UNEP

GLOBAL OUTLOOK FOR ICE & SNOW

The Cryosphere

- Snow
- Sea ice
- Ice shelves
- Ice sheets
- Glaciers and ice caps
- Permafrost (continuous)
- Permafrost (discontinuous)
- Permafrost (isolated)

Sources:

Armstrong, R.L. and Brodzik, M.J. (2005). *Northern Hemisphere EASE-Grid weekly snow cover and sea ice extent version 3.* (Digital media). National Snow and Ice Data Center, Boulder

Armstrong, R.L., Brodzik, M.J., Knowles, K. and Savoie, M. (2005). *Global monthly EASE-Grid snow water equivalent climatology*. (Digital media). National Snow and Ice Data Center, Boulder

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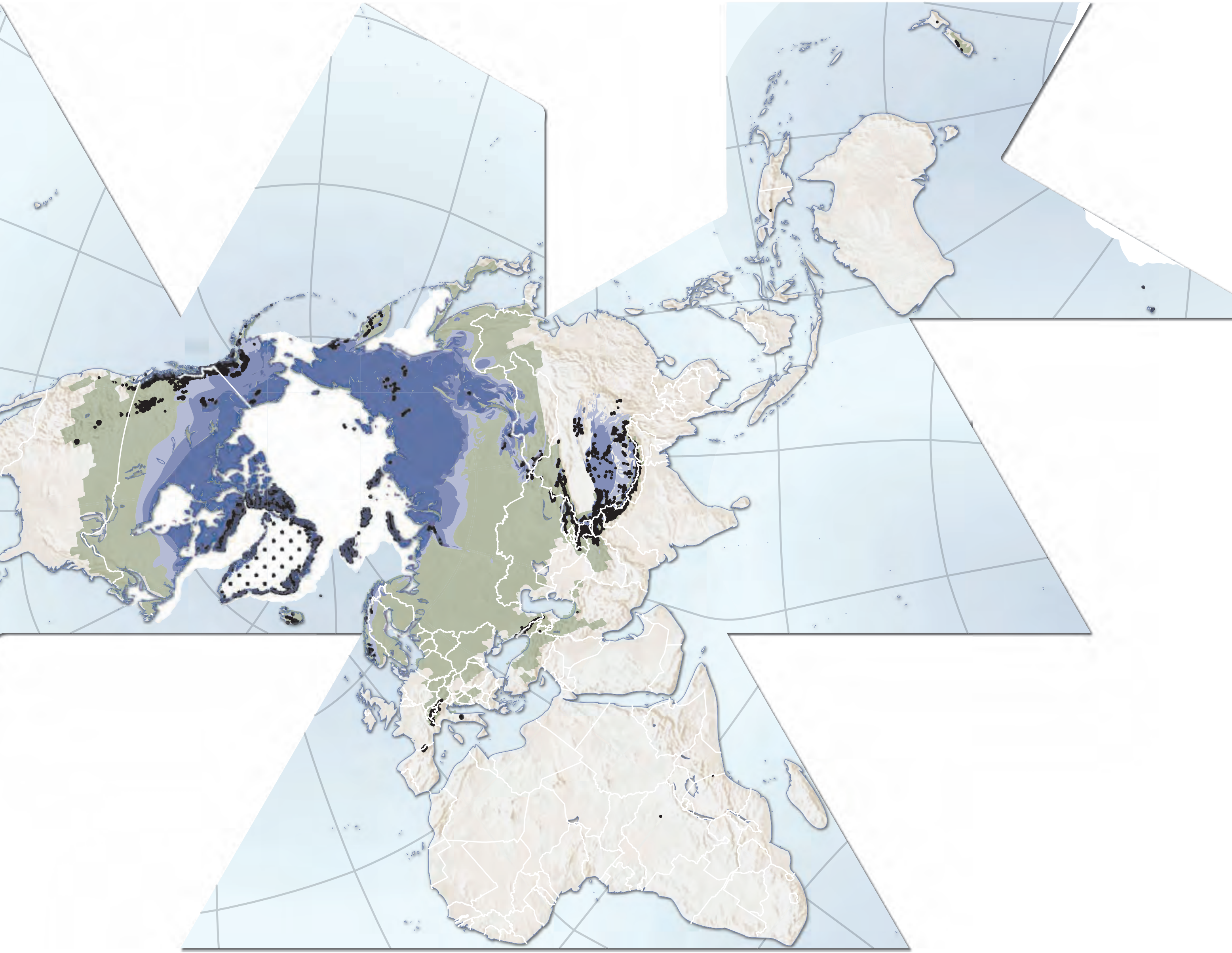
Notes:

Snow cover extent for Northern Hemisphere is represented by the 1966–2005 February average, for Southern Hemisphere by the 1987–2003 August average.

Sea ice extent for Northern Hemisphere is represented by the 1979–2003 March average, for Southern Hemisphere by the 1979–2002 September average.

Permafrost data for mountain areas and for the Southern Hemisphere are not represented in this map.



GLOBAL OUTLOOK FOR

ICE & SNOW

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GLOBAL OUTLOOK FOR ICE & SNOW

6 Foreword

7 **1 Highlights**
19 **2 Why are Ice and Snow Important to Us?**
29 **3 Why are Ice and Snow Changing?**
39 **4 Snow**
63 **5 Ice in the Sea**
97 **6 Ice on the Land**
99 **6A** Ice Sheets
115 **6B** Glaciers and Ice Caps
153 **6C** Ice and Sea-level Change
181 **7 Frozen Ground**
201 **8 River and Lake Ice**
215 **9 Policy and Perspectives**

230 Production and Editorial Team and Authors
234 Steering Committee and Reviewers
235 Acknowledgements

Components of the Cryosphere		Area Covered (million square km)	Ice Volume (million cubic km)	Potential Sea Level Rise (cm) **6C**
Snow on land (Northern Hemisphere) (annual minimum ~ maximum)	**4**	1.9 ~ 45.2	0.0005 ~ 0.005	0.1 ~ 1
Sea ice, Arctic and Antarctic (annual minimum ~ maximum)	**5**	19 ~ 27	0.019 ~ 0.025	0
Ice shelves	**6A**	1.5	0.7	0
Ice sheets (total)	**6A**	14.0	27.6	6390
Greenland		1.7	2.9	730
Antarctica		12.3	24.7	5660
Glaciers and ice caps (lowest and [highest] estimates)	**6B**	0.51 [0.54]	0.05 [0.13]	15 [37]
Permafrost (Northern Hemisphere)	**7**	22.8	4.5	~7
River and lake ice	**8**	(n/a)	(n/a)	(n/a)

Source: IPCC (2007). Climate Change 2007: The Physical Science Basis. Contribution of Working Group 1 to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (eds. S. Solomon, D. Qin, M. Manning, Z. Chen, M.C. Marquis, K. Averyt, M. Tignor and H.L. Miller). Intergovernmental Panel on Climate Change, Cambridge and New York

Foreword

Ice, snow and climate change are closely linked. The *Global Outlook for Ice and Snow* investigates those connections, the current situation of ice and snow and the global significance of changes, now and in the years to come. The book was prepared for World Environment Day 2007 to provide an up-to-date assessment on this year's theme: Melting Ice – A Hot Topic? The *Global Outlook for Ice and Snow* is the second thematic assessment report in UNEP's Global Environment Outlook series.

It was written by teams of experts from different disciplines and many countries and has included leading research organizations in the preparation and the reviewing of the book.

Ice and snow on land, in the seas, and in the ground, collectively known as the cryosphere, are defining components of ecosystems in the northern part of the Northern Hemisphere, in Antarctica and in the world's mountain regions. Changes in ice and snow alter the distribution of Earth's heat and water, and influence regional and global ocean circulation.

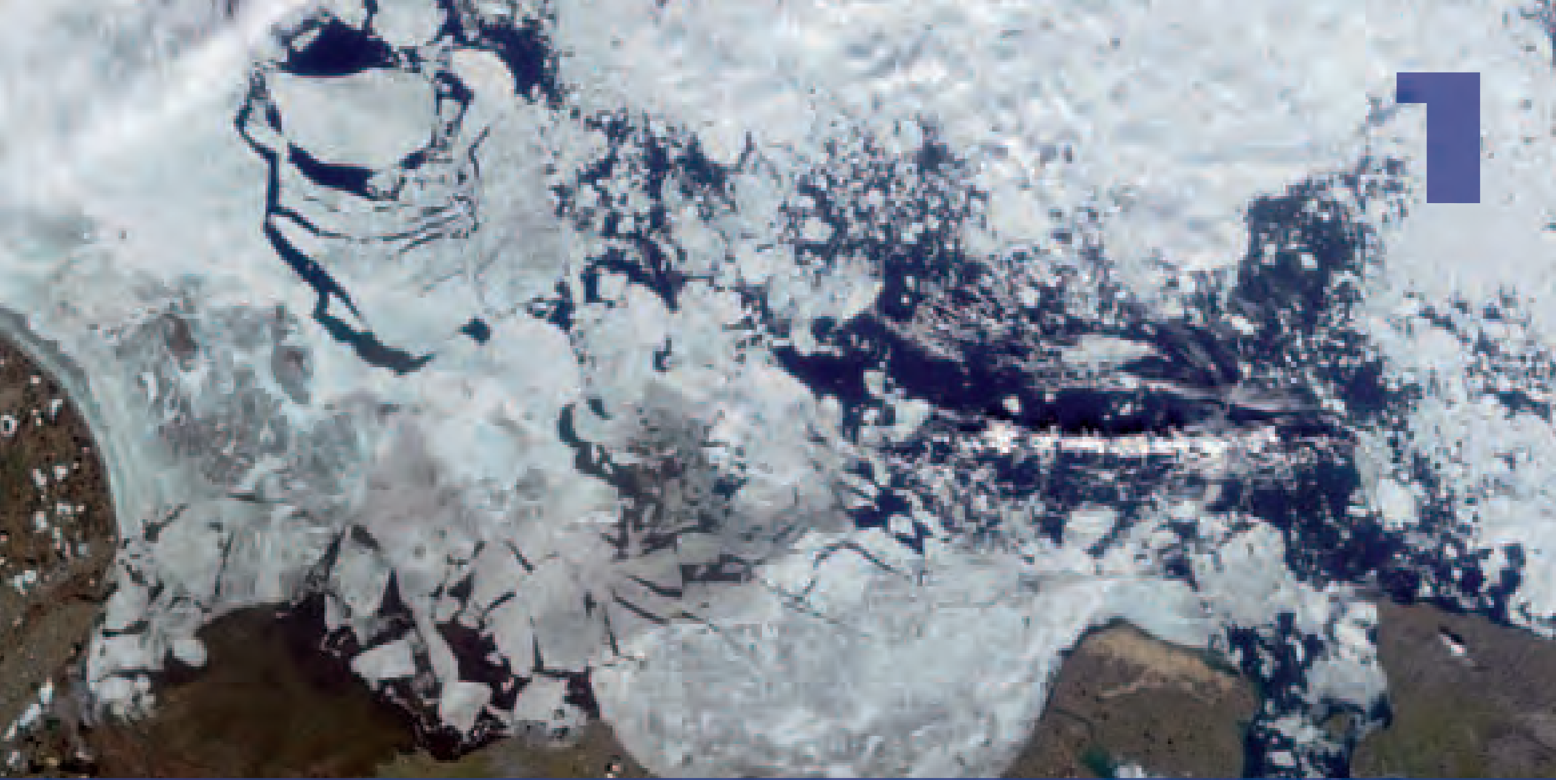
Many plants and animals such as the polar bear have evolved to live on, in and around ice and cannot survive without it. Traditional cultures are intimately tied to ice and snow in the far North and in mountain areas. For many people in northern and mountain regions, ice and snow are part of daily winter life, a resource for recreation and income generation, and an important part of national and regional identity.

In high mountain areas, particularly in the Himalayas and Andes, ice and snow are important sources of water for billions of downstream users; frequently maintaining river flows and the recharge of aquifers in dry seasons. Glaciers are melting, sea ice is shrinking, permafrost is thawing. These changes have widespread impacts, from collapsing infrastructure in the Arctic to increased flooding of small islands in the South Pacific.

