expected change.

bound on possible levels of future emissions. The climatic and environmental changes in the Arctic projected using the two scenarios are similar through about 2040, but diverge thereafter, with projections forced with the A2 emissions scenario showing greater warming.

These projections are not intended to capture a large range of possible futures for the Arctic under scenarios of continuing emissions of GHGs and other pollutants. For practical reasons, only a limited number of future change scenarios could be developed for this assessment. Nonetheless, while the ACIA used only two different emissions scenarios, five global climate models were used to project change under the two emissions scenarios, capturing a good range of the uncertainty associated with how different models represent climate system processes.

Under the A2 and B2 emissions scenarios, the models projected that mean annual arctic surface temperatures north of 60° N will be 2 to 4 °C higher by mid-century and 4 to 7 °C higher toward the end of the 21st century (Fig. 18.4), compared to the present. Precipitation is projected to increase by about 8% by mid-century and by about 20% toward the end of the 21st century. There are differences among the projections from the different models, however. Although the projected trends are similar for the next few decades, the scatter of results for either the A2 or B2 emissions scenarios is about 2 to 3 °C toward the end of the 21st century. The reasons for this scatter are differences in the representation of physical processes and feedbacks that are particularly important in the Arctic (e.g., changes in albedo due to reduced snow and ice cover, clouds, atmosphere–ocean interactions, ocean circulation), and natural variations that remain significant compared with the induced changes for at least the next few decades. While observations seem to indicate some increase in the frequency and severity of extreme events, these are very difficult to project.

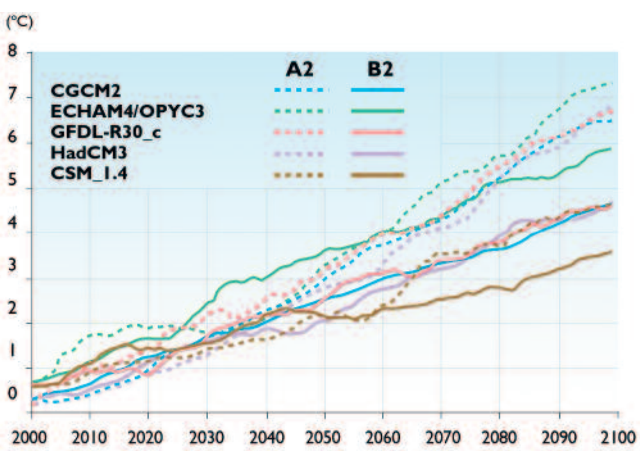

Fig. 18.4. Changes in surface air temperature north of 60° N between the 1981–2000 baseline and 2100 as projected by the five ACIA-designated models forced with the A2 and B2 emissions scenarios.

Composite five-model projections for annual and winter mean surface air temperature changes in the Arctic between 1981–2000 and 2071–2090 using the B2 emissions scenario are shown in Fig. 18.5a (annual) and Fig. 18.5b (winter). Projected annual temperatures show a fairly uniform warming of 2 to 4 °C throughout the Arctic by the end of the century, with a slightly higher warming of up to 5 °C in the East Siberian Sea. Summer temperatures are projected to increase by 1 to 2 °C over land, with little change in the central Arctic Ocean, where sea ice melts each summer, keeping the ocean temperature close to 0 °C. Winter temperatures show the greatest warming: about 5 °C over land, and up to 8 to 9 °C in the central Arctic Ocean, where the feedback due to reduced sea-ice extent is largest. Regional and seasonal differences between the individual model results can be large, however, for the reasons previously discussed.

Changes in the Arctic affect the global system in several ways. Global climate change is influenced by feedback processes operating in the Arctic; these also amplify climate change in the Arctic itself. Apart from the well-known and often quoted ice- and snow-albedo feedback, another important arctic feedback is the thawing of permafrost, which is likely to lead to additional GHG releases. Arctic cloud feedbacks are also important but are still poorly understood. Some of these arctic feedbacks are adequately represented in general circulation models while others are not. Changes in the Arctic also affect the global system in other ways. Climate change is likely to increase precipitation throughout the Arctic and increase runoff to the Arctic Ocean; such a freshening is likely to slow the global thermohaline circulation with consequences for global climate. The melting of arctic glaciers and ice sheets is another effect of climate change that contributes to global sea-level rise with all its inherent problems. The global implications of these feedbacks are discussed in greater detail in section 18.2.2.

18.2.1.4. Ozone and UV radiation change

Atmospheric ozone is vital to life on earth. The stratosphere contains the majority of atmospheric ozone, which shields the biosphere by absorbing UV radiation from the sun. Anthropogenic chlorofluorocarbons are primarily responsible for the depletion of ozone in the stratosphere, particularly over the poles. Atmospheric dynamics and circulation strongly influence ozone

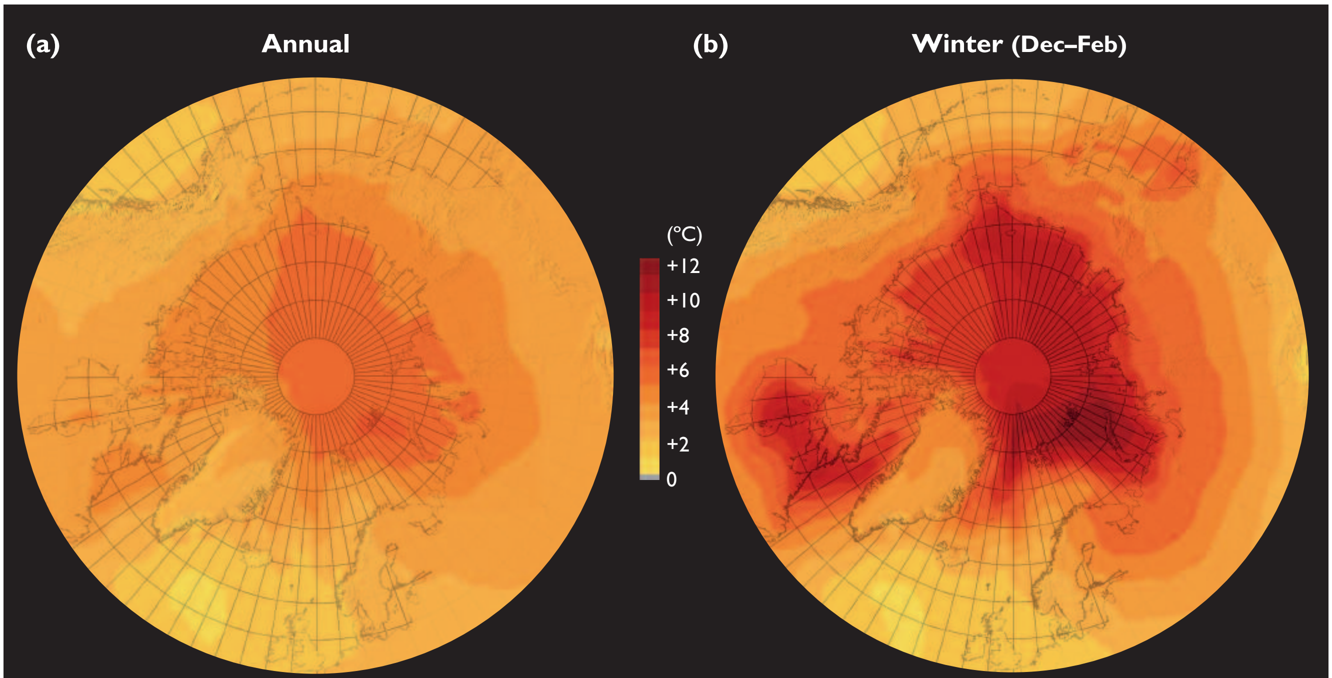

Fig. 18.5. (a) Projected annual surface air temperature change from the 1990s to the 2090s, based on the average change projected by the five ACIA-designated climate models using the B2 emissions scenario. (b) Projected surface air temperature change in winter from the 1990s to the 2090s, based on the average change projected by the five ACIA-designated climate models using the B2 emissions scenario.

amounts over the poles, which in normal conditions tend to be higher than over other regions on earth. During conditions of ozone depletion, however, ozone over the polar regions can be substantially reduced. This depletion is most severe in the late winter and early spring, when unperturbed ozone amounts are typically high. Ozone losses over the Arctic are also strongly influenced by meteorological variability and large-scale dynamical processes. Winter temperatures in the polar stratosphere tend to be near the threshold temperature for forming polar stratospheric clouds, which can accelerate ozone destruction, leading to significant and long-lasting depletion events. Because climate changes due to increasing GHGs are likely to lead to a cooling of the stratosphere, polar stratospheric cloud formation is likely to become more frequent in future years, causing episodes of severe ozone depletion to continue to occur over the Arctic.

Decreases in stratospheric ozone concentrations are very likely to lead to increased UV radiation levels at the surface of the earth. Clouds, aerosols, surface albedo, altitude, and other factors also influence the amount of UV radiation reaching the surface. Achieving an accurate picture of UV radiation doses in the Arctic is complicated by low solar elevations and by reflectance off snow and ice. Ultraviolet radiation has long been a concern in the Arctic, as indicated by protective goggles found in the archaeological remains of indigenous peoples. Depletion of ozone over the Arctic, as has been observed in several years since the early 1980s, can lead to increased amounts of UV radiation, particularly UV-B radiation, reaching the surface of the earth, exposing humans and ecosystems to higher doses than have historically been observed. These higher doses are most likely to occur during spring, which is also the time of year when many organisms produce their young and when plants experience new growth. Because ecosystems are particularly vulnerable to UV radiation effects during these stages, increased UV radiation doses during spring could have serious implications throughout the Arctic.

Chapter 5 discusses observed and projected changes in atmospheric ozone and surface UV radiation levels. Satellite and ground-based observations since the early 1980s indicate substantial reductions in ozone over the Arctic during the late winter and early spring. Between 1979 and 2000, mean spring and annual atmospheric ozone levels over the Arctic declined by 11 and 7%, respectively. During the most severe depletion events, arctic ozone losses of up to 45% have occurred. Although international adherence to the Montreal Protocol and its amendments is starting to lead to a decline in the atmospheric concentrations of ozone-depleting substances, ozone levels over the Arctic are likely to remain depleted for the next several decades. For the Arctic, most models project little recovery over the next two decades. Episodes of very low spring ozone levels are likely to continue to occur, perhaps with increasing frequency and severity because of the stratospheric cooling projected to result from increasing concentrations of GHGs. These episodes of very low ozone can allow more UV radiation to reach the earth's surface, suggesting that people and ecosystems in the Arctic are likely to be exposed to higher-than-normal UV radiation doses for perhaps the next 50 years.

Table 18.2 summarizes some of the major aspects of changes in ozone and UV radiation levels.

Table 18.2. Observed and projected trends in ozone and ultraviolet radiation levels and factors affecting levels of ultraviolet radiation in the Arctic. This table is mainly based on Chapter 5.

	Observed	Projected
Ozone and UV radiation trends	Combined satellite and ground-based observations indicate that mean spring and annual atmospheric ozone levels over the Arctic declined by 11 and 7%, respectively, between 1979 and 2000. These losses allowed more UV radiation to reach the surface of the earth. Individual measurements suggest localized increases in surface UV radiation levels, although high natural variability makes it difficult to identify a trend conclusively.	Future ozone levels over the Arctic are difficult to project, partly owing to the link with climate change. Current projections suggest that ozone over the Arctic is likely to remain depleted for several decades. This depletion would allow UV radiation levels to remain elevated for several decades. The elevated levels are likely to be most pronounced in spring, when many ecosystems are most sensitive to UV radiation exposure.
Low ozone episodes	Multi-week episodes of very low ozone concentration (depletion of 25 to 45%) have been observed in several springs since the early 1990s.	Decreasing stratospheric temperatures resulting from climate change may cause low ozone episodes to become more frequent.
Seasonal variations in ozone and UV radiation levels	There is high seasonal and interannual variability in arctic ozone levels, due to atmospheric processes that influence ozone production and distribution. Over the Arctic, stratospheric ozone levels are typically highest in late winter and early spring, when ozone depletion is most likely to occur. Surface UV radiation amounts vary with solar angle and day length throughout the year. In general, UV radiation doses are highest in summer, but can also be significant in spring due to ozone depletion combined with UV radiation enhancements from reflection off snow.	
Cloud effects	Cloud cover typically attenuates the amount of UV radiation reaching the surface of the earth. When the ground is snow-covered, this attenuation is diminished and UV radiation levels reaching the surface may increase due to multiple scattering between the surface and cloud base.	Future changes in cloud cover are currently difficult to project, but are likely to be highly regional.
Albedo effects	Changes in snow and ice extent affect the amount of UV radiation reflected by the surface. Reflection off snow can increase biologically effective UV irradiance by over 50%. In addition, high surface albedo affects UV radiation amounts incident on vertical surfaces more strongly than amounts incident on horizontal surfaces. Snow-covered terrain can substantially enhance UV radiation exposure to the face or eyes, increasing cases of snow blindness and causing potential long-term skin or eye damage.	Climate changes are likely to alter snow cover and extent in the Arctic. Reduced snow and ice cover means less reflection of UV radiation, decreasing the UV radiation levels affecting organisms above the snow.
Snow and ice cover	Snow and ice cover shields many arctic ecosystems from UV radiation for much of the year.	Climate changes are likely to alter snow cover and extent in the Arctic. Reduced snow and ice cover will increase the UV radiation levels experienced by organisms that would otherwise be shielded by snow or ice cover.
Impacts of increased UV radiation levels	Ultraviolet radiation effects on organisms in human health and on terrestrial and aquatic ecosystems include skin cancer, corneal damage, immune suppression, sunburn, snow blindness. Ultraviolet radiation also damages wood, plastics, and other materials widely used in arctic infrastructure.	All the impacts noted in the "Observed" column are likely to worsen.

18.2.2. Arctic-wide impacts

18.2.2.1. Impacts on the environment

Changes in snow, ice, and permafrost

Recent observational data, discussed in detail in Chapter 6, present a generally consistent picture of cryospheric variations that are shaped by patterns of recent warming and variations in atmospheric circulation. Consistent with the overall increase in global temperatures, arctic snow and ice features have diminished in extent and volume. While the various cryospheric and atmospheric changes are consistent in an aggregate sense and are quite large in some cases, it is possible that natural, low-frequency variations in the atmosphere and ocean have played at least some role in forcing the cryospheric and hydrological trends of the past few decades.

Model projections of anthropogenic climate change indicate a continuation of the recent trends through the 21st century, although the rates of the projected changes vary widely due to differences in model representations of feedback processes. Models project a 21st-century decrease in sea-ice extent of up to 100% in summer; a widespread decrease in snow-cover extent, particularly in spring and autumn; and permafrost degradation over 10 to 20% of the present permafrost area and a movement of the permafrost boundary northward by several hundred kilometers. The models also project river discharge increases of 5 to 25%; earlier breakup and later freeze-up of rivers and lakes; and a sea-level rise of several tens of centimeters resulting from glacier melting and thermal expansion, which is amplified or reduced in some areas due to long-term land subsidence or uplift.

Table 18.3 summarizes observed and projected trends in the snow and ice features of the Arctic, including snow cover, glaciers, permafrost, sea ice, and sea-level rise. Because the snow and ice features of the Arctic are not only sensitive indicators of climate change but also play a crucial role in shaping the arctic environment, any changes in these features are very likely to have profound effects on the environment, biota, ecosystems, and humans.