Reports of the Intergovernmental Panel on Climate Change (IPCC), founded by UNEP and the WMO, reflect our best understanding and knowledge on climate change, and identify uncertainties and research needs. March 1 of this year marked the start of International Polar Year (IPY) 2007–2008, the largest-ever international polar research programme. Much IPY research is directed to answering questions and resolving uncertainties about the cryosphere and climate change.

The IPCC's 4th Assessment reports underline the far reaching implications of changes in ice and snow. For example a total loss of Himalayan glaciers could happen within the lifetimes of many alive today affecting the water supplies of hundreds of millions of people. Climate change has indeed moved to the top of the global sustainable development agenda. The *Global Outlook for Ice and Snow* will serve as a reference publication in the debate, contribute to effective decision-making and ultimately the action so urgently needed.

Achim Steiner
United Nations Under-Secretary-General
and Executive Director,
United Nations Environment Programme



1

Highlights

Highlights

Ice and snow are important components of the Earth's climate system and are particularly sensitive to global warming. Over the last few decades the amount of ice and snow, especially in the Northern Hemisphere, has decreased substantially, mainly due to human-made global warming. Changes in the volumes and extents of ice and snow have both global and local impacts on climate, ecosystems and human well-being.

Snow and the various forms of ice play different roles within the climate system. The two continental **ice sheets** of Antarctica and Greenland actively influence the global climate over time scales of millennia to millions of years, but may also have more rapid effects on, for example, sea level. **Snow** and **sea ice**, with their large areas but relatively small volumes, are connected to key interactions and feedbacks at global scales, including solar reflectivity and ocean circulation. Perennially **frozen ground** (permafrost) influences soil water content and vegetation over continental-scale northern regions and is one of the cryosphere components most sensitive to atmospheric warming trends. As permafrost warms, organic material stored in permafrost may release greenhouse gases into the atmosphere and increase the rate of global warming. **Glaciers and ice caps**, as well as **river and lake ice**, with their smaller areas and volumes, react relatively quickly to climate effects, influencing ecosystems and human activities on a local scale. They are good indicators of climate change.

Photo: Ian Britton/FreeFoto.com

Why are Ice and Snow Changing?

- A main conclusion of the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report of 2007 was that it is very likely that most of the global warming during the last 50 years is due to the increase in human-made greenhouse gases.
- The largest recent increases in annual temperatures for the planet are over the North American Arctic, north central Siberia and on the Antarctic Peninsula.
- The climate system is influenced both by natural variability and external factors such as greenhouse gases and the sun. During the 21st century the most important external influence on snow and ice will be the increase in greenhouse gases.
- Overall Arctic temperatures have been increasing at almost double the global rate. Climate model simulations for the Arctic project further increases in average temperatures plus a trend to warmer high and low temperature extremes.
- In Antarctica the recent warming has not been widespread, but model projections for the end of the 21st century indicate a broader pattern of warmer surface temperatures.
- Ongoing changes to ice and snow have a predominantly positive feedback effect which will result in accelerating rates of change.

Photo: Artis Rams/iStock

Snow

- Mean monthly snow-cover extent in the Northern Hemisphere has declined at a rate of 1.3 per cent per decade over the last 40 years with greatest losses in the spring and summer.
- Major reductions in snow cover are projected for mid-latitudes by the end of this century. Parts of the Canadian Arctic and Siberia are projected to receive increased snow fall.
- Air temperatures are projected to continue increasing in many mountainous regions, which will raise snow lines and cause other changes in mountain snow cover.
- Snow is an important ecological factor. Increased frequency of snow thaw due to rise in air temperatures changes the properties of snow cover, with implications for plants and animals that interact with snow. Projected changes in amount of snow cover will affect the structure of ecosystems.
- Snow cover is a major influence on climate due to its high reflectivity of sunlight and its insulating properties. Decreases in snow-cover extent will act as a positive feedback to global warming by changing the reflectivity of the land surface.
- Changes in snow cover have a dramatic impact on water resources. Snow in mountain regions contributes to water supplies for almost one-sixth of the world's population.
- Changes in snow cover affect human well-being through influences on water resources, agriculture, infrastructure, livelihoods of Arctic indigenous people, environmental hazards and winter recreation.

Photo: Jon Aars/NPI

Ice in the Sea

- In the last three decades there have been declines in the extent of Arctic sea ice of 8.9 per cent per decade in September and 2.5 per cent per decade in March. The retreat of sea ice is particularly noticeable along the Eurasian coast. Sea-ice thickness has declined in parts of the Arctic since the 1950s and both the extent and the thickness of Arctic sea ice are projected to continue to decline with the possibility of a mainly ice-free Arctic Ocean in summer by 2100 or earlier.
- Antarctic sea ice is projected to decline in extent at a similar rate as in the Arctic, but it is not expected to thin as much.
- Declines in the extent of sea ice accelerate the rate of melting because more sunlight is reflected by the bright surface of snow and sea ice than by the dark surface of open water. This is the same feedback process that results from decline of snow-cover extent on land. This feedback process affects climate globally.
- Melting sea ice may influence global patterns of ocean circulation; increasing melting of sea ice in combination with increased freshwater influx from melting glaciers and ice sheets may result in major changes to ocean circulation.
- Sea ice is vital habitat for organisms ranging from tiny bacteria, algae, worms and crustaceans to sea birds, penguins, seals, walrus, polar bears and whales. Some sea-ice dependent animals are already at risk and the predicted declines in sea ice may lead to extinctions.
- Shrinking sea ice is forcing coastal Arctic indigenous people to adopt different methods of travel and to change their harvesting strategies. Further loss of sea ice threatens traditional livelihoods and cultures.
- Increasing extent of open water in polar regions will provide easier access to economic activities such as exploration and exploitation of petroleum resources, and shipborne tourism, with accompanying benefits and risks.
- The Northern Sea Route along Russia's Arctic coast is currently navigable for 20–30 days annually. Predictions are that by 2080 the navigable period will increase to 80–90 days. This, combined with the potential of future opening of the Northwest Passage through Canada's waters, will likely have a major impact on world shipping.

Photo: Konrad Steffen

- Annual total loss of mass from the Greenland Ice Sheet more than doubled in the last decade of the 20th century and may have doubled again by 2005. This is related to more melting and also to increased discharge of ice from outlet glaciers into the ocean. Warmer Greenland summers are extending the zone and intensity of summer melting to higher elevations. This increases both meltwater runoff into the ocean and meltwater drainage that lubricates glacier sliding and potentially increases ice discharge into the ocean.
- There is uncertainty concerning recent overall changes in ice mass in the Antarctic Ice Sheet but there is probably an overall decline in mass with shrinking in the west and addition in the east due to increased snowfall. Ice shelves are thinning and some are breaking up. Glaciers that feed the ice shelves are observed to accelerate, as much as eight-fold, following ice-shelf break-up.
- Observations made over the past five years make it clear that existing ice-sheet models cannot simulate the widespread rapid glacier thinning that is occurring, and ocean models cannot simulate the changes in the ocean that are probably causing some of the ice thinning. This means that it is not possible now to predict the future of the ice sheets, in either the short or long term, with any confidence.
- The Greenland and Antarctic ice sheets hold about 99 per cent of the world's freshwater ice (the equivalent of 64 m of sea level rise) and changes to them will have dramatic and world-wide impacts, particularly on sea level but also on ocean circulation.

Photo: Igor Smichkov/iStock

Ice on the Land

Glaciers and Ice Caps

- Over the past 100 years, and particularly since the 1980s, there has been worldwide and dramatic shrinkage of glaciers. This shrinking is closely related to global warming.
- Projected increases in global air temperatures will ensure the continuing shrinkage of glaciers and ice caps and may lead to the disappearance of glaciers from many mountain regions over the coming decades.
- Disappearance of glaciers will have major consequences on water resources, especially in regions such as the Himalayas–Hindu Kush, the Andes, Rocky Mountains and European Alps, where many dry-season river flows depend on glacier meltwater.
- Shrinkage of glaciers leads to the deposition of unstable debris, the formation of ice and debris dammed lakes and it increases instability of glacier ice. These conditions pose increased risk of catastrophic flooding, debris flows and ice avalanches.

Photo: Bruce Richmond/USGS

Ice and Sea-level Change

- Sea level is rising at an increasing rate which is associated with global warming. The rate of sea-level rise is now 3.1 mm per year; the average for the 20th century was 1.7 mm per year.
- More than a third of sea-level rise is from meltwater from glaciers and ice sheets with most of the remaining rise being due to thermal expansion of the oceans. The contribution of meltwater to sea-level rise can be expected to continue and accelerate as more land ice melts. Over the long term the ice sheets of Greenland and Antarctica have the potential to make the largest contribution to sea-level rise, but they are also the greatest source of uncertainty.
- For the next few decades, the rate of sea-level rise is partly locked in by past emissions and will not be strongly dependent on 21st century greenhouse gas emissions. However, sea-level projections closer to and beyond 2100 are critically dependent on future greenhouse gas emissions.
- The IPCC Fourth Assessment Report projects a global sea level rise over the 21st century in the range of about 20 to 80 cm. However, the upper bound of this projection is very uncertain.
- Climate change is also projected to increase the frequency and severity of extreme sea-level events such as storm surges. This will exacerbate the impacts of sea-level rise.
- The impacts of sea level rise in any region will depend on many interacting factors, including whether the coastal region is undergoing uplift or subsidence, and to what degree development has altered natural flood protection such as coastal vegetation.
- Rising sea levels will potentially affect many millions of people on small islands and at and near coasts worldwide. A wide range of adaptation and mitigation measures will be required to assist people to cope with the consequences; these will require cooperation among nations as well as among all levels of government, the private sector, researchers, non-government organizations and communities.

Photo: V. Romanovsky

Frozen Ground

- Permafrost temperatures have increased during the last 20–30 years in almost all areas of the Northern Hemisphere. Warming of permafrost is also reported from areas of mountain permafrost. This warming has not yet resulted in widespread permafrost thawing.
- Climate changes are projected to result in permafrost thawing across the subarctic by the end of this century, with the most significant thawing occurring in North America.
- Permafrost stores a lot of carbon, with upper permafrost layers estimated to contain more organic carbon than is currently contained in the atmosphere. Permafrost thawing results in the release of this carbon in the form of greenhouse gases which will have a positive feedback effect to global warming.
- Thawing of ice-rich permafrost results in the formation of thermokarst, land forms in which parts of the ground surface have subsided. Thermokarst affects ecosystems and infrastructure and can accelerate permafrost thawing.
- The construction and everyday use of existing infrastructure can result in permafrost thawing, with subsequent effects on infrastructure. Increases in air temperatures may accelerate this ongoing permafrost degradation associated with infrastructure.
- Thawing of permafrost has significant impacts on ecosystems, with the potential to completely change habitats, for example, from boreal forest to wetlands.
- In mountainous areas thawing permafrost may increase slope instability, raising the risk of natural hazards such as landslides and rock falls.

Photo: Esko Kuusisto

River and Lake Ice

- Changes that have largely mirrored rising air temperatures are affecting river and lake ice, mainly seen as earlier spring break up and, to a lesser extent, later autumn freeze up.
- The trend to longer ice-free periods is projected to continue. Details are uncertain but strong regional variation is expected, with the amount of change depending on the degree of warming that is forecast.
- Ice formation on rivers and lakes is a key factor controlling biological production and changes in the length and timing of ice cover have ecosystem effects.
- In remote areas frozen rivers and lakes are used as transport corridors and longer ice-free periods mean reduced or more expensive access to communities and industrial developments. Many northern indigenous people depend on frozen lakes and rivers for access to traditional hunting, fishing, reindeer herding or trapping areas.
- Spring break up often causes damming of rivers by ice, resulting in costly flooding. Lowered temperature gradients along north-flowing rivers in the Northern Hemisphere may lead to reductions in ice-jam flooding. This has potential negative ecological consequences for deltas where annual flooding is needed to maintain ponds and wetlands.

Photo: Christian Lambrechts

Policy and Perspectives

Changes in ice and snow raise policy issues at global, regional and local scales.

Global

- Ice, snow and climate change are closely linked. Mitigating climate change by reducing greenhouse gases emissions is the main global policy response to mitigate changes in ice and snow.
- The IPCC Fourth Assessment Report concluded that, to avoid further and accelerated global warming with major negative consequences, greenhouse gases must stop increasing and start decreasing no later than 15 to 25 years from now. Economic assessments indicate that this is achievable without significant welfare losses.

Regional

- Adaptation policy must be tailored to regions and requires regional scientific knowledge and assessment of impacts of climate change.
- In the Arctic, key policy issues centre on the prospect of retreating sea ice and the implications for shipping and exploitation of oil and gas reserves. This raises issues of jurisdiction and of regulatory regimes in the Arctic marine environment.
- In Antarctica, the projected decrease in sea-ice extent is likely to contribute to an already rapid expansion of the tourism industry with potential impacts on the environment and on the value of Antarctica in research. This points to the need for a regulatory framework for Antarctic tourism.
- In the Himalayas–Hindu Kush region, projected changes in snowfall and glacier melt are expected to increase risks of both floods and water shortages, potentially affecting hundreds of millions of people. Strategies for water management and land-use planning are needed to reduce vulnerability to the impacts of global warming.

Local

- Impacts of changes in ice and snow are already major concerns in many Arctic communities. Examples of local impacts are damage to coastal infrastructure from thawing permafrost and increased storm surges, and loss of access to subsistence resources for indigenous people. Expansion of shipping and oil and gas development will bring both local opportunities and potential for negative economic and social effects. Most individual communities currently lack the capacity to cope effectively with these stresses. Responses to these challenges are likely to reflect differences in political and legal systems among Arctic states.

2

Why are Ice and Snow Important to Us?

Pål Prestrud (Center for International Climate and Environmental Research, Oslo, Norway)

Why are Ice and Snow Important to Us?

This report demonstrates how we are affected by ice and snow, whether we live in the northern regions or tropical climates or in between. Ice and snow are important components of the Earth's climate system and are particularly vulnerable to global warming. Ice and snow are important parts of northerners' identity and culture, especially for indigenous people, whose cultures have adapted to a world in which ice and snow are not only integral parts of the ecosystem but also support a sustainable way of life. Reduction of ice and snow damages the ecosystems that support these cultures and livelihoods.

"As our hunting culture is based on the cold, being frozen with lots of snow and ice, we thrive on it," says Sheila Watt-Cloutier, former Chair of the Inuit Circumpolar Council. *"We are in essence fighting for our right to be cold."*[1]

Ice and snow are also important in temperate and tropical areas. Hundreds of millions of people are affected by the ice and snow that accumulate in mountain regions. The slow melt from glaciers provides water to rivers supporting agriculture, domestic water supplies, hydroelectric power stations, and industry. If the glaciers disappear, people distant from these mountains, in the lowlands and big cities of Asia and South America, will suffer from the loss of this dry-season water flow.

Photo: ICC

The global significance of ice and snow is profound. Less ice, snow and permafrost may amplify global warming in various ways. Melting glaciers and ice sheets in Greenland and Antarctica will raise the mean sea level. The retreating sea ice, in combination with increased supply of fresh water from melting glaciers and warmer ocean temperatures, could affect the strength of major ocean currents.

Over the last few decades, the amount of ice and snow, especially in the Northern Hemisphere, has decreased substantially[2,3]. The primary reason for this decrease is the ongoing global warming that the WMO/UNEP Intergovernmental Panel on Climate Change[3] (see Chapter 9) attributes mainly to human activities. This trend will accelerate if the global warming continues.

This book looks at the forces driving this unprecedented change (Chapter 3), and at the current state and outlook for the components of the cryosphere (see Box 1): snow (Chapter 4), ice in the sea (Chapter 5), ice on the land (Chapter 6), frozen ground (Chapter 7) and river and lake ice (Chapter 8). The societal and ecological impacts of changes in the different components of ice and snow are discussed in each chapter. The final chapter (Chapter 9) returns to a holistic view, presenting some regional perspectives and looking at implications of current and projected changes, and at policy responses. The report is based on scientific knowledge and each chapter is written by experts in their field.

Snow cover in the Rocky Mountains.
Photo: Sean Linehan, NOS/NGS

Changes in the polar regions are important to the rest of the world

In addition to receiving less sun radiation than temperate and tropical regions, the polar regions are cold because ice and snow reflect most of the solar radiation back to space, while open sea and bare ground absorb most of the solar radiation as heat. When the ice and snow cover begin to shrink because the climate is getting warmer, more solar radiation tends to be absorbed, which in turn accelerates the melting. This process develops slowly, but as more and more bare ground and open sea are exposed, the warming will increase and the snow melting will accelerate. Less ice and snow cover also means that less heat will be used for melting, which will contribute to the warming trend. In these ways, reduced ice and snow cover warms up polar regions and accelerates global warming. This is an example of what scientists call positive feedback, a self-reinforcing effect, in the climate system.

Climate scientists call the changes in the external natural and human-made factors that can explain the global warming over the last 150 years "climate forcings" (see also Chapter 3). Forcing is measured in watts per square metre of the Earth's surface – in other words, the rate of adding (warming) or subtracting (cooling) energy or heat from the Earth's heat balance. If all ice and snow were to disappear, and the effect of this were to be evened out across the globe, the Earth would receive 3 to 4 watts more heating per square metre than it does now[4]. For comparison, scientists believe that the climate forcing from all the additions and subtraction resulting from greenhouse gases, particulate matter, aerosols, solar radiation changes, and volcanic eruptions over the last hundred years equal about 1.6 watts per square metre[3]. This illustrates that the ice and snow covered surfaces in high latitude and high altitude regions contribute an important and essential cooling function for the whole planet.

Some of the feedbacks and interactions that result from warming in the polar regions are complex and very hard to predict. In the Arctic there is another positive climate feedback that may amplify global warming significantly. The uppermost part of the frozen tundra contains between 200 and 400 billion tonnes of carbon stored in organic material produced by the tundra vegetation[2] (Chapter 7). This organic material breaks down slowly and if the permafrost starts to thaw, decomposition will speed up and release the greenhouse gases methane and carbon dioxide. In addition, there are probably some thousand billion tonnes of methane frozen deep

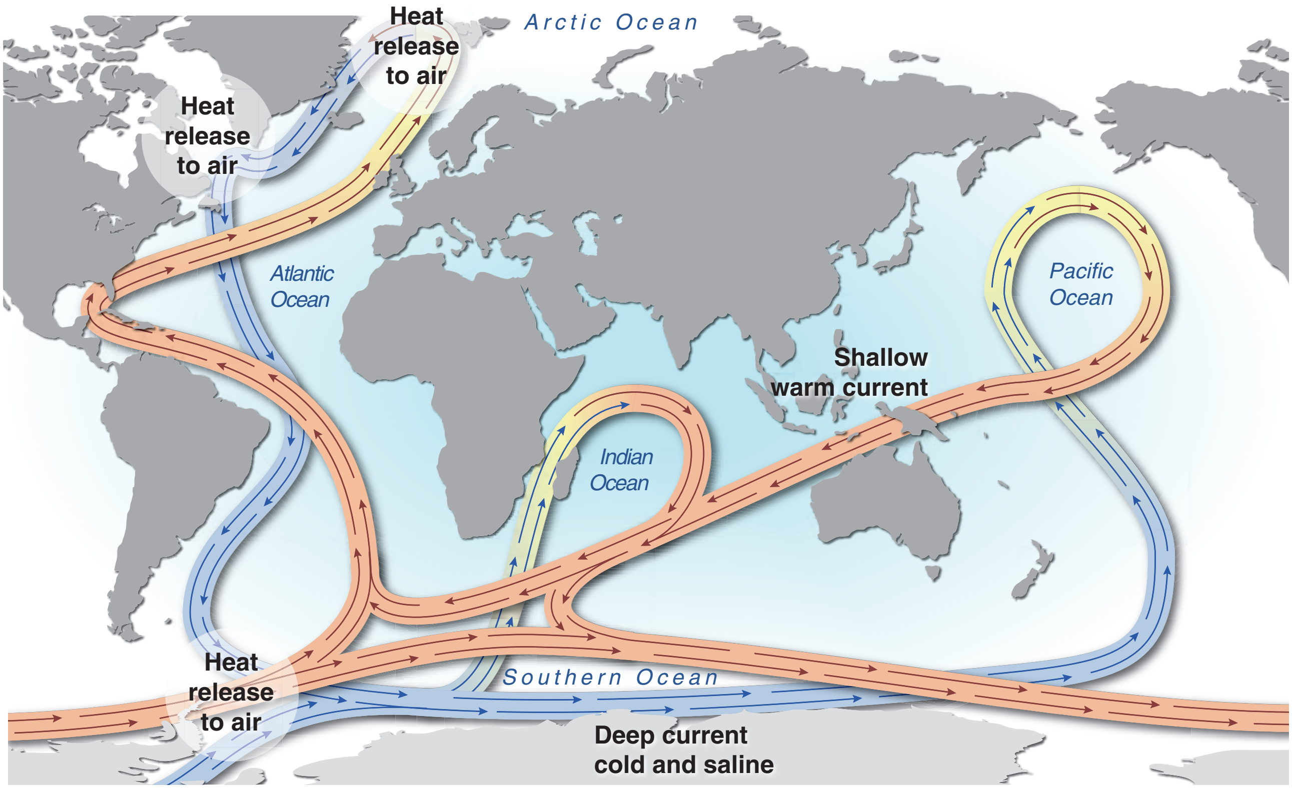


Figure 2.1: Thermohaline circulation, showing areas of major ocean–air heat transfer.

inside or below the permafrost (methane hydrates). We thus risk a situation where global warming melts the permafrost, which in turn adds extra greenhouse gases to the atmosphere, in all likelihood amplifying the warming. On the other hand, a considerable melting of the deep permafrost is necessary before the store of frozen methane could be affected, and that will take many years. During that time, the warming may cause the boreal forest to expand across the tundra, which will remove carbon from the atmosphere. But tree crowns absorb more heat from solar radiation than the flat, white tundra, which can again increase warming[2]. Thus, what the net effect will be on the global climate from these processes is unknown.

Another factor that may affect the global distribution of heat is a change in the major ocean currents caused by melting of ice, excess warming of ocean waters and their freshening. One of the main factors driving the ocean circulation is the formation of deep, dense water in the Greenland Sea, the sea near Baffin Island in eastern Canada, and in the Weddell Sea in Antarctica[3]. Water becomes heavier as it gets saltier and colder. The cold and saline water in these areas sinks and flows along the bottom of the world's oceans while the warmer water flows closer to the surface of the ocean to these colder areas, where it releases its warmth, and becomes colder and more saline. This thermohaline circulation (Figure 2.1) forms a major system of ocean currents, which is also called the Great Ocean Conveyor Belt. The North Atlantic Current is a part of this system. Thermohaline circulation may be affected by melting and freezing processes, such as reductions in the extent and thickness of sea ice (Chapter 5) and input of lighter fresh water from melting glaciers (Chapter 6). The IPCC[3] projects a 25 per cent reduction in this century of the North Atlantic Current because of a weakening of the deep water formation.

Changes from melting ice and snow affect people's homes and livelihoods worldwide

Sea-level rise is one of the most obvious consequences of melting ice on land (Chapter 6). The global sea level is currently rising by about 3 mm per year mostly because seawater expands as it gets warmer and because melting glaciers and ice sheets add fresh water to the oceans[3] (Chapter 6). The IPCC[3] projects that the sea level may rise by as much as half a metre in this century, mainly caused by the thermal expansion of seawater. There is,

Malekula Islands, Vanuatu.
Photo: Topham Picturepoint TopFoto.co.uk


Rhone glacier in Switzerland.
Photo: Konrad Steffen


Polar bear mother and cub on the sea ice – Baffin Bay.
Photo: Peter Van Wagner/iStock

of course, also the potential for the sea level to continue to rise a great deal more. If all the ice masses on land melted the sea level could eventually rise by around 65 metres[3]. This is virtually unthinkable, since the average temperature on Antarctica, where most of this ice is located, is now about –30 °C to –40 °C. But even a minor melting of these ice masses would have significant consequences. For example, if the ice melts by 20 per cent in Greenland and 5 per cent in Antarctica at the same time, the sea level will rise by 4 to 5 metres. This will have not only major consequences for the small islands in the Pacific, Caribbean, and the Indian Ocean, but also for countries like the Netherlands and Bangladesh; and cities and coastal infrastructure in many other countries will be affected negatively.