Changes on land

Climate change is also likely to have profound effects on the tundra and boreal forest ecosystems of the Arctic. Arctic plants, animals, and microorganisms adapted to climate change in the past primarily by relocation, and their main response to future climate change is also likely to be relocation. In many areas of the Arctic, however, relocation possibilities are likely to be limited by regional and geographical barriers. Nevertheless, changes are already occurring in response to recent warming. Chapters 7, 8, and 14 provide details of the major conclusions presented here.

Some arctic species, especially those that are adapted to the cold arctic environment (e.g., mosses, lichens, and some herbivores and their predators) are especially at risk of loss in general, or displacement from their present locations. Present species diversity is more at risk in some ACIA regions than others; for example, Beringia (Region 3) has a higher number of threatened plant and animal species than any other ACIA region. While there will be some losses in many arctic areas, movement of species into the Arctic is likely to cause the overall number of species and their productivity to increase, thus overall biodiversity measured as species richness is likely to increase along with major changes at the ecosystem level.

Freshwater systems in the Arctic will also be affected due to changes in river runoff, including the timing of runoff from thawing permafrost, and changes in river-

Table 18.3. Observed and projected trends for the arctic cryosphere. This table is mainly based on Chapter 6.

	Observed	Projected for the 21st century
Snow cover	Snow-cover extent in the Northern Hemisphere has decreased by 5 to 10% since 1972; trends of such magnitude are rare in GCM simulations.	Snow-cover extent is projected to decrease by about 13% by 2071–2090 under the projected increase in mean annual temperature of about 4 °C. The projected reduction is greater in spring. Owing to warmer conditions, some winter precipitation in the form of rain is likely to increase the probability of ice layers over terrestrial vegetation.
Glaciers	Glaciers throughout the Northern Hemisphere have shrunk dramatically over the past few decades, contributing about 0.15 to 0.30 mm/yr to the average rate of sea-level rise in the 1990s.	The loss of glacial mass through melting is very likely to accelerate throughout the Arctic, with the Greenland Ice Sheet also starting to melt. These changes will tend to increase the rate of sea-level rise.
Permafrost	Permafrost temperatures in most of the Arctic and subarctic have increased by several tenths of a degree to as much as 2 to 3 °C (depending on location) since the early 1970s. Permafrost thawing has accompanied the warming.	Over the 21st century, permafrost degradation is likely to occur over 10 to 20% of the present permafrost area, and the southern limit of permafrost is likely to move northward by several hundred kilometers.
Sea ice	Summer sea-ice extent decreased by about 7% per decade between 1972 and 2002, and by 9% per decade between 1979 and 2002, reaching record low levels in 2002. The extent of multi-year sea ice has also decreased, and ice thickness in the Arctic Basin has decreased by up to 40% since the 1950s and 1960s due to climate-related and other factors.	Sea-ice extent is very likely to continue to decrease, particularly in summer. Model projections of summer sea-ice extent range from a loss of several percent to complete loss. As a result, the navigation season is projected to be extended by several months.
River discharge	River discharge has increased over much of the Arctic during the past few decades and the spring discharge pulse is occurring earlier.	Models project that total river discharge is likely to increase by an additional 5 to 25% by the late 21st century.
Breakup and freeze-up	Earlier breakup and later freeze-up of rivers and lakes across much of the Arctic have lengthened the ice-free season by 1 to 3 weeks.	The trend toward earlier breakup and later freeze-up of rivers and lakes is very likely to continue, consistent with increasing temperature. Breakup flooding is likely to be less severe.
Sea-level rise	Global average sea level rose between 10 and 20 cm during the 20th century. This change was amplified or moderated in particular regions by tectonic motion or isostatic rebound.	Models project that glacier contributions to sea-level rise will accelerate in the 21st century. Combined with the effects of thermal expansion, sea level is likely to rise by 20 to 70 cm (an average of 2 to 7 mm/year) by the end of the 21st century.

and lake-ice regimes. Changes in water flows as permafrost thaws are very likely to alter the biogeochemistry of many areas and create new wetlands and ponds, connected by new drainage networks. More water will alter the winter habitats in freshwater systems and increase survival of freshwater and sea-run fish. On hill slopes and higher ground, permafrost thawing is likely to drain and dry existing soils and wetlands. The productivity of these systems is likely to increase, as well as species diversity.

Table 18.4. Projected impacts on terrestrial ecosystems. This table is mainly based on Chapter 7.

	Projected impact
Ecotone transitions	Warming is very likely to lead to slow northward displacement of tundra by forests, while tundra will in turn displace high-arctic polar desert. Tundra is projected to decrease to its smallest extent in the last 21 000 years. In dry areas where thawing permafrost leads to drainage of the active layer, forests are likely to be replaced by tundra–steppe communities. Where thawing permafrost leads to waterlogging, forest will be displaced by bogs and wetlands.
Forest changes	Forests are likely to expand and in some areas, where present-day tundra occupies a narrow zone, are likely to reach the northern coastline. The expansion will be slowed by increased fire frequency, insect outbreaks, and vertebrate herbivory, as has already been observed in some parts of the Arctic.
Species diversity	Climate warming is very likely to lead to northward extension of the distribution ranges of species currently present in the Arctic and to an increase in the total number of species. Individual species will move at different rates and new communities of associated species are likely to form. Climate warming is also likely to lead to a decline or extirpation of populations of arctic species at their southern range margins. As additional species move in from warmer regions, the number of species in the Arctic and their productivity are very likely to increase.
Species at risk	Specialist species adapted to the cold arctic climate, ranging from mosses, lichens, vascular plants, some herbivores (lemmings and voles) and their predators, to ungulates (caribou and reindeer), are at risk of marked population decline or extirpation locally. This will be largely as a consequence of their inability to compete with species invading from the south. The biodiversity in Beringia is at risk as climate warms since it presently has a higher number of threatened plant and animal species than any other arctic region.
UV radiation effects	Increased UV radiation levels resulting from ozone depletion are likely to have both short- and long-term impacts on some ecosystem processes, including reduced nutrient cycling and decreased overall productivity. Many arctic plant species are assumed to be adaptable to high levels of UV-B radiation. Adaptation involves structural and chemical changes that can affect herbivores, decomposition, nutrient cycling, and productivity.
Carbon storage and fluxes	Over the long term, replacement of arctic vegetation with more productive southern vegetation is likely to increase net carbon storage in ecosystems, particularly in regions that are now tundra or high-arctic polar desert. Methane fluxes are likely to increase as vegetation grows in tundra ponds, and as wetlands become warmer (until they dry out). Methane fluxes are also likely to increase when permafrost thaws.
Albedo feedback	The positive feedback of albedo change (due to forest expansion) on climate is likely to dominate over the negative (cooling) feedback from an increase in carbon storage. The albedo reduction due to reduced terrestrial snow cover will be a major additional feedback.

Table 18.5. Projected impacts on freshwater ecosystems. This table is mainly based on Chapter 8.

	Projected impact
Lakes	Reduced ice cover and a longer open-water season are very likely to affect thermal regimes, particularly lake stratification. Permafrost thaw in ice-rich environments is very likely to lead to catastrophic lake drainage; increased groundwater flux will drain other lakes. A probable decrease in summer water levels of lakes and rivers is very likely to affect the quality and quantity of, and access to, aquatic habitats.
Rivers	A likely shift to less intense ice breakup will reduce the ability of flow systems to replenish riparian ecosystems, particularly in river deltas. Reduced climatic gradients along large northern rivers are likely to alter ice-flooding regimes and related ecological processes. A very likely increase in winter flows and reduced ice-cover growth will increase the availability of under-ice habitats.
Water quality	Enhanced permafrost thawing is very likely to increase nutrient, sediment, and carbon loadings to aquatic systems, with a mixture of positive and negative effects on freshwater chemistry. An earlier phase of enhanced sediment supply will probably be detrimental to benthic fauna but the balance will be ecosystem- or site-specific. Freshwater biogeochemistry is very likely to alter following changes in water budgets.
Wetlands	Changes in climate are very likely to lead to an increased extent of wetlands, ponds, and drainage networks in low-lying permafrost-dominated areas, but also to losses of wetlands on hill slopes and higher ground. Coastal erosion and inundation will generate new wetlands in some coastal areas. Conversely, increased evapotranspiration is likely to dry peatlands, particularly during the warm season.
Species diversity	Changes in the timing of freshwater habitat availability, quality, and suitability are very likely to alter the reproductive success of species. Correspondingly, the rate and magnitude of climate change and its effects on aquatic systems are likely to outstrip the capacity of many aquatic biota to adapt or acclimate. Climate change is very likely to act cumulatively and/or synergistically with other stressors to affect the overall biodiversity of aquatic ecosystems.
UV radiation effects	Reduced ice cover in freshwater ecosystems is likely to have a greater effect on underwater UV radiation exposure than projected levels of stratospheric ozone depletion. Little is known about the adaptive responses of aquatic organisms to changing UV radiation levels.

Changes in animal and plant populations are often triggered by extreme events, particularly winter processes. Weather extremes in winter are likely to have greater effects on the mammals and birds that remain active in winter, than on plants, insects, and other invertebrates that are dormant in winter. While some projections indicate a likely increase in the frequency and severity of extreme events (storms, floods, icing of snow layers, drought) the distribution of these events is very difficult to project. Rapid changes present additional stresses if they exceed the ability of species to adapt or relocate since they are likely to lead to increased incidence of fires, disease, and insect outbreaks, as well as to restricted forage availability.

The impact of changes in climate and UV radiation levels on species and ecosystems is likely to make the current use of many protected areas as a conservation practice almost obsolete. Although local measures to reduce hunting quotas might moderate impacts of climate change on wildlife species, habitat protection requires a new, more flexible paradigm. Comparison of areas in the Arctic in which vegetation is likely to dramatically change with the location of current protected areas shows that many habitats will be altered so that they will no longer serve to support the intended species or communities. These impacts will be reduced if simple measures are incorporated into the design of protected areas, for example, designating flexible boundaries that encompass extended latitudinal tracts of land and protect corridors for species movement.

As warming allows trees to grow, forests are projected to replace a significant proportion of the tundra. This process is very likely to be slowed locally by natural barriers to movement, human activities, fires, insect attacks, browsing by vertebrate herbivores, and drying or waterlogging of soils, but the long-term effect on species composition will be significant. Displacement of tundra by forest will also lead to a decrease in albedo, which will increase the positive (warming) feedback to the climate system, especially during spring when snow melts, and amplify changes in the local climate. Warming and drying of tundra soils are likely to lead to an increased release of carbon, at least in the short term. However, current models suggest that the Arctic may become a net sink for carbon (although the uncertainties associated with the projections are high). There are also uncertainties about changes in methane (CH_4) fluxes (although current CH_4 emissions from arctic ecosystems are already forcing climate) from wetlands, permafrost, and CH_4 hydrates, so it is not known if the circumpolar tundra will become a carbon sink or carbon source in the long term.

Tables 18.4 and 18.5 summarize the most important impacts projected for terrestrial and freshwater ecosystems, respectively.

Changes in the ocean

Through its influence on the Atlantic thermohaline circulation, the Arctic plays a critical part in driving the global thermohaline circulation. It is possible that increased precipitation and runoff of fresh water and the melting of glaciers and ice sheets, and thawing of the extensive permafrost underlying northern Siberia, could

Table 18.6. Projected impacts in the Arctic Ocean and subarctic seas. This table is mainly based on Chapters 9 and 13.

	Projected impact
Ocean regime	Increased runoff from major arctic rivers and increased precipitation over the Arctic Ocean are very likely to decrease its salinity.
Thermohaline circulation	A slow-down of the global thermohaline circulation is likely as a result of increased freshwater input from melting glaciers and precipitation. This is likely to delay warming for several decades in the Atlantic sector of the Arctic as a result of reduced ocean heat transport.
Sea-ice regime	All the ACIA-designated models project substantial reductions in sea-ice extent and likely opening of the Northern Sea Route to shipping during summer. Some of the models project an entirely ice-free Arctic Ocean in summer by the end of the 21st century. Greater expanses of open water will also increase the positive feedback of albedo change to climate.
Marine ecosystems	Reduced sea-ice extent and more open water are very likely to change the distribution of marine mammals (particularly polar bears, walrus, ice-inhabiting seals, and narwhals) and some seabirds (particularly ivory gulls), reducing their populations to vulnerable low levels. It is likely that more open water will be favorable for some whale species and that the distribution range of these species is very likely to spread northward.
UV radiation effects	Ultraviolet radiation can act in combination with other stressors, including pollutants, habitat destruction, and changing predator populations, to adversely affect a number of aquatic species. In optically clear ocean waters, organisms living near the surface are likely to receive harmful doses of UV radiation. Sustained, increased UV radiation exposure could also have negative impacts on fisheries.
Fisheries	Changes in the distribution and migration patterns of fish stocks are likely. It is possible that higher primary productivity, increases in feeding areas, and higher growth rates could lead to more productive fisheries in some regions of the Arctic. New species are moving into the Arctic and competing with native species. The extinction of existing arctic fish species is unlikely.
Coastal regions	Serious coastal erosion problems are already evident in some low-lying coastal areas, especially in the Russian Far East, Alaska, and northwestern Canada, resulting from permafrost thawing and increased wave action and storm surges due to reduced sea-ice extent and sea-level rise. Ongoing or accelerated coastal-erosion trends are likely to lead to further relocations of coastal communities in the Arctic.

freshen arctic waters, causing a reduction in the overturning circulation of the global ocean and thus affecting the global climate system and marine ecosystems. The IPCC 2001 assessment considers a future reduction of the Atlantic thermohaline circulation as likely, while a complete shutdown is considered as less likely, but not impossible. If half the oceanic heat flux were to disappear with a weakened Atlantic inflow, then the associated cooling would more than offset the projected heating in the 21st century. Thus, there is the possibility that some areas in the Atlantic Arctic will experience significant *regional* cooling rather than warming, but the present models can assess neither its probability, nor its extent and magnitude.

The most important projected trends for the marine systems of the Arctic are summarized in Table 18.6.

18.2.2.2. Impacts on people's lives

Several chapters address the impacts of climate change on people, including Chapters 10, 11, 12, 14, 15, and 16. The Arctic is home to a large number of distinct groups of indigenous peoples and the populations of eight nations. Between two and four million indigenous and non-indigenous people live in the Arctic, depending on how the Arctic is defined. Most live in cities; in Russia large urban centers include Vorkuta and Norilsk with populations listed as exceeding 100000, and Murmansk with about 500000 people, although the population of these cities has decreased in recent years. Arctic towns in Scandinavia and North America are smaller; Reykjavik has around 110000 inhabitants and Rovaniemi about 65000. In total there are probably around 30 towns in the Arctic with more than 10000 inhabitants.

Table 18.7 summarizes the projected social impacts of climate change and UV radiation on the people of the Arctic. Climate change is only one, and perhaps not the most important, factor currently affecting people's lives and livelihood in the Arctic. For example, the people living in Russia's Far North have experienced dramatic political, social, and economic changes since the collapse of the former Soviet Union; and Europeans, Canadians, and Alaskans have experienced major changes resulting from the discovery of minerals, oil and gas reserves, and the declines or increases of some of the northern fisheries.