With few exceptions, all the alpine glaciers of the world are losing mass and it is predicted that this trend will continue as global warming progresses[5]. Glaciers in alpine areas act as buffers. During the rainy season, water is stored in the glaciers and the melt water helps maintain river systems during dry periods. An estimated 1.5 to 2 billion people in Asia (Himalayan region) and in Europe (The Alps) and the Americas (Andes and Rocky Mountains) depend on river systems with glaciers inside their catchment areas. In areas where the glaciers are melting, river runoff will increase for a period before a sharp decline in runoff. Without the water from mountain glaciers, serious problems are inevitable and the UN's Millennium Development Goals for fighting poverty and improving access to clean water will be jeopardized.

The ecosystems and biological diversity in polar and mountain regions will change significantly in a warming world. The zone along the edge of the sea ice is bursting with life despite what at first glance appears to us to be one of the most hostile environments on the Earth. Both the underside and the top surface of pack ice, as well as openings in the ice, are home to myriad marine plants and animals – from long strands of algae under the ice and innumerable small crustaceans, to seals, marine birds, and polar bears (Chapter 5). The ice-edge zone is a biological oasis in the spring and summer when the sun shines around the clock[2]. Many species are specifically adapted to the ice and they will have major problems surviving if the ice should disappear. The same goes for the tundra, where many species are completely dependent on an environment of snow and permafrost. If large parts of the tundra are replaced by trees and shrubs, an expected result of global warming, many of the species that live on the tundra will lose much of their current ranges[2]. Paradoxically, we can expect a greater biological diversity because different species will migrate north from the south.

People who depend on the living resources in the northern regions will have to adapt to major changes. Agriculture and the fishing industry may profit from a moderate warming, while those who live in a traditional way from the land – such as Saami, Arctic Athabaskan, Inuit and other Peoples – will face great challenges. This has already become evident.

Access to energy and mineral resources in the polar regions will increase as ice melts. The sea ice is the main barrier to maritime transport and access to the major continental shelves that surround the Arctic Ocean, where projections place a large part of the world's remaining petroleum resources. The increased interest in petroleum resources in the North is undoubtedly also linked to the decline of the sea ice. For example, it has been calculated that the length of navigation season through the Northern Sea Route along the Siberian coast will increase from 30 days to 120 days in this century, if

Snowfall in China.
Photo: UNEP/Still Pictures

Looking out on sea ice covering Hudson Bay, Canada.
Photo: John Main

Snowshoeing in Massachusetts, USA.
Photo: Nicholas Craig Zwinggi/iStock

the projections of the scientists come true[2]. Ironically, the feasibility of recovering petroleum resources from polar regions has increased because of global warming and the consequent thaw.

Because ice and snow are crucial components of the climate system, extensive research is conducted on them both in the polar and alpine areas of the world. In addition to extensive national research programmes, a global project entitled Climate and Cryosphere (CliC) is developed by the World Climate Research Programme (WCRP) of the World Meteorological Organization (WMO), the International Council for Science (ICSU) and the Intergovernmental Oceanographic Commission of United Nations Educational, Scientific and Cultural Organization. The International Geosphere-Biosphere Programme (IGBP) of ICSU is also important. The International Polar Year 2007-2008 (IPY) is jointly conducted by WMO and ICSU and represents one of the most ambitious coordinated science programmes ever attempted. It includes research and observation in both the Arctic and the Antarctic and explores the strong links these regions have with the rest of the globe. IPY is a truly international endeavour with over 60 countries participating in more than 200 projects covering a wide range of research disciplines, from geophysics to ecology to social science and economics.

The Cryosphere

Ice and snow in the seas, on the surface of the earth, and in the ground are collectively known as the cryosphere (see 'The Cryosphere', inside front cover). Snow, ice sheets and sea ice cover about 15 per cent of the Earth's surface during the peak period in March to April, and about 6 per cent in August to September. Permanently-frozen ground, or permafrost, is found in both polar and alpine areas and covers about 20 per cent of Earth's land areas. Ice and snow store more than 80 per cent of the fresh water on Earth, mainly in the big ice sheets in Greenland and Antarctica with a combined volume of about 30 million cubic kilometres.

The various components of the cryosphere play strong but different roles within the climate system.

- Due to their large volumes and areas, the two continental ice sheets of Antarctica and Greenland **actively influence the global climate** over time scales of millennia to millions of years.
- Snow and sea ice cover large areas too, but have relatively small volumes. They vary in size over the seasons. Snow and sea ice are connected to **key interactions and feedbacks** at global scales (albedo, ocean circulation). Permafrost is another important feedback component in the climate system through the methane cycle. Together with seasonal snow, permafrost influences soil water content and vegetation over continental-scale northern areas.
- Glaciers and ice caps, as well as seasonal ice on lakes, with their smaller areas and volumes, react relatively quickly to climate effects, influencing ecosystems and human activities on a local scale. They are good **indicators of change**, reflecting trends in a range of conditions and seasons, from winter lowlands (lake ice) to summer alpine areas (mountain glaciers). Despite the total volume of glaciers being several orders of magnitude smaller than that of the two major ice sheets, they currently contribute more to sea-level rise.

Seasonal variation in the extent of ice and snow cover is greatest in the Northern Hemisphere. Imagine the Earth with white caps on the top and bottom (2.2). The top cap increases by a factor of six from summer to winter, while the bottom cap only doubles from summer to winter. This difference is due to snow cover: in the Northern Hemisphere snow cover on land varies from less than 2 million km^2 in the summer to 40 to 50 million km^2 in the winter[3]. There is little snow cover in the Southern Hemisphere. In Antarctica, land ice covers about 14 million km^2 year-round, with little change from summer to winter. Sea ice cover in the Arctic varies between approximately 7 and 15 million km^2 seasonally, while sea ice cover in the Antarctic, though about the same extent at its peak, varies much more – from around 3 million km^2 during summer to 18 million km^2 in winter. This means that there is less multi-year sea ice in the Antarctic than in the Arctic, where much of the sea ice is older than one year.

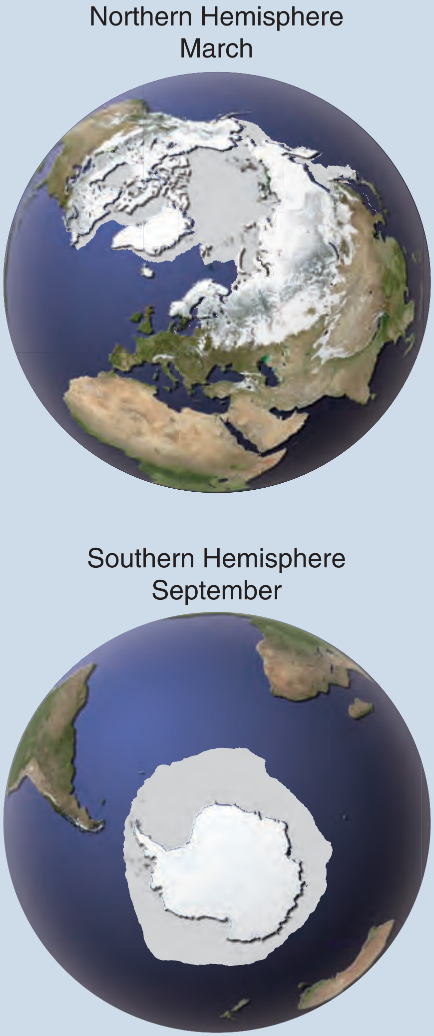


Figure 2.2: Ice and snow cover at peak periods in the annual cycles, Northern and Southern Hemispheres.

Source: Based on NASA Blue Marble NG, with data from the National Snow and Ice Data Centre

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3

Why are Ice and Snow Changing?

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Why are Ice and Snow Changing?

Summary

Changes in ice and snow are influenced by variability within the climate system itself and by external factors such as greenhouse gases, solar variability, and volcanic dust – factors that act on time scales from months to hundreds of thousands of years. During the 21st century, the most important external influence on high latitude climate and on ice and snow conditions will be the increase in greenhouse gases. Natural climate variability will still impose regional, decadal, and year-to-year differences, and feedbacks will become increasingly important in the climate system. Before 2050 the ice albedo feedback will accelerate the loss of Arctic sea ice. Warmer temperatures will reduce the area of snow cover and produce an earlier melt in snow-covered regions. This reduced snow cover will itself speed up warming.

Forces that drive the climate system

Atmospheric climate, represented primarily by temperatures, precipitation, and winds, undergoes externally-forced changes as well as natural, internal variations.

External forcing factors include greenhouse gas fluctuations, dust from volcanic eruptions, and variations in the amount of solar radiation reaching the top of the atmosphere. These changes in atmospheric conditions influence the amount of ice and snow cover in a particular region and the regional climate is affected by them in turn. In the 21st century the most significant change in external forcing for high latitude climate, and therefore the largest influence on ice and snow conditions, will be the increase in greenhouse gases. The IPCC 4th Assessment Report[1] notes that it is highly likely (90 per cent confidence) that humans have already contributed to a rise in global temperatures due to an increase in greenhouse gas forcing. Carbon dioxide (CO_2), a primary greenhouse gas, is now near 380 ppm (parts per million of the atmosphere) and currently has a greater concentration than during any of the previous interglacial warm periods over the last 500,000 years. CO_2 is projected to reach 480 ppm by mid-century.

In addition to external factors, there is a large and natural random aspect to climate change that produces differences from year to year, decade to decade, and place to place. This variability is caused by instabilities in the air flow on the rotating Earth and this effect is greater near the poles than near the equator. Examples of natural variability are the warmer temperatures in the European Arctic in the 1920s and 1930s, and the cooler temperatures in the 1960s.

When the climate trend from future greenhouse gas forcing is added to the natural range of climate variability, the result is a shift during the 21st century to overall warmer temperatures, with many consequences for the cryosphere. The Arctic will experience warmer high and low temperature extremes. The warmer average will lead to a loss of sea ice and to earlier snow melt and river break-up – trends that are observed now. Globally, the freezing level (also called snow line) in mountainous regions will continue to move up mountain slopes and larger proportions of precipitation will fall as rain rather than as snow. In Antarctica, where current warming trends are not widespread, models project that increased warming will affect the central parts of the huge Antarctic ice sheet later in the century.

During the 21st century, the most important external influence on ice and snow conditions will be the increase in greenhouse gases.
Photo: Ian Britton/FreeFoto.com

Learning from the past

The direct influence of variability of the sun's radiation at the Earth's surface is the major influence on the Earth's climate over a scale of hundreds of thousands of years. Long-term variation in temperatures and CO_2 are inferred from Antarctic ice cores (see the timeline on the inside back cover). The last 10 000 years have been a warm period in the Earth's history. Before then were the ice ages, each lasting approximately 100 000 years, with interglacial warm periods. The timing of the ice ages is set by changes in solar radiation, amplified by CO_2 and water vapour changes and by the position of continents and oceans. These solar changes over glacial time periods are caused by changes in the Earth's orbit, and by the tilt and orientation of the Earth's axis.

Evidence from tree rings and other temperature proxies (Figure 3.1) suggests that during the previous 500 years global temperatures were 1.0ºC cooler than those of the 20th century during a period roughly from 1300 to 1870 – known as the Little Ice Age. While overall temperatures during the Little Ice Age were cooler than now, there was much year-to-year variability and some warm periods[2]. The coldest part of the Little Ice Age, from 1645 to 1715, was also a time of minimum sun spots, referred to as the Maunder minimum. Although there is a correspondence in time, the causal connection between sun variability and Earth climate is a subject of ongoing debate. It is clear, however, that the 20th century was recovering from the average colder temperatures of the 19th century and earlier.

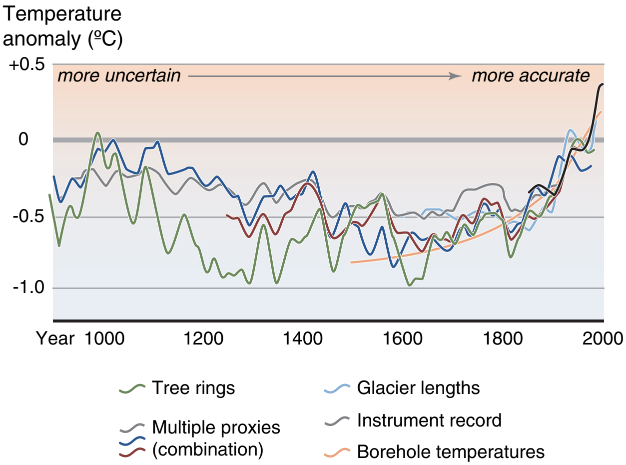


Figure 3.1: Global mean surface temperatures over previous centuries from various proxy records. Temperature estimates before 1500 are considered much less reliable.