For the indigenous population, and particularly for those people who depend on hunting, herding, and fishing for a living, climate change is likely to be a matter of cultural survival, however. Their uniqueness as people with cultures based on harvesting marine mammals, hunting,

Table 18.7. Projected social impacts on arctic residents. This table is mainly based on Chapters 12, 15, and 16.

	Projected impact
Impacts on arctic residents	
Infrastructure	Permafrost thawing is very likely to threaten buildings, roads, and other infrastructure. This includes increases in the settling and breaking of underground pipes and other installations used for water supply, heating systems, and waste disposal, and threats to the integrity of containment structures such as tailing ponds and sewage lagoons.
Water	While increased river runoff is projected to occur mainly in winter and spring, lower water tables in rivers and lakes in summer will reduce available water and impede river travel in some areas (e.g., the Mackenzie River watershed).
Health	Circumpolar health problems such as those associated with changes in diet and UV radiation levels are likely to become more prominent. Increases in zoonotic diseases and injury rates are likely, due to environmental changes and climate variability.
Income	Impacts on the economy are expected as a consequence of climate change in the Arctic and will affect work opportunities and income of arctic residents. Expected increases in productivity and greater opportunity for settlement are also likely to benefit people within and beyond the region.
Impacts specific to indigenous communities	
Food security	Obtaining and sharing traditional foods, both cultural traditions, are very likely to become more difficult as the climate changes, because access to some food species will be reduced. The consequences of shifting to a more Western diet are likely to include increased incidence of diabetes, obesity, and cardiovascular diseases. Food from other sources may also be more costly.
Hunting	Hunter mobility and safety and the ability to move with changing distribution of resources, particularly on sea ice, are likely to decrease, leading to less hunting success. Similarly, access to caribou by hunters following changed snow and river-ice conditions is likely to become more difficult. Harvesting the threatened remaining populations of some marine mammals could accelerate their demise.
Herding	Changing snow conditions are very likely to adversely affect reindeer and caribou herding (e.g., ice layers and premature thawing will make grazing and migration difficult and increase herd die-offs). Shorter duration of snow cover and a longer plant growth season, on the other hand, are likely to increase forage production and herd productivity if range lands and stocking levels are adequately managed.
Cultural loss	For many Inuit, climate change is very likely to disrupt or even destroy their hunting culture because sea-ice extent is very likely to be reduced and the animals they now hunt are likely to decline in numbers, making them less accessible, or they may even disappear from some regions. Cultural adaptation to make use of newly introduced species may occur in some areas.

herding caribou and reindeer, or fishing, is at risk because climate change is likely to deprive them of access to their traditional food sources, although new species, as they move north, may become available in some regions. Indigenous peoples have adapted to changes in the past through careful observations and skillful adjustments of their traditional activities and lifestyles, but the addition of climate and UV radiation changes and impacts on existing social, political, and other environmental stresses is already posing serious challenges. Today, the indigenous peoples live in greatly circumscribed social and economic situations and their hunting and herding activities are determined to a large extent by resource management regimes and local, regional, and global economic market situations that reduce their ability to adapt and cope with climate variability and change. While they experience stress from other sources that threatens their lifestyles and cultures, climate change magnifies these threats.

Improvements in human health are very likely to continue through advances in technology, but the potential for emerging diseases (via the introduction of new insect and animal vectors) in northern communities makes it difficult to project how climate change is likely to affect the overall health of arctic residents. Several types of impacts seem likely. Because it will be more difficult to access marine animals when hunting, and because there is greater danger to the hunters when traveling over thinner sea ice, and in open water in less predictable weather conditions, direct health effects through a changing diet and increased accident rates are likely. Increased UV radiation levels are also likely to directly affect health, increasing incidences of skin cancer, cataracts, and viral infections, owing to effects on the immune system. Studies by the World Health Organization estimate that a person receives the majority of their lifetime UV radiation exposure before 18 years of age. An entire generation of people in the

Table 18.8. Projected impacts on important economic activities in the Arctic. This table is mainly based on Chapters 13, 14, and 16, but also draws information from other chapters.

	Projected impact
Non-renewable resources	
Oil and gas	
Exploration	Reduced sea ice is likely to facilitate some offshore operations but hamper winter seismic work on shore-fast ice. Later freeze-up and earlier melting are likely to limit the use of ice and snow roads.
Production	Reduced extent and thinner sea ice are likely to allow construction and operation of more economical offshore platforms. Storm surges and sea-level rise are likely to increase coastal erosion of shore facilities and artificial islands. The costs of maintaining infrastructure and minimizing environmental impacts are likely to increase as a result of thawing permafrost, storm surges, and erosion.
Transportation	Reduced extent and duration of sea and river ice are likely to lengthen the shipping season and shorten routes (including trans-polar routes). Permafrost thawing is likely to increase pipeline maintenance costs.
Coal and minerals	
Production	The costs of maintaining infrastructure and minimizing environmental impacts are likely to increase as a result of thawing permafrost, storm surges, and erosion.
Transportation	Reduced extent and duration of sea ice are likely to lengthen the shipping season. Thawing permafrost is likely to affect roads and infrastructure.
Renewable resources	
Fish, shellfish, freshwater fish	
Fish stocks	Temperature, currents, and salinity changes are likely to lead to changes in species availability (positive in some areas, negative in others).
Harvests	Changes in migration patterns are likely to lead to changes in distances to fishing grounds, and possible relocation of processing plants. Increased storms, and icing of ship superstructure are likely to increase risks and reduce catches.
Timber	Productivity is likely to increase if there is adequate soil moisture but decrease if there are summer droughts. Fire and insect outbreaks are likely to decrease productivity.
Agricultural products	A warmer climate is likely to lengthen the growing season and extend the northern range of agriculture. Increased insect problems are likely to decrease productivity.
Energy	
Hydropower	Precipitation changes are likely to affect the water supply. Melting glaciers are likely to reduce future seasonal water supply.
Power lines	Icing events, storms, and ground thaw are likely to affect power lines.
Wildlife	
Harvests	Changes in distribution and migration patterns are likely to affect access to wildlife and change harvests. Invasive species are likely to compete with existing populations.
Conservation	Habitat loss, longer seasons, and boat access are likely to lead to over-harvesting in protected areas and affect conservation.

Arctic is likely to continue to be exposed to above-normal UV radiation levels, and a new generation will grow to adulthood under increased UV radiation levels. Although behavioral adaptations can reduce the expected impacts, adequate information and education about these effects must be available.

18.2.2.3. Impacts on the economy

The three most important sectors of the commercial economy of the Arctic are oil and gas, fish, and minerals, each of which will be influenced by changes in the climate. There are also other economic sectors that will be affected by climate change, including forestry, agriculture, and tourism. Impacts on industry and commerce are described in greater detail in Chapters 13, 14, and 16. The use of local resources for traditional purposes, including fish, wildlife, plants, and wood for fuel and home construction, are also part of the arctic economy and have been addressed in Chapters 11, 12, and 17.

Oil and gas

The Arctic has large oil and gas reserves. Most are located in Russia: oil in the Pechora Basin, gas in the Lower Ob Basin, and other potential oil and gas fields along the Siberian coast. In Siberia, oil and gas development has expanded dramatically over the past few decades, and this region produces 78% of Russia's oil and 84% of its natural gas. Canadian oil and gas fields are concentrated in two main basins in the Mackenzie Delta/Beaufort Sea region and in the high Arctic. Oil and gas fields also occur in other arctic waters, for example the Barents Sea. The oil fields at Prudhoe Bay, Alaska, are the largest in North America, and by 2002, around 14 billion barrels had been produced at this site. There are also substantial reserves of natural gas and coal along the North Slope of Alaska. The Arctic is an important supplier of oil and gas to the global economy. Climate change impacts on the exploration, production, and transportation activities of this industry could have both positive and negative market and financial effects. These are summarized in Table 18.8.

Fish

The arctic seas contain some of the world's oldest and most productive commercial fishing grounds. In the Northeast Atlantic and the Bering Sea and Aleutian region, annual fish harvests in the past have exceeded two million tonnes in each of the two regions. In the Bering Sea, overall harvests have remained stable at about two million tonnes, but while some species like pollock (*Theragra chalcogramma*) are doing well, others like snow crab (*Chionoecetes opilio*) have declined. Important fisheries also exist around Iceland, Greenland, the Faroe Islands, and Canada. Fisheries are important to many arctic countries, as well as to the world as a whole. For example, Norway is one of the world's biggest fish exporters with exports worth US$ 4 billion in 2001. In some arctic regions aquaculture is a growing industry, providing local communities with jobs and income. Freshwater fisheries are also important in some areas. Changes in climatic conditions are likely to have both positive and negative financial impacts (see Table 18.8).

Minerals

The Arctic has large mineral reserves, ranging from gemstones to fertilizers. Russia extracts the greatest quantities of these minerals, including nickel, copper, platinum, apatite, tin, diamonds, and gold, mostly on the Kola Peninsula but also in the northern Ural Mountains, the Taymir region of Siberia, and the Far East. Canadian mining in the Yukon and Northwest Territories and Nunavut is for lead, zinc, copper, gold, and diamonds. In Alaska, lead and zinc are extracted at the Red Dog Mine, which sits atop two-thirds of US zinc resources, and gold mining continues in several areas. Coal mining occurs in several areas of the Arctic. Mining activities in the Arctic are an important contributor of raw materials to the global economy and are likely to expand with improving transportation conditions to bring products to market, due to a longer ice-free shipping season (Table 18.8).

Transportation industry

The cost of transporting products and goods into and out of the Arctic is a major theme of the potential impacts of climate change on many of the economic sectors described above. While climate change will affect many different modes of transport in the Arctic, the likelihood of reduced extent and duration of sea ice in the future will have a major impact. The projected opening of the Northern Sea Route (the opening of the Northwest Passage is less certain) to longer shipping seasons (Chapter 16) will provide faster and therefore cheaper access to the Arctic, as well as the possibility of trans-arctic shipping. This will provide new economic opportunities, as well as increased risks of oil and other pollution along these routes. Other regions of the Arctic will also benefit from easier shipping access due to less sea ice.

Projected climate-related impacts on the major economic sectors in the Arctic are listed in Table 18.8. This is a qualitative assessment only, since detailed financial estimates of economic impacts are not available at present, except in very few instances. Over the 21st century, new types of activities could arise (for example trans-arctic shipping) but there are likely to be others. This analysis focuses on how future climate change could affect the present economy, and is not based on projections of economic and demographic development in the Arctic over the 21st century.

Forestry, agriculture, and tourism

Forestry is an important economic activity in six of the eight arctic countries, and agriculture in its various forms also contributes to local economies in all eight countries. The basis for agricultural activities varies throughout the Arctic. In North America, the limited agriculture helps to meet the need for local fresh produce during the short summer. In northern Europe and across the Russian North, crop production along with reindeer husbandry and some other domestic livestock production serve traditional cultural needs and provide opportunities for income. Tourism is also becoming an increasingly important economic factor in many arctic regions. Impacts on these economic sectors in monetary terms are difficult to project and quantify since factors other than climate, including future regional economic development, play a major role.

Wildlife

Arctic wildlife resources support communities throughout the Arctic, through whaling, fishing, and hunting, and wildlife contributes to both the monetary and traditional economies of the Arctic. Climate change threatens the culture and traditional lifestyles of indigenous communities but is not discussed here. Likely economic impacts due to climate change are relevant here but are not easily quantified at present.

18.3. A synthesis of projected impacts in the four regions

This section examines impacts within a more regional setting. A spatial division is necessary because the Arctic is very large and different regions are likely to experience patterns of climate change in the coming decades that are significantly different. Different regions of the Arctic are also distinguished by different social, economic, and political systems, which will mediate the impacts of and responses to climate change. These distinctions are captured broadly by the four regions defined in this assessment (see Fig. 18.6).

Fig. 18.6. The four regions of the Arctic Climate Impact Assessment.

Differences in large-scale weather and climate-shaping factors were primary considerations in selecting the four regions. Observations also indicate that the climate is presently changing quite differently in each of these regions, and even within them, especially where there are pronounced variations in terrain, such as mountains versus coastal plains. There are also large north–south gradients in climate variability within each region. The scale was thought to be roughly appropriate given that a larger number of smaller regions would not have been practical for this assessment, or compatible with a focus at the circumpolar level.

Region 1 includes East Greenland, northern Scandinavia, and northwestern Russia, as well as the North Atlantic with the Norwegian, Greenland, and Barents Seas. This region is projected to experience similar types of changes because the entire area is under the influence of North Atlantic atmospheric and oceanic conditions, particularly the Icelandic Low.

Region 2 includes Central Siberia, from the Urals to Chukotka, and the Barents, Laptev, and East Siberian Seas. This region represents the coldest part of the Arctic and is under the influence of the Siberian high-pressure system during winter.

Region 3 includes Chukotka, Alaska, the western Canadian Arctic to the Mackenzie River, and the Bering, Chukchi, and Beaufort Seas. This region is largely under the influence of North Pacific atmospheric and oceanic processes and the Aleutian Low.

Region 4 includes the central and eastern Canadian Arctic east of the Mackenzie River, the Queen Elizabeth Islands south to Hudson Bay, and the Labrador Sea, Davis Strait, and West Greenland. The region's weather systems are connected to large-scale North American and western North Atlantic weather patterns.

Major impacts due to observed and projected climate change for each of the four regions are summarized in sections 18.3.1 to 18.3.4. Details, including relevant references and publications on earlier impact assessments in the four regions, can be found in the preceding 17 chapters. The previous regional impact assessments were useful source material and laid a critical foundation for the ACIA. Some impacts apply to more than one or to all of the regions; such impacts are described in section 18.2 and are not necessarily listed separately for each region.

While the importance of providing information at the regional level has been emphasized here, the focus of the ACIA was at the circumpolar scale. The following sections attempt to synthesize significant findings for each of the four regions where these have been provided by the relevant chapters of the assessment. In some cases, the evaluated literature did not support a very extensive assessment of the nature of changes in the four regions.

Table 18.9. Key consequences of climate change on the environment, the economy, and on people's lives in the four ACIA regions. Unless otherwise stated these key consequences are considered likely to occur.

	Environment	Economy	People's lives
Region 1 Eastern Greenland, North Atlantic, northern Scandinavia, northwestern Russia	• Northward shifts in the distribution ranges of plant and animal species (terrestrial, freshwater, and marine) • Many tundra areas disappear from the mainland, except in arctic Russia where bog growth prevents forest development • Carbon storage increases and albedo decreases, but less so than in other regions	• Change in the location of North Atlantic and Arctic fisheries due to warmer waters and change in yields of many commercial fish stocks • Improved access to oil, gas, and mineral resources in presently ice-covered waters and adjacent land areas • Rising sea level and more storm surges affect coastal facilities	• Reduced and changing snow cover, affecting reindeer herding and hunted wildlife • Traditional harvest of animals is riskier and less predictable • Emergence of zoonotic diseases as a threat to human health • Increased outdoor leisure and recreational opportunity, plus lower heating costs
Region 2 Siberia	• Northward shifts in the distribution ranges of plant and animal species (terrestrial, freshwater, and marine) • Changing forest character due to warmer climate and permafrost thawing, with possibly greater fire and pest threats • Tundra changing to shrub and forest, but northern tundra extension limited by the ocean • Increased river discharge, affecting sediment and nutrient fluxes	• Reopening of the Northern Sea Route (Northeast Passage), due to reduced extent and duration of sea ice, providing new economic possibilities, and also increased pollution risks (tankers) • Improved access to oil, gas, and mineral resources in presently ice-covered waters and adjacent land areas • Rising sea level and more storm surges affect coastal facilities	• Permafrost thawing, causing serious damage to buildings in Siberian cities and to houses and facilities in villages • Traditional harvest of animals is riskier and less predictable • Emergence of zoonotic diseases as a threat to human health • Lower heating costs
Region 3 Chukotka, Bering Sea, Alaska, western Canadian Arctic	• Northward shifts in the distribution ranges of plant and animal species (terrestrial, freshwater, and marine) • Forest disruption due to warming and increased pest outbreaks • Reduced sea ice and general warming, disrupting polar bears, marine mammals, and other wildlife • Low-lying coastal areas more frequently inundated by storm surges and sea-level rise	• Damage to infrastructure due to thawing permafrost • Improved access to oil, gas, and mineral resources in presently ice-covered waters and adjacent land areas • Change in recruitment, growth rates, abundance, and distribution of Bering Sea fish due to warmer waters • Rising sea level and storm surges, affect coastal facilities	• Retreating sea ice and earlier snowmelt, altering traditional lifestyle patterns and food security, increasing risks taken by hunters, further stressing nutritional status • Coastal erosion and flooding forcing relocation of villages • Emergence of zoonotic diseases as a threat to human health • Increased outdoor leisure and recreational opportunity, plus lower heating costs
Region 4 Central and Eastern Canadian Arctic, Labrador Sea, Davis Strait, West Greenland	• Thawing of warm permafrost and reduced river and lake ice, changing hydrological regimes • Northward shifts in the distribution ranges of plant and animal species (terrestrial, freshwater, and marine) • High-arctic polar desert replaced by tundra in some areas, leading to potential large carbon gains • Increased melting of the Greenland Ice Sheet, changing the coastal environment • Decreasing sea-ice extent; threatening the extinction of polar bears	• Potential increased shipping in the Northwest Passage as sea ice retreats, providing economic incentives such as cheaper transport of goods, but also increasing pollution and oil-spill risks • Shorter operating season for ice and snow roads • Changes in marine and freshwater fisheries with impacts on tourism and local economic development • Rising sea level and storm surges affect coastal facilities	• Traditional lifestyles and survival of indigenous hunting culture threatened by retreating sea ice and changing environment • Health impacts via stresses on food security and safety of travel conditions • Emergence of zoonotic diseases as a threat to human health • Increased outdoor leisure and recreational opportunity, plus lower heating costs

Table 18.9 summarizes the key consequences of climate change on the environment, the economy, and people's lives in each of the four regions. The following sections provide additional information by region. Projections of climate change for each region are based on output from the five ACIA-designated climate models.

18.3.1. Region 1

18.3.1.1. Changes in climate

Most of Region 1 experienced a modest increase in mean annual temperature (about 1 ºC) between 1954 and 2003, with slightly higher winter temperature increases over this period, except for Iceland, the Faroe Islands, and southern Greenland, where there has been some cooling (see Fig. 18.2 for regional details). From 1990 to 2000, greater warming was observed in northern Scandinavia, including Iceland, Svalbard, and East Greenland, but cooling was observed in other areas such as the Kola Peninsula.

Model projections (see Fig. 18.5 for regional details) indicate that this region is likely to experience additional increases in mean annual temperature of 2 to 3 ºC in Scandinavia and East Greenland and up to 3 to 5 ºC in northwestern Russia by the late 21st century. Although changes in atmospheric and oceanic circulation contributed to some cooling of the region during the 20th century, warming has occurred in recent decades and is projected to dominate throughout the 21st century. Precipitation has increased slightly and is projected to increase further by up to about 10% by the end of the century.

18.3.1.2. Impacts on the environment

The geography and environment of Region 1 are dominated by the North Atlantic Ocean, which has extensive connections with the Arctic Ocean via the Norwegian, Greenland, and Barents Seas. The North Atlantic Ocean separates Greenland in the west from the Fennoscandian, European, and western Russian landmasses in the east. Relatively isolated islands of Iceland, the Faroe Islands, and the Svalbard and Franz Josef archipelagos span the low to high arctic latitudes. The land areas are characterized by a north–south climatic contrast between low-arctic environments in the south isolated by ocean from the high-arctic environments of the high-latitude islands, and by an east–west climatic contrast between the Scandinavian landmass, which is uncharacteristically warm for its latitude, and East Greenland in the west of the region, which is heavily glaciated. The continuous south–north land corridors for movement of terrestrial and freshwater species and people found in Region 2, for example, are missing.

The Greenland, Iceland, Norwegian, and Barents Seas constitute a major part of this region. This vast oceanic area is influenced by the inflow of relatively warm Atlantic water, which enters along the coast of Norway and is the most northward branch of the Gulf Stream. Variability in the volume of this inflow, as experienced in the past and as projected by models for the future due to global climate change, is expected to have major consequences for the physical and biological regimes of the region. Sea surface temperature is expected to increase, and the Barents Sea is expected to be totally ice free in summer by 2080. Changes in the distribution of important fish stocks are expected to occur. Past integrative impact assessments of climate change in this region include publications by Lange et al. (1999, 2003) for the Barents Sea.

The arctic seas in Region 1 are projected to experience a temperature increase that will lead to a decrease in sea-ice cover, especially in summer, as well as earlier ice melt and later freeze-up. Unless compensated for by an increase in low-level cloudiness, decreases in sea-ice cover would reduce the overall planetary albedo of the region and provide a positive feedback to the global climate. The reduction in sea ice is likely to enhance primary productivity, lead to increases in zooplankton production, and possibly to increased fisheries production. Such changes would also lead to decreased natural habitat for polar bears (*Ursus maritimus*) and ringed seals (*Phoca hispida*) to an extent that is likely to threaten the survival of their populations in this region. Conversely, more open water is expected to favor some whale and seabird species.

Biodiversity is high in Region 1: around 6000 marine and terrestrial species have been recorded for Svalbard (Prestrud et al., 2004) and around 7200 species have been recorded for 22 705 km^2 between 68º and 70º N in northern Finland (Callaghan et al., 2004). The European Arctic and subarctic are important breeding areas for many bird species overwintering in more temperate regions. Excluding the Russian Arctic, over 43% of the European bird species pool occurs in Region 1.

Observations indicate very variable climate trends and ecological responses to them in Region 1 (see Chapter 7). Treelines in northern Sweden increased in altitude by up to 40 m during the first part of the 20th century, and a further 20 m during the warming of the past 40 years, giving recent rates of treeline increase of 0.5 m/yr and 40 m/ºC (Callaghan et al., 2004). In northern Finland, the pine treeline is increasing in altitude and density, and in the Polar Ural Mountains, treeline has advanced. However, there is little evidence of a northward shift of the latitudinal treeline west of the Polar Ural Mountains. Unexpectedly, evidence shows a southward movement of the treeline in parts of the forest tundra of the Russian European Arctic, a change that appears to be associated with localized pollution, deforestation, agriculture, and the growth of bogs leading to tree death. In the Faroe Islands, there has been a lowering of the alpine altitudinal treeline in response to a cooling of 0.25 ºC during the past 50 years. In some areas of Finland and northern Sweden, there is evidence of an increase in rapidly changing warm and cold episodes in winter that lead to increasing bud damage in birch. Recent warming in northern Sweden and Finland has led to a reduction in the extent of discontinuous permafrost in mires and a change in vegetation resulting in increased CH_4 flux to the atmosphere (Christensen et al., 2004).

Recent warm winters have resulted in unusual conditions (causing ice layers in the snow) unfavorable for reindeer and wildlife, and leading to an absence of lemming population peaks, and on Svalbard, a decline in wild reindeer (*Rangifer tarandus platyrhynchus*) through decreases in the availability of food resources. Changes in animal populations also include reductions in arctic fox (*Alopex lagopus*) and snowy owl (*Nyctea scandiaca*) (as well as several other bird species) populations on mainland Fennoscandia but a northward migration of larger butterflies and moths, the larvae of some being defoliators of trees and shrubs. Moose (*Alces alces*), red fox (*Vulpes vulpes*), and the invasive species mink (*Mustela vison*) are increasing in the east of the region and muskoxen (*Ovibos moschatus*), wolves, and pink-footed (*Anser brachyrhynchus*) and barnacle geese (*Branta leucopsis*) are increasing in northeast Greenland (Callaghan et al., 2004).

If warming occurs as projected, the deciduous mountain birch forest that forms much of the present treeline in the region, the boreal conifer forest and woodland, and the arctic and alpine tundra are very likely to begin shifting northward and upward in altitude. The potential for vegetation change within the region is perhaps greatest in northern Scandinavia, where large shifts occurred in the early Holocene in response to warming. Here, pine forest is projected to invade the lower belt of mountain birch forest. The birch treeline is projected to move upward and northward, displacing shrub tundra vegetation, which in turn is projected to displace alpine tundra. Alpine species in the north are expected to be the most threatened because there is no suitable geographic area for them to shift toward in order to avoid being lost from the Fennoscandian mainland. In Iceland, a warmer climate is likely to facilitate natural regeneration of the heavily degraded native birch woodland as well as aid current and future afforestation efforts (Chapter 14). Model projections suggest that arctic tundra will be displaced totally from the mainland by the end of the 21st century (Fig. 18.1), although in practice, the bogs of the western Russian European Arctic may prevent forests from reaching the coast. Model projections of change from tundra to taiga between 1960 and 2080 (5.0%), and of change from polar desert to tundra (4.2%), are the lowest of any of the four ACIA regions because of the lack of tundra areas and the separation of the high Arctic from the subarctic.

While the climate is changing, local forest damage is projected to occur as a result of winters that are warmer than normal. Warmer winters are likely to lead to an increase in insect damage to forests and decreases in populations of animals such as lemmings and voles that depend upon particular snow conditions for survival. These changes, in turn, are likely to cause decreases in populations of many existing bird species and other animals, with the most severe effects on carnivores, such as Arctic foxes, and raptors, such as snowy owls. Heathland and wetland areas are likely to be partially invaded by grasses, shrubs, and trees, and mosses and lichens are expected to decrease in extent. Unlike other arctic areas, fire is not likely to play a major role in controlling vegetation dynamics. Any changes in land-use patterns, including increased agriculture and domestic stock production in a warmer climate, will encroach on wildlife habitats and further threaten large carnivores.

Some areas in this region, such as East Greenland and the Faroe Islands, have experienced recent cooling, and future warming is expected to reverse the present downward vegetation shifts in the mountains of the Faroe Islands. The island settings in this region, particularly those of Greenland, Svalbard, Franz Josef Land, and Novaya Zemlya, are likely to delay the arrival of immigrant species and substantial change other than expansion and increased growth of some current species.

Changes in arctic ecosystems will not only have local consequences but will also have impacts at a global level because of the many linkages between the Arctic and other regions further south. For example, several hundreds of millions of birds migrate to the Arctic each year and their success in the Arctic determines their populations at lower latitudes. As previously noted, excluding the Russian Arctic, over 43% of the European bird species pool is found in Region 1. Changes in their wintering areas far south of the Arctic also play an important part in the ecology of migratory birds and there are many important stop-over sites and overwintering grounds in Europe. Birds that are already suffering major declines in the region include lesser white-fronted goose (*Anser erythropus*) and shore lark (*Eremophila alpestris*) that have almost become extinct in Fennoscandia, and snowy owls. In contrast, some southern bird species have become established. Examples include blue tit (*Parus caeruleus*) and greenfinch (*Carduelis chloris*) (Callaghan et al., 2004).

Changes in carbon storage and release from ecosystems also have potential global consequences. Christensen et al. (2004) estimated that CH_4 emissions have increased from between 1.8 and 2.2 mg $CH_4/m^2/hr$ to between 2.7 and 3.0 mg $CH_4/m^2/hr$ over the past 30 years in northern Sweden, as a result of permafrost thaw and vegetation change. Terrestrial carbon storage and net primary production are projected to increase, and albedo to decrease, but less than in any other region due to the ocean barriers and general lack of tundra: there is a transition from subarctic to high Arctic separated by seas where the mid-arctic tundra should be.

18.3.1.3. Impacts on the economy

Region 1 has abundant renewable and non-renewable resources (timber, fish, ore, oil, and natural gas). The highly productive marine life makes this region one of the most productive fishing grounds in the circumpolar North. Higher ocean temperatures are likely to cause shifts in the distribution of some fish species, as well as changes in the timing of their migration, possible extension of their feeding areas, and increased growth rates. The occurrence of several "warm years" or "cold years" in a row, which is a sequence that could occur more frequently as a result of continuing global climate change, seems likely to lead to repercussions on the major fish stocks and, ultimately, the lucrative and productive fisheries in the region. Provided that the fluctuations in Atlantic inflow to the area are maintained, along with a general warming of the North Atlantic waters, it is likely that annual recruitment in herring (*Clupea harengus*) and Atlantic cod (*Gadus morhua*) will increase from current levels and will be about the same as the long-term average during the first two to three decades of the 21st century. This projection is also based on the assumption that harvest rates are kept at levels that maintain spawning stocks well above the level at which recruitment is impaired.

Impacts of climate change on the fisheries sector of the region's economy are difficult to assess, however. A scenario of moderate warming could result in quite large positive changes in the catch of many species. A self-sustaining cod stock could be established in West Greenland waters through larval drift from Iceland. Past catches suggest that this could yield annual catches of about 300000 t. Should that happen, it is estimated that catches of northern shrimp (*Pandalus borealis*) will decrease to around 30% of the present level, while those of snow crab and Greenland halibut (*Reinhardtius hippoglossoides*) might remain the same. Such a shift could approximately double the export earnings of the Greenlandic fishing industry, which roughly translates into the same amount as that presently paid by Denmark to subsidize the Greenland economy. Such dramatic changes are not expected in the Icelandic marine ecosystem. Nevertheless, there would be an overall gain through larger catches of demersal species such as cod, pelagic species like herring, and new fisheries of more southern species like mackerel (*Scomber scombrus*). On the other hand capelin (*Mallotus villosus*) catches would dwindle, both through diminished stock size and the necessity of conserving this very important forage fish for other species. Effective fisheries management will continue to play a key role both for Greenland and Iceland, however. Little can be said about possible changes under substantial climate warming because such a situation is outside any recorded experience.

Forestry and agriculture are important in Region 1; both have been affected by climate change in the past and impacts are likely to occur in the future. Longer growing seasons are likely to improve the growth of agricultural crops. While growth (net carbon assimilation) of forests and woodlands is likely to increase, this will not necessarily benefit the forestry industry as forest fires and pests will also increase. Forest pest outbreaks have been reported for the Russian part of the region, including the most extensive damage from the European pine sawfly (*Neodiprion sertifer*), which affected a number of areas, each covering more than 5000 ha. The annual number of insect outbreaks reported between 1989 and 1998 was 3.5 times higher than between 1956 and 1965. The mean annual intensity of forest damage increased two-fold between 1989 and 1998. Factors other than climate change are also important to forest-based economies. For example, while most of the region has seen modest growth in forestry, Russia has experienced a decline due to political and economic factors. These socio-economic problems are expected to be aggravated by global climate change, which in the short term will have negative effects on timber quality owing to fire and insect damage and on infrastructure and winter transport when permafrost thaws.