Source: based on NRC 2006[3]

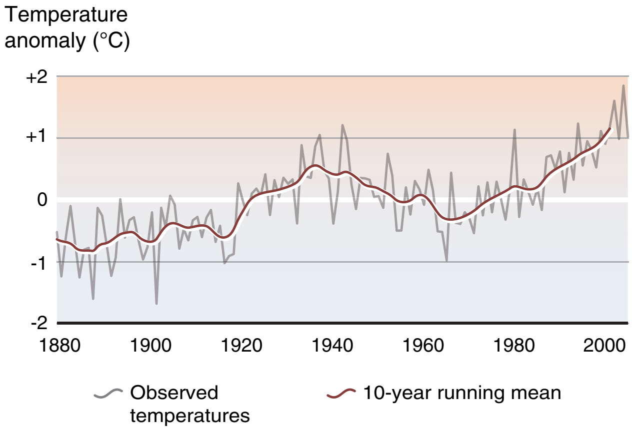


Figure 3.2: Changes in Arctic mean annual land temperatures from 1880 through 2006. The zero line represents the average temperature for 1961–1990.

Source: M. Wang ; data from CRU 2007[4]

A history of Arctic land temperature anomalies from 1880 through 2006 is shown in Figure 3.2. In the late 1800s the Arctic was relatively cold, although there is some uncertainty around these early temperature estimates. The Arctic warmed by about 0.7°C over the 20th century. There was a warm period in the 1920s to 1940s and cold periods in the early 1900s and in the 1960s. Over the last decade the temperatures were about 1.0°C above the 20th century average.

Figure 3.3 shows that the largest recent gains in annual temperatures for the planet are over the North American Arctic, north central Siberia, and on the Antarctic Peninsula. These recent increases in temperature are confirmed by changes in other features: loss of sea ice, shift of tundra to shrub vegetation, and migration of marine and terrestrial ecosystems to higher latitudes[5].

Natural climate variability is organized into spatial patterns of high and low pressure regions, represented by the Arctic Oscillation (also called the Northern Annular Mode) and North Pacific patterns in the Northern Hemisphere, and the Southern Annular Mode in the Southern Hemisphere. The patterns of surface temperature anomalies when the Arctic Oscillation and Northern Pacific patterns are in their positive extreme are shown in Figure 3.4. When either of the patterns is in its positive extreme, the pattern contributes to an overall Arctic warm period. In recent years (2000–2005), however, the pattern of warm temperature anomalies is circumpolar in distribution and different from either of the two major 20th century climate patterns. We are truly in a new and uncertain climate state for the northern polar region[6,7].

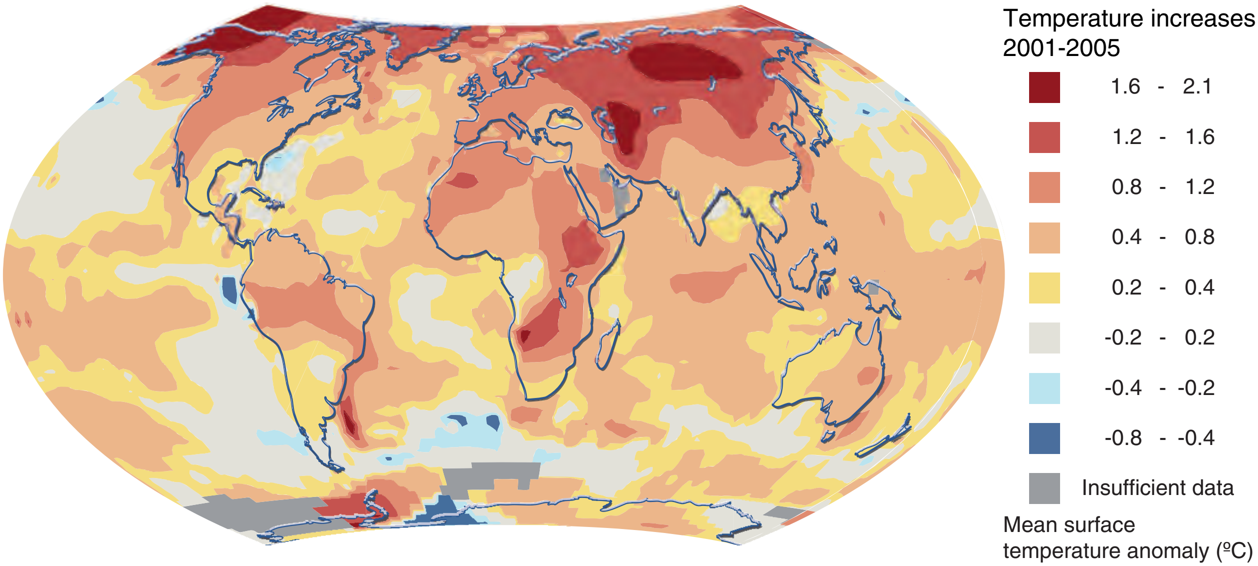


Figure 3.3: Increases in annual temperatures for a recent five-year period relative to 1951–1980. Warming is widespread, generally greater over land than over oceans, and greatest at high latitudes in the Northern Hemisphere.

Source: based on Hansen and others 2006[8]

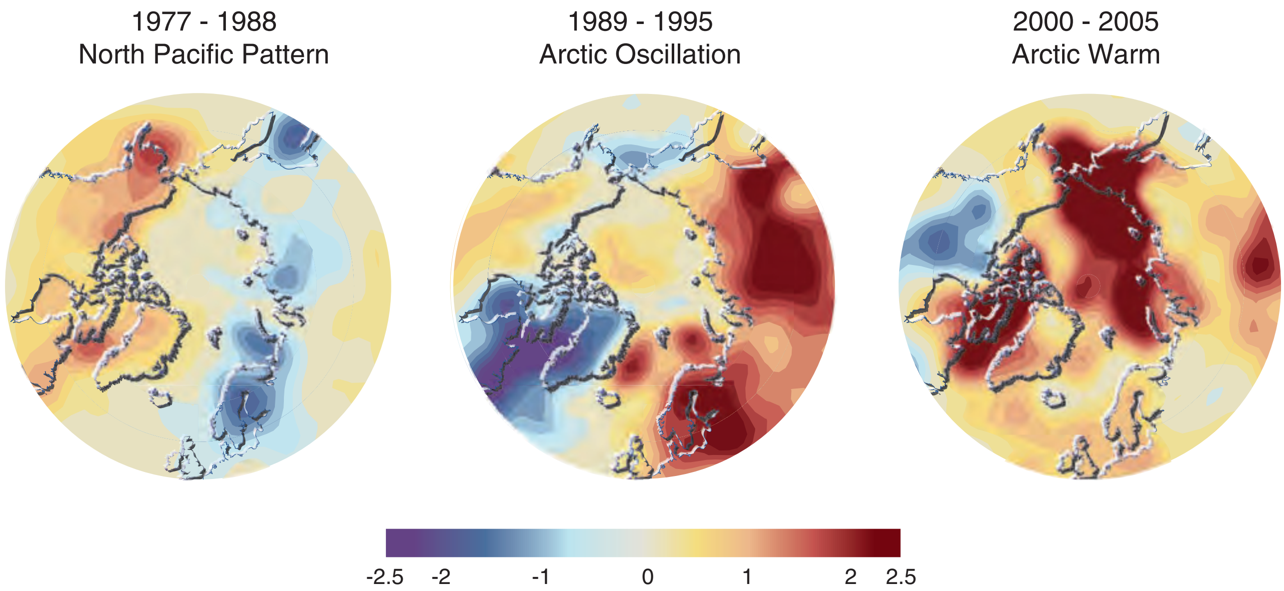


Figure 3.4: Recent Northern Hemisphere surface temperature anomalies averaged over periods with different types of dominating pattern of natural variability. The Northern Pacific pattern was dominant in the Arctic from 1977 to 1988, while the Arctic Oscillation dominated the region from 1989 to 1995. In spring 2000 to 2005 neither of these alternate states is evident – the recent warm period in the Arctic represents a new and uncertain climate pattern.

Source: J.E. Overland; data from NOAA/ESRL 2007[9]

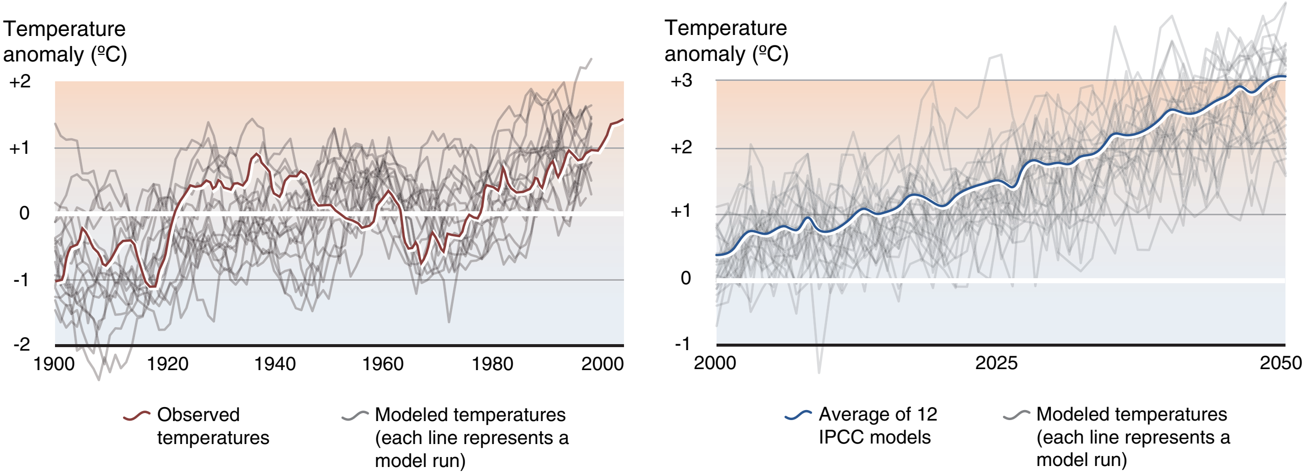
Using climate models to examine the 20th century and to look ahead

We can understand the relative influence of external forcing from greenhouse gases and internal natural variability of the climate system for the 20th and 21st centuries through the use of atmosphere-ocean coupled climate models. To enable comparisons of the climate model runs for the Intergovernmental Panel on Climate Change Fourth Assessment Report[1], the World Climate Research Programme (WCRP) established an archive containing model results from over 20 national climate centres around the world, for the recent past and for the future. These models were run several times, starting with slightly different conditions but with the same external forcing, to simulate the effects of natural variability.

Arctic

Figure 3.5(a) shows model runs for a subset of models, recreating the Arctic winter land temperatures of the 20th century. By the end of the century virtually all model runs arrive at temperatures that are above the 20th century mean, implying the importance of greenhouse gas forc-

Figure 3.5: 20th century (a) and 21st century (b) Arctic land temperatures: results from IPCC models



(a) Observed Arctic winter land temperatures and model recreations for the 20th century. Note that although these model runs are able to capture the range of Arctic warm and cold periods, the timing of the peaks varies, suggesting that the early 20th century warming was due to random causes, while the increases at the end of the century shown by all the models supports CO_2 as an external forcing of the Arctic climate system.

Source: based on Wang and others 2007[10]

(b) Projected Arctic annual land temperature increases for the first half of the 21st century relative to the average temperature for 1980–99. The average of the models (the blue line) shows an increase of 3°C by 2050. The averages of the runs from each of the 12 models show increases from 2–4°C, the range of uncertainty in these model projections.

Source: based on Wang and others 2007[10]

ing in raising Arctic temperatures in recent decades. Earlier in the 20th century, observed temperature extremes are similar to those generated by the models, but the timing is different. This difference in timing indicates that the warm period in the early 20th century was a result of natural variability of the Arctic climate system, and that the late warm period of the 20th century had contributions both from an anthropogenic, forced trend due to greenhouse gases and from natural variability. There is no evidence from the internal atmospheric structure of these early and late 20th century warm events that would indicate that they are both part of a simple climate oscillation.