18.3.1.4. Impacts on people's lives

The prospects and opportunities of gaining access to important natural resources, both renewable and non-renewable, have attracted a large number of people to Region 1. The relatively intense industrial activities, particularly on the Kola Peninsula, have resulted in population densities that are the highest throughout the circumpolar North. Impacts of climate change on terrestrial and marine ecosystems and implications for the availability of natural resources may lead to major changes in economic conditions and subsequent shifts in demography, societal structure, and cultural values.

Because they would affect food, fuel, and culture, changes in arctic ecosystems and their biota are particularly important to the peoples of the Arctic. Reindeer herding by the Saami and other indigenous peoples is an important economic and cultural activity and the people who herd reindeer are concerned about the impacts of climate change. Observations have shown that during autumn the weather in recent years has fluctuated between raining and freezing so that the ground surface has often been covered with an ice layer and reindeer in many areas have been unable to access the underlying lichen. These conditions are quite different from those in earlier years and have caused massive losses of reindeer in some years. Changes in snow conditions also pose problems. Since reindeer herding has become motorized, herders relying on snowmobiles have had to wait for the first snows to start herding. In some years, this has led to delays up to the middle of November. Also, the terrain has often been too difficult to travel over when the snow cover is light. Future changes in snow extent and condition have the potential to lead to major adverse consequences for reindeer herding and those aspects of health (physical, social, and mental) relating to the livelihood of reindeer herders.

The beneficial effects of a warmer climate on people's recreational and leisure activities (camping, hiking, and other outdoor activities) should not be overlooked. Even relatively modest warming will improve people's mental and physical health. A warmer climate is also likely to reduce heating costs.

18.3.2. Region 2

18.3.2.1. Changes in climate

Region 2, which experiences the coldest conditions in the Arctic, has experienced an increase in mean annual temperature of about 1 to 3 ºC since 1954, and an increase of up to 3 to 5 ºC in winter (see Fig. 18.2 for regional details).

Models project that the mean annual temperature of Region 2 is likely to increase by a further 3 to 5 ºC by the late 21st century, and by up to 5 to 7 ºC in winter (see Fig. 18.5 for regional details). In the far north, winter warming of up to 9 ºC over the Arctic Ocean as a result of reduced sea-ice extent and thickness is projected. The summer warming over the land areas is projected to be 2 to 4 ºC by the end of the century, but there is likely to be very little change in summer over the Arctic Ocean.

18.3.2.2. Impacts on the environment

This region has the largest continuous land mass, which stretches from the tropical regions to the high Arctic. It is very likely to experience major changes as the boreal forest expands northward, but tundra will persist, although with reduced area. For example, extensive tundra is likely to remain in the Taymir region but is likely to be displaced completely from the mainland in the Sakha region.

The large Siberian rivers draining into the Arctic Ocean are projected to experience major impacts. Projected increases in winter precipitation, and more importantly in precipitation minus evaporation, imply an increase in water availability for soil infiltration and runoff. The total projected increase in freshwater supplied to the Arctic Ocean could approach 15% by the latter decades of the 21st century. An increase in the supply of freshwater has potentially important implications for the stratification of the Arctic Ocean, for its sea-ice regime, and for its freshwater export to the North Atlantic. In addition, increased freshwater input into the coastal zone is likely to accelerate the degradation of coastal permafrost.

On land, the projected increase in precipitation is likely to lead to wetter soils when soils are not frozen, wetter active layers in summer, and greater ice content in the upper soil layer during winter. To the extent that the increase in precipitation occurs as an increase in snowfall during the cold season, snow depth and snow water equivalent will increase, although the seasonal duration of snow cover may be shorter if, as projected, warming accompanies the increased snowfall.

The projected changes in terrestrial watersheds will increase moisture availability in the upper soil layers in some areas, favoring plant growth in areas that are presently moisture-limited. The projected increase in river discharge during winter and spring is likely to result in enhanced fluxes of nutrients and sediments to the Arctic Ocean, with corresponding impacts on coastal marine ecosystems. Higher rates of river and stream flow are likely to have especially large impacts on riparian regions and flood plains in the Arctic. One important consequence is that the vast wetland and bog ecosystems of this region are very likely to expand, leading to higher CH_4 emissions.

18.3.2.3. Impacts on the economy

A potentially major impact on the economy of Region 2 and on the global economy could be the opening of the Northern Sea Route (Northeast Passage) to commercial shipping. Model projections of ice cover during the 21st century show considerable development of ice-free areas around the entire Arctic Basin. Most coastal waters of the Eurasian Arctic are projected to become relatively ice free during September by 2020, with more extensive melting occurring later in the century. Ships navigating the Northern Sea Route would clearly benefit from these ice-free conditions. In addition, if winter multi-year sea ice in the central Arctic Ocean continues to retreat, it is very likely that first-year sea ice will dominate the entire maritime Eurasian Arctic, with a decreasing frequency of multi-year ice intrusions into the coastal seas and more open water during the summer. By 2100, one of the ACIA-designated models projects that the navigation season could be as long as 200 days, while the mean of the five ACIA-designated models projects a navigation-season length of 120 days (when defined as the period with sea-ice concentrations below 50%).

Such changes in sea-ice conditions are likely to have important implications for ship design and construction and route selection along the Northern Sea Route in summer and even in winter. The need for navigational aids, refueling and ship maintenance, and sea-ice monitoring will require major financial investment, however, to assure security and safety for shipping and protection of the marine environment.

The coal and mineral extraction industries in Region 2 are important parts of the Russian economy, but climate change is likely to have little effect on the actual extraction process. On the other hand, transportation of coal and minerals will be affected in both a positive and negative sense. Mines in Siberia that export their products by ship will experience savings resulting from reduced sea-ice extent and a longer shipping season. However, mining facilities relying on transport over roads on permafrost will experience higher maintenance costs as the permafrost thaws.

Forestry, another important sector of the Siberian economy, is likely to experience both positive and negative impacts. A potentially longer growing season and warmer climate are likely to enhance productivity. However, more frequent fires and insect outbreaks are likely as the climate warms and insects invade from warmer regions. Drying of soils as permafrost thaws is also likely to affect forest productivity in some areas. To meet the demands of the global economy, forestry is likely to become more important and transportation of wood and wood products to markets will improve as reduced sea-ice extent facilitates marine transport along the Siberian coast.

18.3.2.4. Impacts on people's lives

The change to a wetter climate is likely to lead to increased water resources for the region's residents. In permafrost-free areas, water tables are very likely to be closer to the surface, and more moisture is projected to be available for agricultural production. During the spring when enhanced precipitation and runoff are very likely to cause higher river levels, the risk of flooding will increase. Summer soil moisture changes remain an open question since the models do not give clear signals. It is possible that lower water levels will occur in summer, as projected for other regions (for example the Mackenzie River in Region 3), affecting river navigation in some areas, increasing the risk of forest fires, and affecting hydropower generation.

Other major environmental impacts projected for Region 2 are associated with thawing permafrost and melting sea ice. Warming during the 20th century produced noticeable impacts on permafrost, causing deeper seasonal thawing and changes in the distribution and temperature of the frozen ground. For example, from the late 1980s to 1998, temperatures in the upper permafrost layers increased by 0.1 to 1.0 ºC on the western Yamal Peninsula. Permafrost degradation in the developed regions of northeast Russia, coupled with inadequate building design, has led to serious problems. For example, in 1966 a building affected by thermokarst and differential thaw settlement collapsed in Norilsk, killing 20 people. In Yakutsk, a city built over permafrost in central Siberia, more than 300 structures, including several large residential buildings, a local power station, and a runway at the airport, have been seriously damaged by thaw-induced settlement. Considerable advances in knowledge and technology for building on permafrost have been made in recent decades. Nevertheless, as global climate change continues to intensify changes in arctic climate, detrimental impacts on infrastructure and therefore on the economy, health, and well-being of the population throughout the permafrost regions are expected to increase.

18.3.3. Region 3

18.3.3.1. Changes in climate

Alaska experienced an increase in mean annual temperature of about 2 to 3 ºC between 1954 and 2003. The temperature increase was similar in the western Canadian Arctic, but was only about 0.5 ºC in the Bering Sea and Chukotka. Winter temperatures over the same period increased by up to 3 to 4 ºC in Alaska and the western Canadian Arctic, but Chukotka experienced winter cooling of between 1 and 2 ºC (see Fig. 18.2 for regional details).

The five ACIA-designated models project that mean annual temperatures will increase by 3 to 4 ºC by the late 21st century (see Fig. 18.5 for regional details). All the models project that the warming is likely to be greater in the north, reaching up to 7 ºC in winter. In the central Arctic Ocean, winter temperatures are projected to increase by up to 9 ºC as a result of reduced sea-ice extent and thickness, but there is likely to be very little change in summer temperature. Trends in and future projections of ozone and UV radiation levels follow the Arctic-wide patterns.

18.3.3.2. Impacts on the environment

Two detailed assessments of the potential consequences of climate variability and change have been conducted in Region 3: one for the Mackenzie River watershed in Canada (Cohen, 1997a,b) and the other for Alaska and the Bering Sea (NAST, 2000, 2001; Weller et al., 1999) as part of the US Global Change Research Program. The Canada Country Study (Environment Canada, 1997) described impacts in the Yukon Territory. These assessments provided background information and input for this assessment. No detailed impact studies have been conducted for Chukotka.

The entire region, but particularly Alaska and the western Canadian Arctic, has undergone a marked change over the last three decades, including a sharp reduction in snow-cover extent and duration, shorter river- and lake-ice seasons, melting of mountain glaciers, sea-ice retreat and thinning, permafrost retreat, and increased active-layer depth. These changes have caused major ecological and socio-economic impacts, which are likely to continue or worsen under projected future climate change. Thawing permafrost and northward movement of the permafrost boundary are likely to increase slope instabilities, which will lead to costly road replacement and increased maintenance costs for pipelines and other infrastructure. The projected shift in climate is likely to convert some forested areas into bogs when ice-rich permafrost thaws. Other areas of Alaska, such as the North Slope, are expected to continue drying. Reduced sea-ice extent and thickness, rising sea level, and increases in the length of the open-water season in the region will increase the frequency and intensity of storm surges and wave development, which in turn will increase coastal erosion and flooding.

Warmer temperatures have resulted in some northward expansion of boreal forest, as well as significant increases in fire frequency and intensity, unprecedented insect outbreaks, and a 20% increase in growing-degree days. The latter has benefited both agriculture and forestry. The expansion of forests in most areas and their increased vulnerability to fire and pest disruption are projected to increase. One simulation projects a three-fold increase in the total area burned per decade, destroying coniferous forests and eventually leading to a deciduous forest-dominated landscape on the Seward Peninsula in Alaska, after a warmer climate has led to forestation of the present tundra areas. Shrubbiness is already increasing in this area, a trend that is likely to continue.

Observations in the Bering Sea have shown abnormal conditions during recent years. The changes observed include significant reductions of seabird and marine mammal populations, unusual algal blooms, abnormally warm water temperatures, and low harvests of salmon on their return to spawning areas. Some of the changes observed in the 1997 and 1998 summers, such as warmer ocean temperatures and altered currents and atmospheric conditions, may have been exacerbated by the very strong El Niño event, but the area has been undergoing change for several decades. While the Bering Sea fishery has become one of the world's largest, the abundance of Steller sea lions (*Eumetopias jubatus*) has declined by between 50 and 80%. Northern fur seal (*Callorhinus ursinus*) pups on the Pribilof Islands – the major Bering Sea breeding grounds – declined by 50% between the 1950s and the 1980s. There have been significant declines in the populations of some seabird species, including common murre (*Uria aalge*), thick-billed murre (*U. lomvia*), and red- and blacklegged kittiwakes (*Rissa brevirostris* and *R. tridactyla*, respectively). Also, the number of salmon has been far below expected levels, the fish were smaller than average, and their traditional migratory patterns seemed to have altered.

Differentiating between the various factors affecting the Bering Sea ecosystem is a major focus of current and projected research. Well-documented climatic regime shifts occurred in the Bering Sea during the 20th century on roughly decadal time scales, alternating between warm and cool periods. A climatic regime shift occurred in the Bering Sea in 1976, changing the marine environment from a cool to a warm state. Information from the contrast between the warm and subsequent cool period forms the basis of projected responses of the Bering Sea ecosystem to scenarios of future warming. These projections show increased primary and secondary productivity with greater carrying capacity, poleward shifts in the distribution of some cold-water species, and possible negative effects in ice-associated species.

18.3.3.3. Impacts on the economy

Large oil and gas reserves exist in Alaska along the Beaufort Sea coast and in the Mackenzie River/Beaufort Sea area of Canada. To date, climate change impacts on oil and gas development in Region 3 have been minor but are likely to result in both financial costs and benefits in future. For example, offshore oil exploration and production is likely to benefit from less extensive and thinner sea ice, allowing savings in the construction of platforms that must withstand ice forces. Conversely, ice roads, now used widely for access to offshore activities and facilities, are likely to be less safe and useable for shorter periods; the same applies for over-snow transport on land given projected reductions in snow depth and duration. The thawing of permafrost, on which buildings, pipelines, airfields, and coastal installations supporting oil development are located, is very likely to adversely affect these structures and greatly increase the cost of maintaining or replacing them.

It is difficult to project impacts on the lucrative Bering Sea fisheries because many factors other than climate are involved, including fisheries policies, market demands and prices, harvesting practices, and fisheries technology. Large northward changes in the distribution of fish and shellfish are likely with a warmer climate. Relocating the fisheries infrastructure (fishing vessels, home ports, processing plants) may be necessary, and would incur substantial costs. Warmer waters are likely to lead to increased primary production in some regions, but a decline in cold-water species such as salmon and pollock.

Other economic sectors in this region, including forestry and agriculture, are far less developed and currently less important than oil and gas and fish and wildlife. Owing to this, economic impacts on forestry and agriculture resulting from climate change are unlikely to be significant, except locally. Impacts on tourism, which is a large economic sector in this and other regions, are more difficult to assess, largely due to the relationship between tourism and economic conditions and social factors outside the Arctic. It is also unclear which features of Region 3 are primarily responsible for attracting tourists – large, undeveloped landscapes will not be directly affected by climate change, whereas marine mammal populations and accessible glaciers are likely to experience major changes. Whether such changes will reduce tourist interest is difficult to assess without more information.

18.3.3.4. Impacts on people's lives

Traditional lifestyles are already being threatened by multiple climate-related factors, including reduced or displaced populations of marine mammals, seabirds, and other wildlife, and reductions in the extent and thickness of sea ice, making hunting more difficult and dangerous. Indigenous communities depend on fish, marine mammals, and other wildlife, through hunting, trapping, fishing, and caribou/reindeer herding. These activities play social and cultural roles that may be far greater than their contribution to monetary incomes. Also, these foods from the land and sea make significant contributions to the daily diet and nutritional status of many indigenous populations and represent important opportunities for physical activity among populations that are increasingly sedentary.

Climate change is likely to have significant impacts on the availability of key marine and terrestrial species as food resources. At a minimum, salmon, herring, char, cod, walrus, seals, whales, caribou, moose, and various species of seabird are likely to undergo shifts in range and abundance. This will entail major local adjustments in harvest strategies and allocations of labor and equipment.