Looking forward, we can project that 21st century climate will have contributions from both greenhouse gas forcing and internal natural variability. Figure 3.5(b) shows projected annual land temperature increases for the Arctic. The average of all the model simulations shows an increase in Arctic annual mean temperatures of 3.0ºC by 2050, with the various models showing increases ranging from 2.0–4.0ºC. The individual model runs show a trend towards warmer high and low temperature extremes. Differences between models reflect the uncertainty around representations of climate physics. Models appear to be less reliable in projecting climate variables other than temperature – such as precipitation or wind conditions[11].

Antarctica

The temperature trends for Antarctica show that late 20th century warming was primarily along the Antarctic Peninsula without significant warming trends elsewhere on the continent. The proximate cause for the warming on the Peninsula was the increase in the magnitude of the Southern Annular Mode during the period from 1960 to 2001, a change that implies stronger winds, reduced sea ice, and warmer temperatures upwind of the Peninsula, which contributed to the local warming. There are indications of warming higher up in the atmosphere over Antarctica over the last 30 years, but causes cannot be assessed[12].

Model experiments for the end of the 21st century do show broader patterns of warm surface temperatures throughout Antarctica. The delay in the response is thought to be the result of the large thermal inertia of the Southern Ocean[13] or details of the internal physics of the Southern Annular Mode[14], but uncertainties are large.

Feedbacks and interactions

Feedback refers to the modification of a process by changes resulting from the process itself. Positive feedbacks accelerate the process, while negative feedbacks slow it down. Part of the uncertainty around future climates relates to important feedbacks between different parts of the climate system: air temperatures, ice and snow albedo (reflection of the sun's rays), and clouds.

An important positive feedback is the ice and snow albedo feedback (see also Chapters 2, 4 and 5). Sea ice and snow have high albedo. This means that they reflect most of the solar radiation. With warmer polar temperatures, the area of sea ice and snow cover decreases, exposing new expanses of ocean and land surfaces that absorb an increased amount of solar radiation. This increase of total absorbed solar radiation contributes to continued and accelerated warming. Many IPCC climate models suggest a major loss in sea ice cover by the mid 21st century caused by albedo feedback from shrinking snow cover and increased open water areas in summer[15].

A second feedback is negative: the cloud-radiative feedback. Its future impact is important but uncertain. Increased cloud cover, an expected result of global warming, increases the reflection of solar radiation away from the Earth's surface, but it also increases the net long-wave radiation emitted downward from the same clouds back to the surface[16]. The net effect of increased cloudiness is expected to be a small decrease in radiation received by the Earth's surface.

One of the great challenges of climate change science is to understand the net effect of these rather complex interactions (Figure 3.6). This is not just a question of understanding the physics of climate systems – many of these interactions and feedbacks also involve the living world. For example, the increase in shrub growth in tundra regions due to high-latitude warming leads to a decrease in albedo in summer, but an increase in snow retention in winter over large areas of land. Another feedback comes from melting permafrost that releases methane, a powerful greenhouse gas, into the atmosphere, which then amplifies the greenhouse effect. The need to understand these interactions has led to an increase in interdisciplinary studies in recent years and is a focus of research being conducted through the International Polar Year 2007–2008.

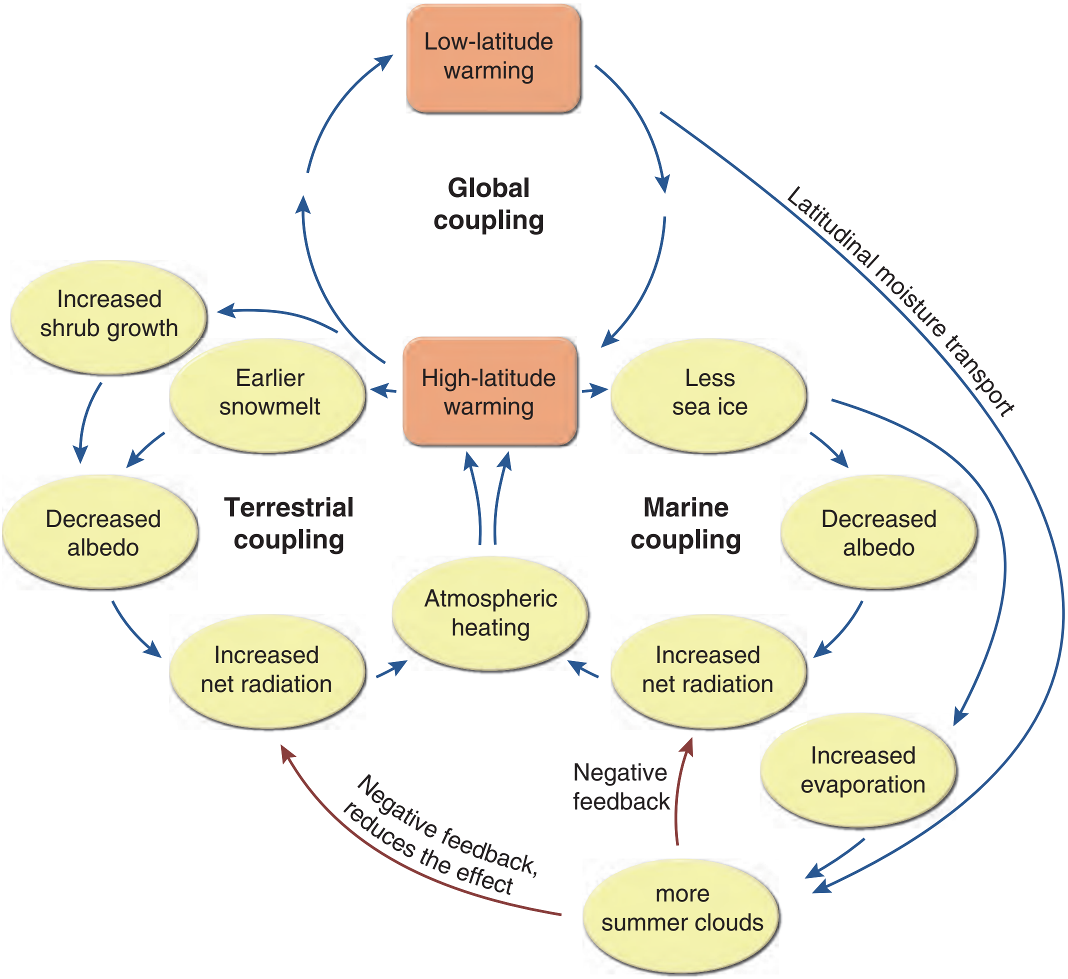


Figure 3.6: Feedbacks. This conceptual diagram illustrates the connectivity of the positive ice/snow albedo feedback, terrestrial snow and vegetation feedbacks and the negative cloud/radiation feedback.

Source: based on Chapin III and others 2005[17]

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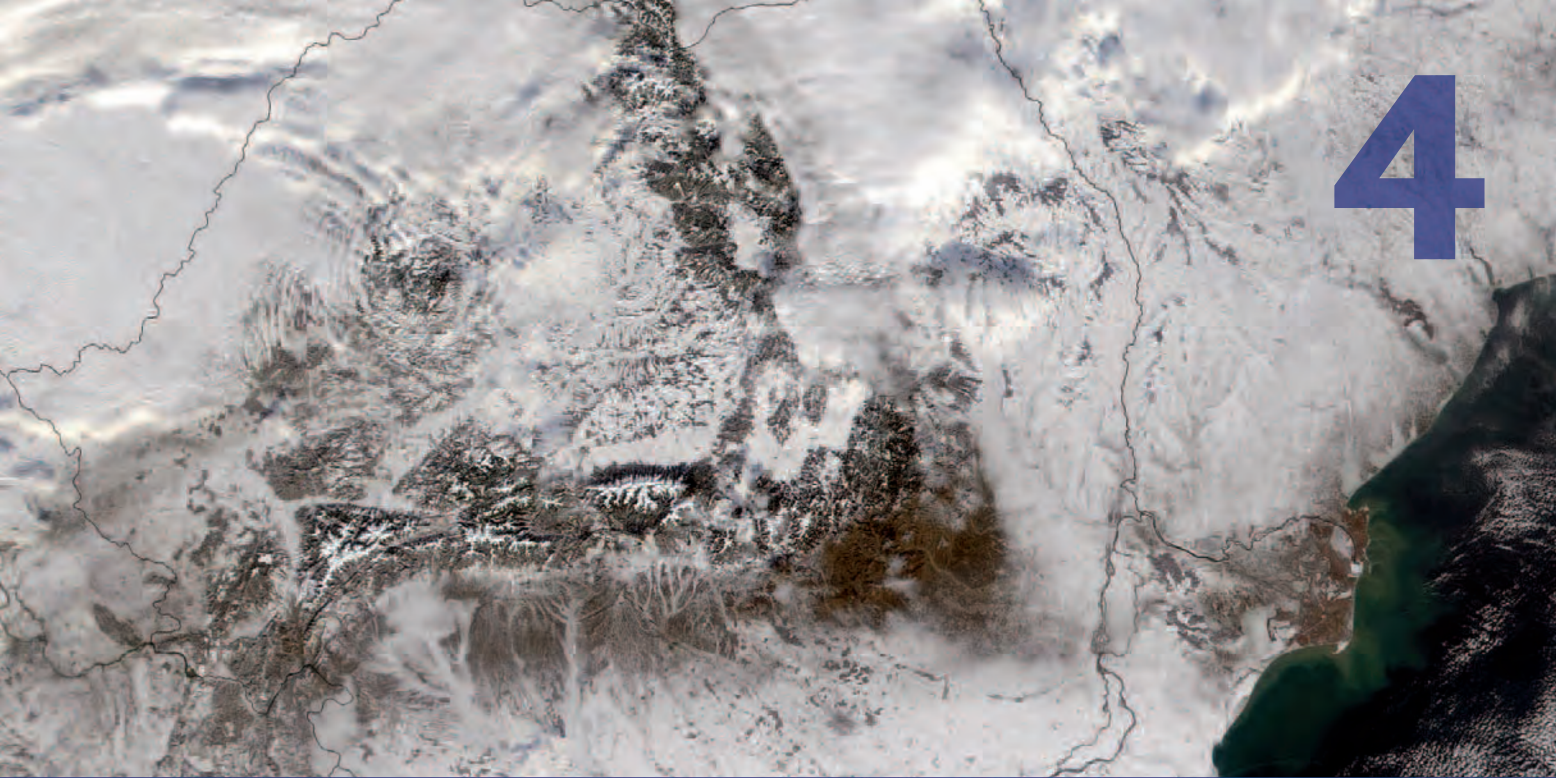

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Snow

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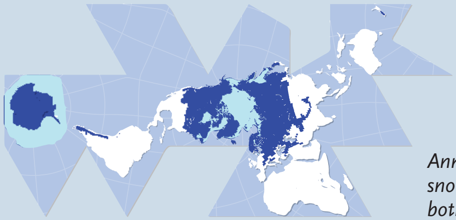
Snow

Summary

Snow exerts a huge influence on climate, through its high reflectivity, insulating properties, and cooling of the atmosphere, and on surface hydrology, through its effects on water resources in many parts of the world. Mean monthly snow-cover extent in the Northern Hemisphere has decreased at a rate of 1.3 per cent per decade during the last 40 years, with greatest losses in the spring and summer months. Climate models project significant decreases in snow cover by the end of this century, with reductions of 60 to 80 per cent in snow water equivalent (depth of water resulting from snow melt) in most mid-latitude regions. Increases are projected for the Canadian Arctic and Siberia. Higher temperatures and rises in snow line are projected for many mountain regions. Changes in snow cover, such as the formation of ice layers in snow due to increased frequency of snow thaw, have widespread impacts as snow is an important ecological factor. Snow-cover changes also have impacts on human well-being and economic activities, including water resources, agriculture, animal husbandry, transportation and winter recreation such as skiing.



Annual maximum snow-cover extent in both hemispheres

Snow: frozen precipitation in the form of ice crystals that fall in soft, white flakes.