The following impacts on the lifestyles in indigenous villages and communities in Alaska and Canada, which depend heavily on fishing and hunting, have been observed in recent years:

- access to tundra and offshore food resources has been impeded by higher temperatures with milder winters, shorter duration of snow cover and sea ice, and less (or no) shore-fast ice and snow;
- recent decreases in anadromous fish stocks, which make up 60% of wildlife resources harvested by local residents, have directly affected their dietary and economic well-being;
- availability of marine mammals for local harvests has declined in some areas due to population declines associated with shifts in oceanographic and sea-ice conditions. Marine mammals are an important food source in many coastal communities;
- sea-level rise, permafrost thawing, and storm surges have triggered increased coastal erosion and threatened several villages along the Bering and Beaufort Sea coasts. The only long-term option

available has been to plan for relocation of villages, which will be very costly;
- storm surges have also reduced the protection of coastal habitats provided by barrier islands and spits, which are highly vulnerable to erosion and wave destruction; and
- infrastructure in villages constructed in or over permafrost has been affected by thawing permafrost and storm surges breaching coastlines into water supplies and sewage lagoons.

Changes in diet, nutritional health, and exposure to air-, water-, and food-borne contaminants are also likely. Adjustments in the balance between the "two economies" of rural areas (traditional and wage) will be accelerated by climate change. This suite of changes will be complex and largely indirect because of the mediating influences of market trends, the regulatory environment, and the pace and direction of rural development.

Other impacts are likely to occur in the future and have a substantial impact on people. For example:

- a decrease in the area of pack ice is projected to have important implications for primary productivity and the entire food chain. For example, walrus (*Odobenus rosmarus*) and bearded seals (*Erignathus barbatus*) require sea ice strong enough to support their weight, and ringed seals require stable shore-fast ice with adequate snow cover. Diving from ice over shallow waters allows walrus to reach the bottom to feed, and reductions in the extent and thickness of sea ice will adversely affect this species;
- as the boreal forest and associated shrub communities expand northward at the expense of tundra, changes in habitats, migration routes, ranges, and distribution and density of a number of wildlife species, particularly caribou and moose, are projected;
- a change in vegetation and landscape, affecting wildlife, is likely to change hunting practices, location of settlements, and local economic opportunities for people in many arctic regions;
- among wildlife species used as food, existing zoonotic diseases such as brucellosis and echinoccus are likely to become a greater threat to humans and wildlife. New diseases, such as West Nile virus, are likely to become established in a progressively warmer climate;
- lower water levels in some river basins, for example the Mackenzie River, cause increased erosion of riverbanks due to thawing permafrost. This erosion is very likely to increase the incidence of landslides, which have the potential to adversely affect community infrastructure; and
- more vigorous atmospheric and oceanic circulations are likely to increase the transport of contaminants from agricultural activities as well as military and industrial installations to arctic communities, both directly and via the food chain.

18.3.4. Region 4

A major integrative impact assessment for the region was published by Maxwell (1997) for the Canadian Arctic (encompassing the regions of the Northwest Territories and Nunavut). The Mackenzie River watershed assessment, mentioned in the summary for Region 3, also covers Region 4 (Cohen, 1997a,b). A number of studies of the traditional ecological knowledge of indigenous peoples of Region 4 have been conducted and are cited in earlier chapters. Detailed studies of integrated climate impacts in Greenland, on the other hand, have not been conducted prior to the ACIA.

18.3.4.1. Changes in climate

Temperature changes over the past decades have varied across Region 4. The amount of change depends on the time period chosen and, as shown in Chapter 2, the warming has been pronounced since 1966. Between 1954 and 2003, mean annual temperatures across most of arctic Canada increased by as much as 2 to 3 ºC (see Fig. 18.2a), while temperatures in northeastern Canada, including Labrador and adjacent waters, showed little change. The southern part of West Greenland (including the surrounding ocean) cooled by about 1 ºC while northern Greenland warmed by 1 to 2 ºC. Winter temperature trends over the same period were noticeably warmer in the west and colder in the east than the annual trends (Fig. 18.2b). The landmass to the west of Hudson Bay warmed by up to 4 ºC in winter while the area around Labrador, Baffin Island, and southwest Greenland experienced winter cooling of more than 1 ºC.

Annual precipitation in Region 4 has increased over the past 50 years or so, and while seasonal differences were evident around the middle of the century, increases in precipitation have been evident in all seasons over the past few decades.

The physical complexity of the Queen Elizabeth Islands and the orography of Greenland create particular challenges for modeling past, present, and future arctic climate. Models project warming throughout Region 4 during the 21st century, with no cooling projected in any season. Figures 18.5a and 18.5b illustrate annual and winter temperature changes for the period 2071–2090 relative to the 1981–2000 baseline, projected by the five ACIA-designated models forced with the B2 emissions scenario. Projected winter warming in the Canadian areas of Region 4 ranges from about 3 ºC up to about 9 ºC, with the greatest warming projected to occur around southern Baffin Island and Hudson Bay, and substantially less warming projected in other seasons. Greenland is also projected to warm but the warming is weaker (up to about 3 ºC by 2071–2090) and more consistent across seasons.

Precipitation increases are projected to be greatest in autumn and winter, and the areas of greatest increase (up to 30% by the end of the 21st century) generally correspond with the areas of greatest warming. Almost all areas of Region 4 are projected to experience some increase in precipitation after the first few decades of the 21st century.

18.3.4.2. Impacts on the environment

The Canadian part of Region 4 has significant areas of warm permafrost that are at risk of thawing with rising regional air temperatures. The boundary between continuous and discontinuous permafrost is projected to shift poleward, following, but with a lag in timing, the several-hundred-kilometer movement of the isotherms of mean annual temperature over the 21st century. This is likely to result in the disappearance of a substantial amount of the permafrost in the present discontinuous zone. Areas of warm permafrost are also likely to experience more widespread thermokarst development where soils are ice-rich, and increases in slope instability. In areas of remaining continuous and cold permafrost, increases in active-layer depth can be expected.

The maximum northward retreat of sea ice during summer is projected to increase from its present range of 150–200 km to 500–800 km. The thickness of fast ice in the Northwest Passage is likely to decrease substantially from its current value of 1 to 2 m.

The Greenland Ice Sheet is presently losing mass in its ablation zone and is likely to contribute substantially to sea-level rise in the future. While precipitation is projected to increase, it is possible that increased evaporation rates will lead to lower river and lake levels during the warm season.

In general terms, and consistent with results for other regions, the biomes of arctic Canada and Greenland are expected to change. Reductions in the area covered by polar deserts in Canada and Greenland are likely to result from the northward shift of the tundra, while reductions in the areas covered by arctic tundra are very likely to result from the northward shift of the treeline. Polar deserts in the region are extensive, and these areas could sequester large amounts of carbon dioxide (CO_2) if tundra vegetation displaces polar deserts. A reduction in polar desert area of about 36% by 2080 is projected, leading to the greatest projected carbon gain of any region. In contrast, increases in temperature and precipitation are likely to lead to relatively small increases in the area of taiga compared with other regions.

Many treelines, such as those in northeast Canada, have been relatively stable for the last few thousand years. A widespread and consistent observation from the late 20th century has been the infilling of sparse stands of trees near the tundra edge into dense stands that no longer retain the features of the tundra. Movement of the treeline northward is likely when climatic conditions become favorable, but the actual movement of trees will lag the climate warming considerably in time. The forests of northwestern Canada have recently experienced forest health problems driven by insects, fire, and tree growth stress that are all associated with recent mild winters and warmer growing seasons. These findings for Region 4 complement those of Region 3 and accord with very large-scale environmental changes in the western North America subarctic. It is very likely that such forest health problems will become increasingly intense and widespread in response to future regional warming.

The Canadian High Arctic is characterized by land fragmentation within the archipelago and by large glaciated areas, leading to constraints on species movement and establishment. In West Greenland, loss of habitat and displacement of species in combination with time delays in species immigration from the south will ultimately lead to loss of the present biodiversity. However, Region 4 contains relatively few rare and endemic vascular plant species and threatened animal and plant species, compared with the other three regions, so biodiversity losses are likely to be less significant here.

Changes in timing and abundance of forage availability, insect harassment, and parasite infestations will increase stress on caribou, tending to reduce their populations. The ability of high-arctic Peary caribou and muskoxen to forage may become increasingly limited as a result of adverse snow conditions, in which case numbers will decline, with local extirpation in some areas. Direct involvement of the users of wildlife in its management at the local level has the potential for rapid management response to changes in wildlife populations and their availability for harvest.

Arctic freshwater systems are particularly sensitive to climate change because many hydro-ecological processes respond to even small changes in climatic regimes. These processes may change in a gradual way in response to changes in climate or in an abrupt manner as environmental or ecosystem thresholds are exceeded. Pronounced potential warming of freshwater systems in the autumn is particularly important because this is typically when these systems along the coastal margins currently experience freeze-up. Such warming is projected to delay freeze-up by up to 25 days in parts of Region 4. Also, high-latitude cold-season warming is likely to lead to less severe ice breakups and flooding as the spring flood wave pushes northward along arctic rivers. Hence, future changes in the spring timing of lake- and river-ice breakup and the export of freshwater to the Arctic Ocean are likely.

With respect to freshwater ecosystems, significant shifts in species range, composition, and trophic relations are also very likely to occur in response to the projected changes. Salmonids of northern Québec and Labrador, such as native Atlantic salmon and brook trout (*Salvelinus fontinalis*) and introduced brown trout (*Salmo trutta*) and rainbow trout (*Oncorhynchus mykiss*), are likely to extend their ranges northward. Because of these range extensions, the abundance of Arctic char (*Salvelinus alpinus*) is likely to be reduced throughout much of the southern part of Region 4, and brook trout are likely to become a more important component of native subsistence fisheries in rivers now lying within the tundra zone. Lake trout (*Salvelinus namaycush*) are also likely to disappear from rivers and the shallow margins of many northern lakes, and northern pike (*Esox lucius*) are expected to reduce in both numbers and size throughout much of their current range.

Marine mammal populations are likely to decline as the sea ice recedes but the populations of beluga and bowhead whales (*Delphinapterus leucas* and *Balaena mysticetus*, respectively) could increase (depending on the extent to which these whales become more vulnerable to predation as sea-ice cover decreases). If the Arctic Ocean becomes seasonally ice free for several years in a row, it is possible that polar bears would become extinct. Sea-level rise will change the location and distribution of coastal habitats for seabirds and some species of marine mammals (e.g., walrus haul-outs may become inundated).

18.3.4.3. Impacts on the economy

Oil and gas extraction and mining are active industries in Region 4. Diamond mining is underway in the Northwest Territories, and the development of a large nickel deposit in Voisey's Bay, Labrador, has recently been announced. Many rivers in the northern parts of Québec, Ontario, and Manitoba have been dammed for their hydroelectric potential. Roads, airstrips, and ports have been constructed and are essential to the economic infrastructure supporting these activities. Any expansion of oil and gas activities, mining, agriculture, or forestry is likely to require expansion of supporting infrastructure, including air, marine, and land transportation systems. Ice roads in nearshore areas and over-snow transport on land, systems that are important and are even now experiencing shorter seasons, are likely to be further curtailed in the future because of reduced extent and duration of sea ice and snow.

With reduced summer sea-ice extent, the shipping season in Canadian arctic waters is likely to be extended, although sea-ice conditions are likely to remain very challenging. Extension of the shipping season will result in costs and benefits, both of which are speculative. Benefits are likely to result from increased access to the natural resources of the region. As sea level rises, this will also benefit shipping by creating deeper drafts in harbors and channels. On the other hand, increased costs would result from greater wave heights, and possible flooding and erosion threats to coastal facilities. Increased rates of sediment movement during longer, more energetic open-water seasons are likely to increase rates of port and harbor infill and increase dredging costs. Increased ship traffic in the Northwest Passage will increase the risks and potential environmental damage from oil and other chemical spills.

Warmer air temperatures would be expected to reduce the power demand for heating, reduce insulation needs, and increase the length of the summer construction season. Other infrastructure likely to be affected by climate change includes northern pipeline design (negative); pile foundations in permafrost (negative but depending on depth of pile); bridges, pipeline river crossings, dikes, and erosion protection structures (negative); and open-pit mine wall stability (negative).

Impacts on marine fisheries in the eastern part of Region 4, under a moderate gradual warming, are likely to include a return to a cod–capelin system with a gradual decline in northern shrimp and snow crabs. Under more modest assumptions of ocean warming, the range of demersal species (those that tend to live near the bottom) are expected to expand northward. If ocean warming is more extreme, it is likely that the southern limit of the range of the demersal species would move northward. Many existing capelin-spawning beaches are likely to disappear as sea levels rise. If there is an increase in demersal spawning by capelin in the absence of new spawning beaches, capelin survival may decline. Seals may experience higher pup mortality as sea ice thins. Increases in regional storm intensities may also result in higher pup mortality. A reduction in the extent and duration of sea ice is likely to permit fishing further to the north and is likely to shorten the duration of Greenland halibut fisheries that are conducted through fast ice.

Impacts on freshwater and anadromous fisheries, and their economic benefits, such as tourism and local economic development, will vary across Region 4 and will depend on the local present-day and future species composition. Initially, local productivity associated with present-day freshwater and anadromous species is likely to increase, but as critical thresholds are reached (e.g., thermal limits) and as new species move in to the area, arctic-adapted species such as Arctic char are likely to experience declines in abundance and ultimately become extirpated. Loss of suitable habitat will result in decreased individual growth and declines of many populations, with resulting impacts on sport fisheries and local tourism.

18.3.4.4. Impacts on people's lives

The changes in climatic and environmental conditions projected for Region 4, and already being observed in some parts, affect people's lives in many ways. Seasonal unpredictability throughout Region 4 has already created dangerous environmental situations. For example, for the Inuit west of Hudson Bay, changing wind patterns and snow conditions make it difficult to build igloos as the snow is packed too hard. As a result, Inuit report increasing difficulty in building shelters during unexpected storms. In areas of Nunavik and Labrador the snow changes can differ, for example the type of snow now seen does not pack well enough. Changes in weather and ice conditions, such as earlier spring melt, later freeze-up, and formation of more cracks, such as those reported in the Kitikmeot region of Nunavut, result in increasingly difficult travel conditions and sometimes shifts in regular travel and harvesting times.

The changes in local environments experienced by the people in the Canadian part of Region 4 include thinner sea ice, early breakup and later freeze-up of sea ice and lake ice, sudden changes in wind direction and intensity, earlier and faster spring melt periods, decreasing water levels in mainland lakes and rivers, and the introduction of non-native animal and bird species. These changes affect lifestyles through changes in the timing of animal migrations as well as in the numbers and health of some animal populations, and in the quality of animal skins and pelts. The distribution and quality of animals and other resources will affect the livelihoods, and ultimately the health of northern communities in Region 4. For example, a shorter winter season with increased snowfall and less extensive and thinner sea ice is likely to decrease the opportunity and increase the risks for indigenous people to hunt and trap.

Other health impacts may arise from the introduction of new or increasingly present zoonotic and/or vector-borne diseases (e.g., potential spread of West Nile virus into warmer regions in the western Arctic), changes in exposure to UV radiation and contaminants that already threaten confidence in and safety of traditional diets, and the associated social and cultural impacts of this combination of changes. Relocation of low-lying communities may be forced by rising sea levels, with serious social impacts. Where these challenges to health already exist, and where infrastructure and support systems are stretched, the effects are likely be experienced to a greater extent and at a faster pace than elsewhere.

Many changes are reported and are currently experienced by Inuit, Dene, Gwitch'in, and other indigenous peoples in Region 4. These changes represent challenges to aspects of northern indigenous cultures and lifestyles that have existed for centuries. The ability of communities to cope with and adapt to climate-driven changes is also influenced by a number of other factors and is constrained by current social and economic aspects. For example, moving people to follow shifting resources is no longer an option with permanent settlements. Other factors complicating adaptations to change include regional resource regulations, industrial development, and global economic pressures. Climate change interacts with such forces and must be considered in assessing local risks and responses. As existing adaptation strategies become obsolete, new adaptations to climate impacts must develop as northern communities adjust to the many social, institutional, and economic changes related to land claim settlements, changes in job opportunities, and the creation of new political and social structures in the North.

18.4. Cross-cutting issues in the Arctic

This assessment has dealt with individual topics that reflect traditional academic and practical organization. However, a strong thread running through the assessment is the interaction between the various topics and processes in the Arctic. This includes, for example, the *interactions* between physical atmospheric processes and biological processes in the major ecosystems, and the strong albedo and other feedback responses; the physical and biological *connections* between land, freshwater, and marine environments; and the integrity of the arctic system as a whole. Three important cross-cutting issues that illustrate the interactions within the Arctic and connections with the global system are carbon storage and carbon cycling, biodiversity, and abrupt climate change and extreme events.

18.4.1. Carbon storage and carbon cycling

18.4.1.1. Global importance of carbon in the Arctic

The Arctic contains large stores of carbon that have historically been sequestered from the atmospheric carbon pool. Estimates of arctic and boreal soil carbon (C) in the upper meter of soil vary considerably, ranging from 90 to 290 Pg C in upland boreal forest soils, 120 to 460 Pg C in peatland soils, and 60 to 190 Pg C in arctic tundra soils. There is also a general sparsity of high-latitude carbon data for aquatic ecosystems relative to arctic terrestrial systems, but some estimates from boreal lakes indicate that reserves can be significant (120 Pg C). An additional 450 Pg of organic C is stored as dissolved carbon in the Arctic Ocean (see Chapter 9). Estimates of carbon stored in the upper 100 meters of permafrost are as high as 10000 Pg C (Semiletov, 1999). In any case, the carbon stored in northern boreal forests, lakes, tundra, the Arctic Ocean, and permafrost is considerably greater than the *global* atmospheric pool of carbon, which is estimated at 730 Pg C (IPCC, 2001). In addition, up to 10000 Pg C in the form of CH_4 and CO_2 is stored as hydrates in marine permafrost below 100 m (Chapter 9), however, this figure is a maximum of estimates that span several orders of magnitude.

18.4.1.2. Spatial patterns of carbon storage

Within the Arctic, carbon storage generally decreases from south to north. On land, this represents parallel decreases from boreal forest to tundra to polar desert and from southern isolated, sporadic, and discontinuous permafrost to continuous permafrost in the north; in freshwater ecosystems there is a decrease from peatlands and lakes with high concentrations of dissolved organic carbon to tundra and high-arctic ponds with low dissolved organic carbon; and in the marine environment there is a decrease from areas of high organic matter production and sedimentation in the south and at the ice margin to relatively clear waters in the Arctic Ocean. Marine permafrost and gas hydrates show a different pattern in that they are concentrated in the area of continental shelves, which are particularly extensive along the northern coastlines of the arctic landmasses.

18.4.1.3. Processes involved in carbon storage and release

Over thousands of years, an imbalance between photosynthesis and decomposition has led to storage of carbon in lake and ocean sediments, and in forest and tundra soils (Chapters 7, 8, 9, and 14). On land, this imbalance was created because low temperatures, particularly when combined with high soil moisture, retarded microbial decomposition more than photosynthesis. In the marine environment, atmospheric carbon is dissolved as inorganic carbon in surface waters and stored at depth as a result of the physical pump; death and decomposition of organisms also lead to carbon storage in the form of dissolved and particulate organic carbon (Chapter 9). Low ocean temperatures have resulted in high solubility of carbon, while extensive sea-ice cover has reduced the duration and area for carbon exchange between air and surface waters (and thus photosynthesis).

Because low temperatures have been so important for the capture and storage of atmospheric carbon in the Arctic, projected temperature increases have the potential to lead to the release of old and more recently captured carbon to the atmosphere, although the older the stored carbon, the less responsive it will be to projected climate changes. The release of stored carbon will increase atmospheric GHG concentrations and provide a positive feedback to the climate system. However, increased temperatures are also likely to increase the photosynthetic capture of atmospheric carbon if other environmental conditions do not become limiting. On land, plants will grow faster and more productive vegetation will successively replace less productive vegetation at higher latitudes and altitudes (Chapters 7 and 14). In freshwater ecosystems, reduced duration of ice cover over lakes and ponds and increased temperatures are likely to increase primary production (Chapter 8). In the marine environment, primary production is expected to increase as areas where production has been limited by sea-ice cover become more restricted in extent. Also, it is likely that more carbon will be buried as deposition shifts from the continental shelves where primary production is currently concentrated to the deeper slope and basin region as the ice edge retreats (Chapter 9).

The balance between the opposing processes of increased carbon capture and release will determine future changes in the carbon feedback from the Arctic to global climate. However, there are great uncertainties in calculating this balance across permafrost, terrestrial soil, ocean, and freshwater systems and no quantitative integrative assessment has been performed to date.

18.4.1.4. Projected changes in carbon storage and release to the atmosphere

There is a consensus from the trace-gas measurement researchers that the terrestrial Arctic is presently a source of carbon and radiative forcing, but is likely to become a weak sink of carbon during future warming (Chapter 7). Modeling approaches suggest that circumpolar mean carbon uptake is likely to increase from the current 12 g $C/m^2/yr$ to 22 g $C/m^2/yr$ by 2100 and that carbon storage is likely to increase by 12 to 31 Pg C depending on the ACIA climate scenario used. However, the uncertainties are great: the projections are limited to terrestrial ecosystems and do not include carbon stored in permafrost and gas hydrates. Potential increases in human and natural disturbances are further uncertainties. The marine environment has been suggested as a weak sink, but the amount of carbon that the Arctic Ocean can sequester is likely to increase significantly under scenarios of decreased sea-ice cover, both through surface uptake and increased biological production, although there may be an abrupt release of CO_2 and CH_4 from thawing permafrost in marine sediments.

In the marine environment, there are vast stores of CH_4 and CO_2 (at least 10000 Pg C in the form of gas hydrates in marine permafrost below 100 m; Semiletov, 1999). As there are currently about 4 Pg C in CH_4 in the atmosphere, even the release of a small percentage of CH_4 from gas hydrates could result in an abrupt and significant climate forcing (Chapter 9). The process of CH_4 release from gas hydrates under continental shelves could already be occurring due to the warming of earlier coastal landmasses during Holocene flooding. On land, however, natural gas hydrates are found only at depths of several hundreds of meters and are relatively inert.

18.4.2. Biodiversity

18.4.2.1. Background

The diversity of species in terrestrial, freshwater, and marine ecosystems of the Arctic is fundamental to the life support of the residents of the region and to commercial interests such as fishing at lower latitudes. Diversity is also important to the functioning of arctic ecosystems: productivity, carbon emissions, and albedo are all related to specific characteristics of current arctic species. While the Arctic contains some specialist species that are well adapted to the harsh arctic environment, it also contains species that migrate and contribute to the biodiversity of more southerly latitudes. Each year, whales, dolphins, and hundreds of millions of birds migrate from the Arctic to warmer latitudes. The Arctic is an area of relatively undisturbed and natural biodiversity because of generally lower human impacts than elsewhere on earth. However, at its southern border, human impacts are greater and particular areas, such as old growth forests on land, preserve biodiversity that is endangered in managed areas.

18.4.2.2. Patterns of diversity in the Arctic

The diversity of living organisms at any one time in the Arctic is a snapshot of complex, dynamic physical and biological processes that create habitats and opportunities or constraints for species, and genetically distinct populations of particular species, to colonize them.

The current diversity of organisms in the Arctic has been shaped by major climatic and associated changes in physical and chemical conditions of the land, wetlands, and oceans over past glacial and interglacial periods. Changes are presently occurring that are also driven by direct human activities such as fishing, hunting, and gathering, changes in land use, and habitat fragmentation, in addition to indirect human activities such as anthropogenic climate change, stratospheric ozone depletion, and transboundary movement of contaminants.

On land, and in freshwater and the marine environment, the fauna and flora are young in a geological context. Recent glaciations resulted in major losses of biodiversity, and recolonization has been slow because of the extreme environmental conditions and overall low productivity of the arctic system. On land, of at least 12 large herbivores and six large carnivores present in steppe–tundra areas at the last glacial maximum, only four and three respectively survive today and of these, only two herbivores (reindeer and musk ox) and two carnivores (brown bear, *Ursus arctos* and wolf, *Canis lupus*) presently occur in the arctic tundra biome. Arctic marine mammals to a large extent escaped the mass extinctions that affected their terrestrial counterparts at the end of the Pleistocene because of their great mobility. However, hunting in historical times had severe impacts on several species that were exterminated (great auk, *Pinguinus impennis*; Steller sea cow, *Hydrodamalis gigas*) or almost harvested to extinction (walrus; bowhead whale; sea otter, *Enhydra lutris*). Polar bears, all the Great Whales, white whales, and many species of colonially nesting birds were dramatically reduced.

The youth of arctic flora and fauna, together with the harsh physical environment of arctic habitats and to some extent over-harvesting, have resulted in lower species diversity in the Arctic compared to other regions. This results in arctic ecosystems, in a global sense, being "simple". Some of the species are specialists that are well adapted to the Arctic's physical environment; others were pre-adapted to the arctic environment and moved north during deglaciation. Overall however, many arctic species – marine, freshwater, and terrestrial – possess a suite of characteristics that allows them to survive in extreme environments. However, these characteristics, together with low diversity and simple relationships between species in food webs, render arctic species and ecosystems vulnerable to the environmental changes now occurring in the Arctic and those projected to occur in the future.

Although diversity of arctic species is relatively low, in absolute terms it can be high: about 6000 marine, freshwater, and terrestrial species have been catalogued in and around Svalbard (Prestrud et al., 2004) and about 7200 terrestrial and freshwater species have been recorded in a subarctic area of northern Finland (Callaghan et al., 2004). About 3% (around 5900 species) of the global flora occurs in the Arctic. The diversity of arctic terrestrial animals beyond the latitudinal treeline (6000 species) is nearly twice as great as that of vascular plants and bryophytes. The arctic fauna accounts for about 2% of the global total. In the arctic region as defined by CAFF (Conservation of Arctic Flora and Fauna), which includes forested areas, some 450 species of birds have been recorded breeding, and around 280 species migrate. The diversity of vertebrate species in the arctic marine environment is less than on land. Species diversity differs from group to group: primitive species of land plants such as mosses and lichens are well represented in the Arctic whereas more advanced flowering plants are not; primitive species of land animals such as springtails are well represented whereas more advanced beetles and mammals are not. In contrast, although most taxonomic groups of freshwater organisms in the Arctic are not diverse, some groups such as fish have high diversity at and below the species level. One consequence of the generally low species diversity is that species will be susceptible to damage by new insect pests, parasites, and diseases. For example, low diversity of boreal trees together with low diversity of parasites and predators that control populations of insect pests exaggerates the impacts of the pests.

The number of species generally decreases with increasing latitude. The steep temperature gradient that has such a strong influence on species diversity occurs over much shorter distances in the Arctic than in other biomes. North of the treeline in Siberia, mean July temperature decreases from 12 to 2 ºC over 900 km, whereas a 10 ºC decline in July temperature is spread over 2000 km in the boreal zone, and July temperature decreases by less than 10 ºC from the equator to the southern boreal zone. Patterns of species diversity in the Arctic also differ according to geography. With its complicated relief, geology, and biogeographic history, there are more species on land in Beringia at a given temperature than on the Taymir Peninsula. Taymir biodiversity values are intermediate between the higher values for Chukotka and Alaska, which have a more complicated relief, geology, and floristic history, and the lower values in the eastern Canadian Arctic with its impoverished flora resulting from relatively recent glaciation. Within any region, biological hot spots occur, for example below predictable leads in the sea ice, polynyas, oceanographic fronts, areas of intense mixing, and the marginal ice zone in the marine environment; in delta areas that lie at the interface between rivers and lakes or oceans; and at the ecotone between tundra and taiga on land where elements of both forest and tundra floras and faunas mix. Such hotspots are centers from which species with restricted distributions can expand during climatic warming.

An important consequence of the general decline in numbers of species with increasing latitude is an increase in abundance and dominance. For example, on land, one species of collembolan, *Folsomia regularis*, may constitute 60% of the total collembolan density in the polar desert.

In freshwater ecosystems, midge and mosquito larvae are particularly abundant but species-level diversity is low. These "super-dominant" species, such as lemmings in peak years of their population cycles, are generally highly plastic, occupy a wide range of habitats, and generally have large effects on ecosystem processes. Similarly, arctic fish communities of the marine environment are dominated by a few species, several of which are commercially important, while the abundance of fish, marine mammals, and birds attracted hunters and fishing enterprises in historical times. Loss/reduction of one or more of these species, particularly fish species, will have disproportionate impacts on economy and ecosystem function.

18.4.2.3. Characteristics of arctic species related to the arctic environment

Several physical factors make arctic marine systems unique from other oceanic regions including: a very high proportion of continental shelves and shallow water; a dramatic seasonality and overall low level of sunlight; extremely low water temperatures (but not compared with arctic terrestrial habitats); presence of extensive permanent and seasonal sea-ice cover; and a strong freshwater influence from rivers and ice melt. Arctic freshwater environments are also characterized by extreme seasonality and low levels of incident radiation, much of which is reflected due to the high albedo of snow and ice. In addition, the thermal energy of a substantive part of this incoming radiation is used to melt ice, rendering it unavailable to biota. However, large arctic rivers with headwaters south of the Arctic act as conduits of heat and biota.

On land, low solar angles, long snow-covered winters, cold soils with permafrost, and low nutrient availability in often primitive soils limit survival and productivity of organisms. Many species of marine and terrestrial environments migrate between relatively warm wintering grounds in the south and the rich, but short-lived, feeding and breeding grounds in the Arctic. In freshwater ecosystems, some fish are highly migratory, moving in response to environmental cues. Those species that do not migrate have a suite of characteristics (behavior, physiology, reproduction, growth, development) that allow them to avoid the harshest weather or to persist. Two characteristics common to marine, freshwater, and terrestrial arctic organisms are a protracted life span with slow development over several years to compensate for the brevity and harshness of each growing/feeding/breeding season, and low reproductive rates. These characteristics render arctic organisms in general vulnerable to disturbance and environmental change.