Snow on land (Northern Hemisphere) (annual minimum ~ maximum):

Area Covered (million square km)	1.9 ~ 45.2
Potential Sea Level Rise (cm)	0.1 ~ 1

Source: IPCC 2007[1a]

Introduction to snow

Snow occurs predominantly on the northern continents, on the sea ice of the Arctic Ocean and on Antarctica. On the Northern Hemisphere continents, snow covers a maximum mean area of 45.2 million km^2, typically in January. The minimum snow-cover extent usually occurs in August and covers a mean area of 1.9 million km^2, most of which is snow on the Greenland ice sheet and on mountain glaciers. As a result, snow cover is the surface characteristic responsible for the largest annual and interannual differences in surface reflectivity (albedo) in the Northern Hemisphere (Figure 4.1). In the Southern Hemisphere, excluding the 14.5 million km^2 area of Antarctica, terrestrial snow covers a much smaller area, mostly in the Andes and Patagonia, and it plays a smaller role in global climate. Limited summer melt occurs in the Antarctic Peninsula and on the coasts of western Antarctica.

Snow is an important climate variable. Due to its high albedo, snow cover increases the amount of sunlight reflected from Earth's surface. The low thermal conductivity of snow insulates the ground, and its cold, moist surface affects the transfer of heat and moisture to and from the atmosphere. Thus, snow cover exerts a signifi-

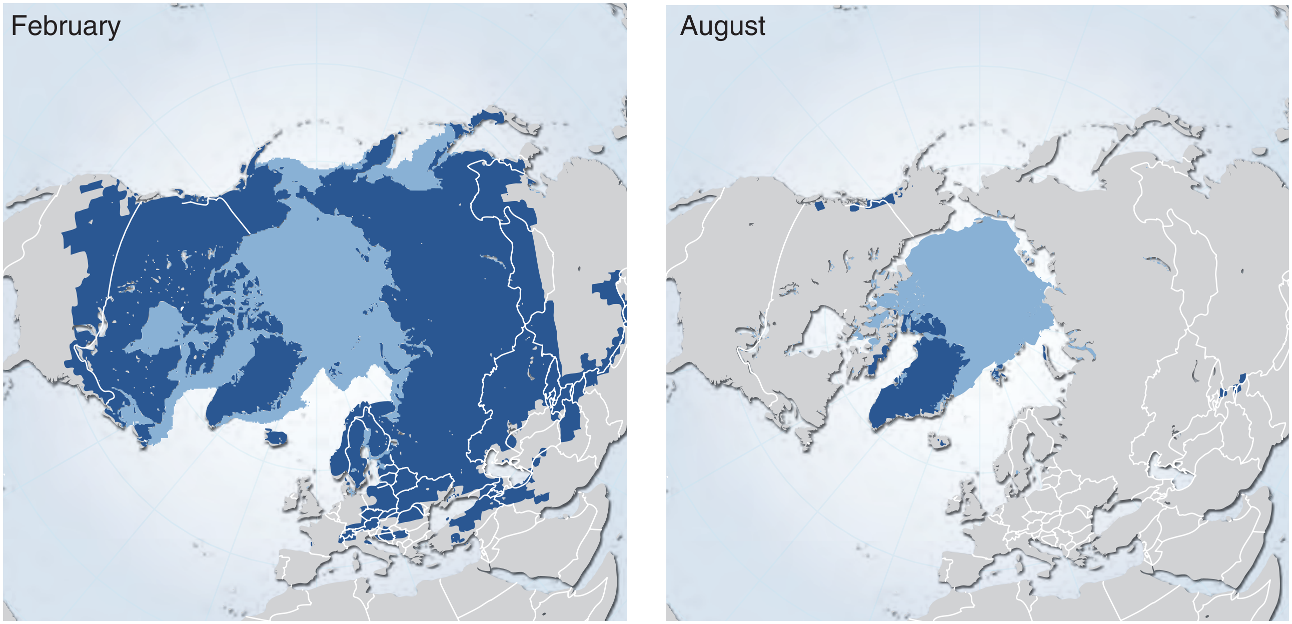


Figure 4.1: Mean snow-cover extent (dark blue) and sea-ice extent (light blue) in the Northern Hemisphere between 1966 and 2006, for February and August. The difference in snow cover between seasons causes significant differences in the surface reflectivity (albedo).

Source: Based on Armstrong and Brodzik 2005[1]

cant influence on climate and hydrology. Snow cover affects large-scale atmospheric circulation. Early season snow-cover anomalies in the Northern Hemisphere, for example, are known to lead to changes in atmospheric circulation. Autumn snow cover can also affect climate on a seasonal scale, with impacts extending into the subsequent winter. Snow cover is also a sensitive indicator of regional climate variability and change. Realistic simulation of snow cover in models and forecast schemes is essential for simulating surface energy balance and predicting winter water storage and year-round runoff.

Snow cover influences human activities directly and indirectly. Seasonal snow cover is the main source of runoff in many mountain regions, and over one billion people depend on it for their water supplies. Snow is a major factor in transportation, winter sports, agriculture and animal husbandry such as reindeer herding. It influences ecosystems and is important for conservation of biodiversity.

Trends and outlook for snow

Snow accumulation and melt are governed primarily by air and soil surface temperature, precipitation, wind and surface relief. Precipitation determines the overall amount of snow but air temperature determines whether the precipitation falls as rain or snow and governs the rate of snow melt. The recent rise in global temperatures, and the warming trends predicted for the future (see Chapter 3) thus affect global snow cover.

Data from satellite monitoring (see box on measuring snow cover extent) from 1966 to 2005 show that mean monthly snow-cover extent in the Northern Hemisphere is decreasing at a rate of 1.3 per cent per decade (Figure 4.2). For the calendar year of 2006 average snow-cover extent was 24.9 million km^2, which is 0.6 million km^2 less than the 37-year average[2]. In the Northern Hemisphere, spring and summer show the strongest decreases in snow-cover extent. Satellite observations of snow-cover extent show a decreasing trend in the Northern Hemisphere for every month except November and December, with the most significant decreasing trends during May to August[3]. The average Northern Hemisphere snow-cover extent for March and April decreased by 7.5 ± 3.5 per cent from 1922–2005[4] (Figure 4.3).

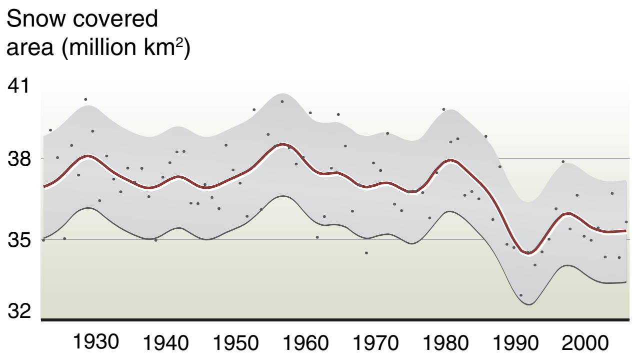


Figure 4.3: Northern Hemisphere snow-covered area (SCA) for the spring (March–April) from 1922–2005. The linear trend shows a decrease in SCA of 2.7 ± 1.5 × 106 km^2 or 7.5 ± 3.5 %. The shaded area represents the 5 to 95% range of the data.

Source: Based on IPCC 2007[4], updated from Brown 2000[5]

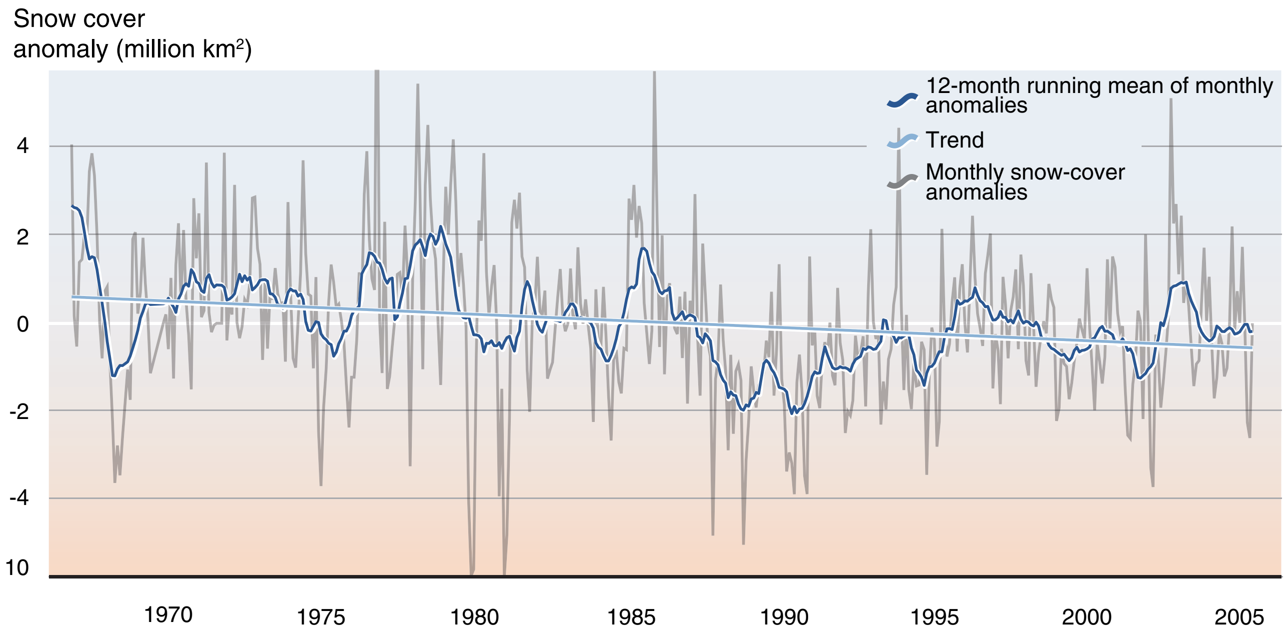


Figure 4.2: Northern Hemisphere snow-cover extent departures from monthly means from 1966 to 2005, with the 12-month running mean also shown. The decreasing trend of –1.3% per decade is significant at the 90% level.

Source: M.J. Brodzik; data from NOAA snow charts revised by D. Robinson, Rutgers University

Snow covered mountains in Alaska.
Photo: P. Slota/USGS National Wildlife Health Center (US)

Measuring snow-cover extent

Snow-cover fluctuations in the hemispheres are monitored by satellite. Since 1966 the National Oceanic and Atmospheric Administration (NOAA) has produced snow-extent charts on at least a weekly basis[6,7]. Until 1999 the charts were primarily derived from the manual interpretation of satellite images taken within the visible band of the electromagnetic spectrum. Passive microwave data, available since 1978, and other data are now included in the source data for the charts[8,9].

Satellite passive microwave sensors can detect the snow surface through clouds and in darkness but may not detect shallow snow that can be seen in visible band imagery. As a result, time series from microwave and visible data sources can differ. Data sets from both sources show a similar range for maximum Northern Hemisphere snow-cover extent that exceeds 40 million km^2 consistently[1,10,11]. NOAA data, derived primarily from visible band sensors, show a significant decreasing trend in mean monthly snow-cover extent (see text). Microwave data indicate a similar decreasing trend that is not significant at a 90% level. While NOAA data show decreasing trends in every month except for November and December (see text), data from passive microwave sensors is less clear. Both data sets indicate significant decreasing trends during May to August (see text).

Regional trends in snow cover

Examination of regional trends in spring snow-cover duration from 1969–2003 using NOAA snow-cover data shows the western United States to be among the regions with the strongest decreases (Figure 4.4). This supports results from studies based on measurements on the ground[12,13]. Springtime snow cover shows a decline particularly in the Pacific Northwest region of the western United States, where snow water equivalent, a common snow cover measurement equivalent to the depth of water which would result from snow melt, has decreased by as much as 50–75 per cent[13]. This decrease is attributed to an increase in temperature[14]; observations of temperatures in the western United States already show warmer winters[15]. There is abundant evidence of earlier spring warm spells in the western United States since 1950 at elevations below 2500 m, with impacts on snow-cover duration as well as amount. There are more frequent rain-on-snow events and snow melt begins earlier, with stream flows increasing in March and April and decreasing in May and June[16].

In contrast, for most of northern Eurasia there has been a long-term increase in snow depth and the duration of snow cover[17]. At Abisko in subarctic Sweden, increases in snow depth have been recorded since 1913[18]. During 1935–1995, snow-cover duration increased by about four days per decade in northern European Russia and small areas of west central Siberia and decreased by about two days per decade over southern and southeastern Siberia[19].

Outlook for snow cover

Decreases in snow-cover extent and duration will contribute to continued and accelerated temperature increases, due to changes in the albedo of the land surface (see Chapter 3). In Alaska, 95 per cent of recent summer warming trends have been attributed to the decrease in snow-cover duration[20].