18.4.2.4. Responses of biodiversity to climate and UV-B radiation change

The past and present patterns of biodiversity in the Arctic, the characteristics of arctic species, and the experimental and modeling assessments described in Chapters 7, 8, and 9, together make it possible to infer the following likely changes to arctic biodiversity:

- The total number of species in the Arctic will increase as new species move northward during warming. Large, northward-flowing rivers are conduits for species to move northward. New communities will form.
- Present arctic species will relocate northward, as in the past, rather than adapt to new climate envelopes, particularly as the projected rate of climate change exceeds the ability of most species to adapt. However, some species, particularly freshwater species, may already be pre-adapted to acclimate successfully to rapid climate change.
- Locally adapted species may be extirpated from certain areas while arctic specialists and particular groups of species that are poorly represented in the Arctic – some through loss of species during earlier periods of climate warming – will be at risk of extinction. Examples of arctic specialists at risk include polar bears, and seals of the ice margins in the marine environment, and large ungulates and predators on land.
- Presently super-abundant species will be restricted in range and abundance with severe impacts on commercial fisheries, indigenous hunting, and ecosystem function. Examples on land include lemmings, mosses and lichens, and some migratory birds.
- On land, shifts in major vegetation zones such as forests and tundra will be accompanied by changes in the species associated with them. For example, tree seed-eating birds, and wood-eating insects will move northward with trees.
- Low biodiversity will render ecosystems more susceptible to disturbance through insect pest infestations, parasites, pathogens, and disease.
- At the small scale, changes will be seen in the representation of different genetically separate populations within species. In cases such as Arctic char, the species may remain but become geographically or ecologically marginalized with the potential loss of particular morphs.
- Changes in UV-B radiation levels are likely to have small effects on biodiversity compared with climate warming. However, UV-B radiation has harmful effects on some fish larvae, on those amphibians that might colonize the Arctic, and on some microorganisms and fungi. In freshwater ecosystems, increased UV-B radiation levels could potentially reduce biodiversity by disadvantaging sensitive species and changing algal communities.
- All the projected changes in biodiversity resulting from changes in climate and UV-B radiation levels are likely to be modified by direct human activities. Protection and management of some areas have led to the recovery of some previously declining species while deforestation, extractive industries, and pollution have prevented forests and associated species from moving northward during

recent warming in some areas. Protection of ecosystems from the impacts of changes in climate and UV-B radiation in the long term is difficult and perhaps impossible.

18.4.3. Abrupt climate change and extreme events

Human activities are causing atmospheric concentrations of CO_2 and other GHGs and aerosols to change slowly from year to year, thereby causing the radiative forcing that drives climate change to shift slowly. However, the resulting changes in climate and associated impacts do not necessarily have to change slowly and smoothly. First, the natural interactions of the atmosphere, oceans, snow and ice, and the land surface, both within and outside the Arctic, can cause climatic conditions to fluctuate. These variations can cause months, seasons, years, and even decades to be warmer or cooler, wetter or drier, and even more settled or more changeable than the multi-decadal average conditions. Intermittent volcanic eruptions and variations or cycles in the intensity of solar radiation can also cause such fluctuations. These types of fluctuations can be larger than the annual or even decadal increment of long-term anthropogenic global climate change. Present model simulations project a slow and relatively steady change in baseline climate while natural factors create fluctuations on monthly to decadal scales. As the baseline climate changes, the ongoing fluctuations are very likely to cause new extremes to be reached and the occurrence of conditions that currently create stress (e.g., summer temperatures greater than 30 ºC) are likely to increase significantly.

The climatic history of the earth shows that instead of climate changing steadily and gradually, change can be intermittent and abrupt in particular regions – even very large regions. Reconstructions of climatic variations over the last glacial cycle and the early part of the current interglacial some 8000 to 20000 years ago suggest that temperature changes of several degrees in the large-scale, long-term climate occurred over a relatively short period. For example, ice cores indicate that temperatures over Greenland dropped by as much as 5 ºC within a few years during the period of warming following the last glacial. These changes were apparently driven by a sharp change in the thermohaline circulation of the ocean (also referred to as the Atlantic meridional overturning circulation), which probably also prompted changes in the atmospheric circulation that caused large climatic changes over land areas surrounding the North Atlantic and beyond. Over multi-decadal time periods, persistent shifts in atmospheric circulation patterns, such as the North Atlantic and Arctic Oscillations, have also caused changes in the prevailing weather regimes of arctic countries, contributing, for example, to warm decades, such as the 1930s and 1940s, and cool decades, such as the 1950s and 1960s.

A recent example of a rapid change in arctic climate was the so-called regime shift in the Bering Sea in 1976, which had serious consequences and impacts on the environment. In 1976, mean annual temperatures in Alaska experienced a step-like increase of 1.5 ºC to a lasting new high level, shown as the average of several measuring stations. Sea-ice extent in the Bering Sea showed a similar step-like decrease of about 5% (Weller et al., 1999). An analysis by Ebbesmeyer et al. (1991) gave statistical measures of deviation from the normal of 40 environmental parameters in the North Pacific region, as a consequence of this rapid change. The parameters included air and water temperatures, chlorophyll, geese, salmon, crabs, glaciers, atmospheric dust, coral, CO_2, winds, ice cover, and Bering Strait transport. The authors concluded that "apparently one of the Earth's large ecosystems occasionally undergo large abrupt shifts".

As anthropogenic climate change continues, the potential exists for oceanic and atmospheric circulations to shift to new or unusual states. Whether such changes, perhaps brought on when a temperature or precipitation threshold is crossed, will occur abruptly (i.e., within a few years) or more gradually (i.e., within several decades or more) remains to be determined. Such shifts could cause the relatively rapid onset of various types of impacts. A warm and wet anomaly might accelerate the onset of pests or infectious diseases. Warming exceeding about 3 ºC might initiate the long-term deterioration of the Greenland Ice Sheet as temperatures above freezing spread across the plateau in summer. The tentative indication of an initial slowing of the thermohaline circulation could change into a significant slowdown, greatly reducing the northward transport of tropical warmth that now moderates European winters. The likelihood of any such shifts or changes occurring is not yet well established, but if the future is like the past, the possibility for abrupt change and new extremes is real.

18.5. Improving future assessments

A critical self-assessment of the ACIA shows achievements as well as deficiencies. Regional impacts were only covered in an exploratory manner and are hence a priority for future assessments. The ACIA did examine climate and UV radiation impacts in the Arctic on (1) the environment, (2) economic sectors, and (3) on people's lives. Impacts on the environment were covered very extensively, but the assessment has only qualitative information on economic impacts, and this must be a priority for future assessments. Impacts on people's lives covered indigenous communities but had little information concerning other arctic residents. Integrative vulnerability studies were only covered in an exploratory manner (in Chapter 17) and need attention in the future.

Regional impacts

While the ACIA was successful in many respects, it mostly addressed impacts at the large-scale circumpolar level. An attempt to differentiate between impacts within the four ACIA regions was exploratory and did not cover these regions in depth. There is a need to focus future assessments on smaller regions (perhaps at the landscape level) where an assessment of impacts of climate change has the greatest relevance and use for residents in the region and their activities.

Economic impacts

There are many important economic sectors in the Arctic, including oil and gas production, mining, transportation, fisheries, forestry and agriculture, and tourism. Some will gain from a warmer climate, others will not. In most cases, only qualitative information about the economic impacts (in monetary terms) of climate change is presently available. It is essential to involve a wide range of experts and stakeholders in future climate impact assessments to fill this gap and provide relevant information to users and decision makers.

Assessing vulnerabilities

Vulnerability is the degree to which a system is susceptible to or unable to cope with adverse effects of multiple and interacting stresses. Climate change occurs amidst a number of other interacting social and environmental changes across scales from local to regional and even global, and includes industrial development, contaminant transport and effects, and changes in social, political, and economic conditions. In this context it has become important to assess the vulnerabilities of coupled human–environment systems in the Arctic.

To undertake improved assessments on these three research topics a suite of improved observations and process studies, long-term monitoring, climate modeling, and impact analyses on society are necessary. These require new research efforts and studies funded by the various arctic countries.

Observations and process studies

To improve future climate impact assessments, many arctic processes require further study, both through scientific investigations and more detailed systematic documentation of indigenous knowledge. Priorities include collection of data ranging from satellite, surface, and paleo data on the climate and physical environment, to rates and ranges of change in arctic biota, and to the health status of arctic people.

Long-term monitoring

Long-term time series of climate and climate-related parameters are available from only a few locations in the Arctic. The need for continuing long-term acquisition of data is crucial, including upgrading of the climate observing system throughout the Arctic and monitoring snow and ice features, the discharge of major arctic rivers, ocean parameters, and changes in vegetation, biodiversity, and ecosystem processes.

Climate modeling

Improvements in numerical modeling of potential changes in climate are needed, including the representation in climate models of key arctic processes such as ocean processes, permafrost–soil–vegetation interactions, important feedback processes, and extreme events. The development and use of very high-resolution coupled regional models that provide useful information to local experts and decision makers is also required.

Analysis of impacts on society

Critical needs for improving projections of possible consequences for the environment and society include development and use of impact models; evaluating approaches for expressing relative levels of certainty and uncertainty; developing linkages between traditional and scientific knowledge; preparing scenarios of arctic population and economic development; and identifying and evaluating potential mitigation and adaptation measures to meet expected impacts.

18.6. Conclusions

With its almost continuous circle of land surrounding an ocean, which has a decadal circulation, the Arctic is a globally unique system and it is no accident that the Arctic Climate Impact Assessment is the first comprehensive regional assessment conducted to date. The ACIA is an authoritative synthesis of the consequences of changes in climate and UV radiation in the Arctic, involving hundreds of arctic experts. The assessment addresses the large climatic change that is very likely to occur over the 21st century and it concludes that changes in climate and in ozone and UV radiation levels are likely to affect every aspect of life in the Arctic.

However, assessment of the projected impacts of changes in climate and UV radiation is a difficult and long-term undertaking and the conclusions presented here, while as complete as present information allows, are only a first step in what must be a continuing process. There are likely to be future surprises, such as relatively rapid shifts in the prevailing trends in climatic regimes and in the frequency and intensity of extreme events; such changes, while likely, are expected to remain very difficult to project with high confidence. In future years, however, as additional data are gathered, a better understanding of the complex processes, interactions, and feedbacks will develop, and as model simulations are refined, findings and projections will be made with increasing confidence. As understanding of the climate system and its interactions with ozone amounts steadily improves, it will be possible to increase the usefulness of projections of the likely impacts in the Arctic, allowing more specificity in planning how best to adapt and respond.

An especially important task for future impact assessments will be to conduct comprehensive vulnerability studies of arctic communities, in which impacts modulated by adaptive capacity are examined in the context of both environmental and societal changes. The latter include changes in resource exploitation, human population, global trade and economies, introduction of new species, contamination, and new technologies. Chapter 17 points the way in this direction. It will be important to consider the interplay between impacts due to climate change and these other drivers. It is possible that many of the adverse impacts of variability and change can be moderated or even offset by implementing strategies for coping and adaptation, for example via changes in public policy and new strategies in resource management. The perspectives and concerns of local people will also be essential to consider more fully in future vulnerability analyses. To begin to address these policy-related issues, a separate process is ongoing to discuss mitigation and adaptation, as well as research, observation, and modeling needs, and communication and education issues pertaining to the Arctic Climate Impact Assessment.

Finally, it is important to re-emphasize that climate and UV radiation changes in the Arctic are likely to affect every aspect of human life in the region and the lives of many living outside the region. While more studies and a better understanding of the expected changes are important, action must begin to be taken to address current and anticipated changes before the scale of changes and impacts further reduces the options available for prevention, mitigation, and adaptation.

References

NOTE: This chapter is a summary based on the seventeen preceding chapters of the Arctic Climate Impact Assessment and a full list of references is provided in those chapters. Only references to major publications and data sources, including integrative regional assessments, and some papers reporting the most recent developments, are listed.

AMAP, 1998. Assessment Report: Arctic Pollution Issues. Arctic Monitoring and Assessment Programme, Oslo, 859p.

Callaghan, T.V., M. Johansson, O.W. Heal, N.R. Sælthun, L.J. Barkved, N. Bayfield, O. Brandt, R. Brooker, H.H. Christiansen, M.C. Forchhammer, T.T. Høye, O. Humlum, A. Järvinen, C. Jonasson, J. Kohler, B. Magnusson, H. Meltofte, L. Mortensen, S. Neuvonen, I. Pearce, M. Rasch, L. Turner, B. Hasholt, E. Huhta, E. Leskinen, N. Nielsen and P. Siikamäki, 2004. Environmental Changes in the North Atlantic Region: SCANNET as a collaborative approach for documenting, understanding and predicting changes. Ambio Special Report, 13:35–58.

Chapman, W.L. and J.E. Walsh, 2003. Observed climate change in the Arctic, updated from Chapman and Walsh, 1993: Recent variations of sea ice and air temperatures in high latitudes. Bulletin of the American Meteorological Society, 74(1):33–47. http://arctic.atmos.uiuc.edu/CLIMATESUMMARY/2003/

Christensen, T.R., T.R. Johansson, H.J. Åkerman, M. Mastepanov, N. Malmer, T. Friborg, P. Crill and B.H. Svensson, 2004. Thawing sub-arctic permafrost: Effects on vegetation and methane emissions. Geophysical Research Letters, 31:L04501,doi:10.1029/2003GL018680.

Cohen, S.J. (ed.), 1997a. Mackenzie Basin Impact Study (MBIS) Final Report. Environment Canada, 372p.

Cohen, S.J., 1997b. What if and so what in Northwest Canada: could climate change make a difference to the future of the Mackenzie Basin. Arctic, 50:293–307.

Ebbesmeyer, C.C., D.R. Cayan, D.R. McLain, F.H. Nichols, D.H. Peterson and K.T. Redmond, 1991. 1976 step in the Pacific climate: forty environmental changes between 1968–1975 and 1977–1984. In: J.L. Betancourt and V.L. Tharp (eds). Proceedings of the Seventh Annual Pacific Climate (PACLIM) Workshop, April 1990. California Dept. of Water Resources. Interagency Ecological Studies Program, Technical Report 26.

Environment Canada, 1997. The Canada Country Study: Climate Impacts and Adaptation. British Columbia and Yukon Summary, 8p.

IPCC, 2001. Climate Change 2001: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Third Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, 1032p.

Lange, M.A., B. Bartling and K. Grosfeld (eds.), 1999. Global changes in the Barents Sea region. Proceedings of the First International BASIS Research Conference, St. Petersburg, Feb. 22–25, 1998, University of Münster, 470p.

Lange, M.A. and the BASIS consortium, 2003. The Barents Sea Impact Study (BASIS): Methodology and First Results. Continental Shelf Research, 23(17–19):1673–1694.

Maxwell, B., 1997. Responding to Global Climate Change in Canada's Arctic. Vol. II. The Canada Country Study: Climate Impacts and Adaptation. Environment Canada, 82p.

Nakićenović, N. and R. Swart (eds.), 2000. Intergovernmental Panel on Climate Change, Special Report on Emissions Scenarios. Cambridge University Press, 599p.

NAST, 2000. Climate Change Impacts on the United States: Overview. National Assessment Synthesis Team, US Global Change Research Program. Cambridge University Press, 153p.

NAST, 2001. Climate Change Impacts on the United States: Foundation. National Assessment Synthesis Team, US Global Change Research Program. Cambridge University Press, 612p.

Prestrud, P., S. Hallvard and H.V. Goldman, 2004. A catalogue of the terrestrial and marine animals of Svalbard. Skrifter 201. Norwegian Polar Institute, Tromsø, Norway, 137p.

Semiletov, I.P., 1999. On aquatic sources and sinks of CO_2 and CH_4 in the polar regions. Journal of Atmospheric Sciences, 56(2):286–306.

Weller, G., P. Anderson and B. Wang (eds.), 1999. Preparing for a Changing Climate: The Potential Consequences of Climate Change and Variability. A Report of the Alaska Regional Assessment Group for the U. S. Global Change Research Program, University of Alaska Fairbanks, 42p.