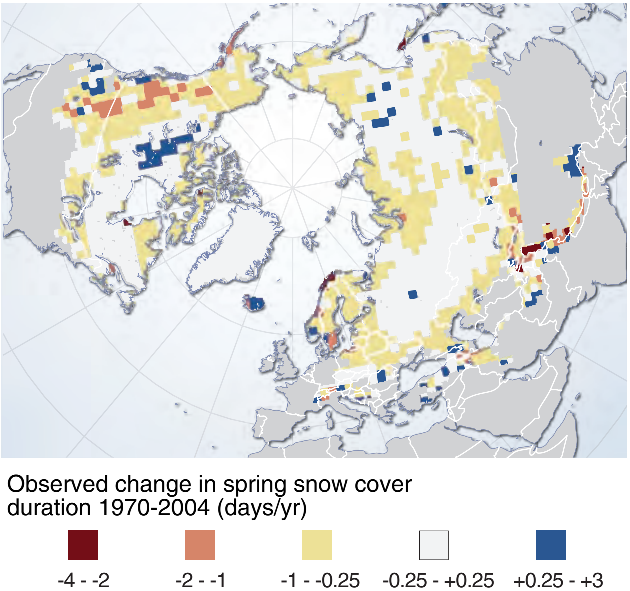


Figure 4.4: Trend (days/year) in spring (February–July) snow-cover duration from 1970–2004 from the NOAA weekly snow-cover dataset. Changes exceeding ~ ±1 represent significant local changes at the 95% level. Greenland was excluded from the analysis.

Source: R. Brown, Environment Canada; data from D. Robinson, Rutgers University

Shallow snow cover at low elevations in temperate regions is the most sensitive to temperature fluctuations and hence most likely to decline with increasing temperature[4]. In locations where snow accumulates at temperatures close to its melting point, small increases in temperature will have large effects on snow cover. For example, in the Pacific Northwest region of the United States, the temperate snow cover of the Cascade Range of mountains could be reduced by over 20 per cent with an increase in mid-winter temperatures of only 2° C[21].

Mountain regions are particularly sensitive to climate change[22], and increases in mean minimum temperatures are more pronounced at higher elevations than in valleys[23]. Temperatures are projected to continue rising in the mountains of the western United States, with accompanying reductions in snow cover[24]. Similar changes are expected in other mountainous regions of the world. In central Chile, air temperature data from 1975 to 2001 show an increase in elevation of the 0° C isotherm (the line on a map linking points at which the mean temperature is 0° C) by 122 m in winter and 200 m in summer[25]. It is estimated that the snow line of the European Alps will rise about 150 m for every 1.0° C increase in winter temperatures[26]. Climate model projections indicate that the Alps and Pyrenees will experience warmer winters with possible increases in precipitation[27], which, as in the western United States, will raise snow lines, reduce overall snow cover, and decrease summer runoff.

Snow water equivalent and snow-covered area are modelled in General Circulation Model experiments to predict global changes in snow cover. A comparison of results

Local observations of snow-cover changes

In many areas of snow cover, there are local people who rely on the snow for water, recreation, travel, and other activities. Through constant and close interaction with snow, these people develop a great body of knowledge about it. People who possess knowledge of snow include mountain villagers, ski patrollers, mountain climbers, and perhaps more than any other group, Arctic residents, especially Indigenous Peoples. These people have the most interaction with snow, as snow is present for most of the year and they depend on it for their livelihoods.

In the Canadian Arctic, Inuit and their ancestors have depended on snow, and held a keen understanding of it, for millennia. Traditionally, Inuit lived in snow houses called *igluit*. The ability to travel depended partly on the condition of snow cover, for example, hard, soft, deep, or drifted snow. Snow forms on the land or sea ice, running parallel with the dominant wind, helped hunters to navigate; this practice is still used by some today (Figure 4.5). Saami reindeer herders in Fennoscandia have also traditionally depended on snow for their activities and survival. Herders closely observe snow conditions and modify their herding strategies accordingly. For example, in hard snow conditions, herders may keep reindeer close together so that strong animals help to crush icy snow layers, allowing weaker animals to graze[30]. If the snow is relatively soft, animals may be allowed to graze a wider area. Today, Inuit no longer live in snow houses and some Saami employ modern technologies, such as helicopters or motorbikes, to herd reindeer. But elders, and many hunters and herders, still possess traditional knowledge about snow. They constantly gain new knowledge about snow and other aspects of the environment, and incorporate this knowledge into their everyday lives.

Many traditional knowledge holders have noticed changes in snow in recent years, along with other changes in the environment and climate. In projects such as the Arctic Climate Impact Assessment, scientists have begun working cooperatively with these people in order to understand environmental change in the Arctic. A number of other projects have documented indigenous knowledge of environmental change in the Arctic, primarily in Alaska and the Canadian Arctic[31–34]. Snow is a common theme in many of these studies. For example, in Nunavik (northern Quebec), residents observe less snow cover in spring time. This restricts travel into the bush by snowmobile to hunt and collect firewood[35]. Less snow in the hills also means fewer cold storage places for fish, which are kept cool in snow patches. This problem is shared by some communities in the Canadian territory of Nunavut[33]. At Clyde River, Nunavut, Inuit observe that permanent snow patches, *aniuvat*, are disappearing and at a quicker rate than in the past. In the community of Baker Lake, Nunavut, changes in snow have already had serious consequences. Changes in wind patterns are packing snow harder than normal, making it difficult or even impossible to build snow houses, which are still used for emergency shelters. Weather events seem to be less predictable to elders in the area, and hunters are being caught in unexpected storms unable to make shelter; several deaths in recent years have been blamed on this change in snow[33,36].

Communities all over the Arctic are living with environmental change and constantly responding to impacts of this change. Snow changes are only one part of this and local observers in the North will acknowledge that snow is bound in a web of environmental processes that are all connected. Knowledge of snow must be accompanied by knowledge of wind, weather, seasons, animals, ice, water, and ocean currents. With their long history in the Arctic and their continued use of the land, ocean, and ice, Arctic Indigenous Peoples play an important role in understanding the Arctic environment and its changes, including snow changes.

Figure 4.5: Arctic Indigenous Peoples have depended on snow for millennia, for example, using snow forms to navigate. This close interaction with snow makes them important observers of snow changes.
Photo: Shari Gearheard

from model simulations to a data set derived from NOAA visible band imagery found the model simulations of annual and interannual variability in snow-covered area to be reasonable at continental to hemispheric scales[28]. At regional scales, however, significant model biases were identified over Eurasia at the southern boundary of the seasonal snow cover. A simulation from one such model projects decreases of 60–80 per cent in monthly maximum snow water equivalent over most middle latitudes by the end of this century (Figure 4.6). The largest decreases are projected over Europe, while simulated increases are seen in the Canadian Arctic and Siberia.

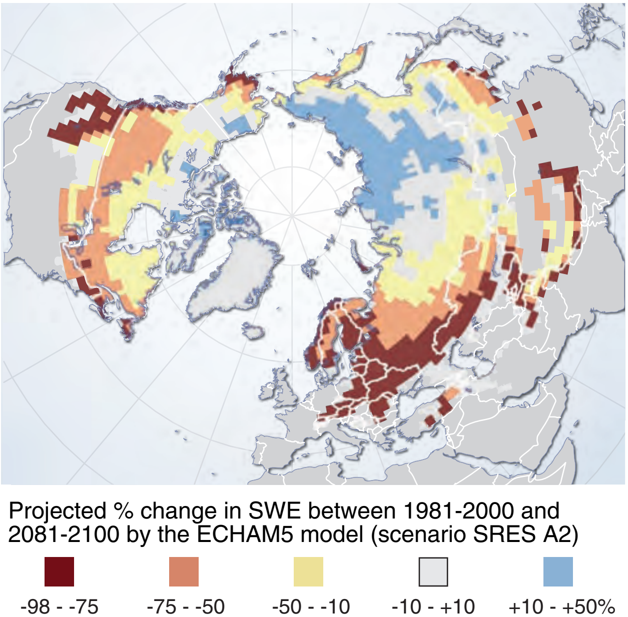


Figure 4.6: Percent change in monthly maximum snow water equivalent (SWE) between 1981–2000 and 2080–2100, simulated by the ECHAM5 climate model under conditions defined by the SRES A2 emission scenario (RUN 2). Results are plotted for grid points with a mean maximum SWE of 10 mm in 1981–2000.

Source: R. Brown, Environment Canada; data from ESG 2007[29]

Snow as an ecological factor

The importance of snow as an ecological factor has been recognized by science since at least the beginning of the 20th century[37,38]. However, even today many observations remain anecdotal. In the 1950s, Gjaerevoll[39] analysed the way in which the alpine plant community structure was shaped by snow. Within the past decade, snow manipulation experiments have explored the effects of snow depth and snow-cover duration on plant communities and ecosystem processes[40–42]. Recently, models of snow cover have been applied to ecological problems[43].

Snow cover plays a dual role in terms of temperature regulation. The high albedo of snow cover reduces net radiation, and snow also acts as a heat sink, removing energy from the atmosphere in the form of heat. This means that the presence of snow cover inhibits soil warming until the snow melts, preventing biological activity that requires temperatures above 0°C. However, snow is an efficient insulator, keeping soil temperatures near 0°C and reducing the extremes of temperature experienced by vegetation and soil in the zone under the snow (subnivean cavity). In autumn, the insulation effect of snow on unfrozen ground can even result in fungal decay of the vegetation, which can kill reindeer calves when they eat the vegetation[44]. The subnivean environment is also very humid. Under thin snow packs in spring, light levels permit limited photosynthesis for lichens and evergreen tundra shrubs[45]. This is an important adaptation given the short growing season. Plants in the “greenhouse of snow” created by the subnivean cavity can start to grow weeks before neighbouring plants covered by deep snow.

Snow exerts forces on the objects that it covers. For example, snow in southern Finland at the end of March, estimated to weigh 100–120 kg per m^2, compresses the

Figure 4.7: Snow has many effects on vegetation, including the ability to deform and break trees with its weight (see beech trees, left). Trees with a narrow canopy (see spruce trees, right) collect less snow and are less likely to suffer damage.
Photo: (left) Fillies Wo/UNEP/Still Pictures, (right) Terry Callaghan

shoots of bog moss[46]. The weight of snow can deform and break trees[38] (Figure 4.7), branches and the soft tissues of plants such as grasses and forbs. Snow can facilitate the spread of some woody plants by pressing branches to the ground surface – the branches then develop roots and form new individuals. Snow pressing directly onto vegetation protects it, to some extent, from grazing. Plants that are covered by the snow are also protected from drying out in the winter and from erosion of tissues by ice crystals. For this reason, the height of vegetation is often uniform and correlated with snow depth[47].

Snow also supports weight, including the various ground pressures that passing animals exert. While snow can support small animals such as birds, small mammals, hares and foxes with only minor deformation, larger mammals such as reindeer and moose experience a critical snow depth above which they cannot move. Snow can, therefore, enhance access across the landscape for animals by smoothing the terrain or forming bridges across gullies, or it can inhibit access by being too deep or too soft. The solid matrix of snow can be shaped and made into dens for polar bears. The consistency of snow also allows the formation of a subnivean cavity in which small mammals nest and feed, protected from predators such as foxes and snowy owls. Along streams in late winter, the subnivean cavity can be as wide as 2 m.

Snow provides a habitat for some "primitive" forms of life. A relatively abundant and diverse array of micro-organisms can be found on both seasonal snow cover[48] and persistent snow on glaciers[49]. These organisms include algae that can colour the snow red, blue or green, bacteria, fungi, diatoms, viruses, rotifers and tardigrades. On Signy Island, a small subantarctic island, cell numbers range from 5000 cells per cubic millimetre for coloured snow to 1 to 2 cells per cubic millimetre for clean snow[49]. The presence of organic matter in and on snow reduces albedo and results in local melt and accumulation of nutrients.

The fractional snow cover (snow in patches) in the spring months affects the breeding of certain ground nesting species, such as waders, ducks and geese (see box on migratory sandpipers and snow). Fractional snow cover, particularly associated with small-scale topographical differences within the landscape, also affects the distribution of plant communities and species. Plant communities that are characteristic of depressions where snow accumulates have short growing seasons and are waterlogged after thaw[39] whereas communities on wind-exposed ridges are more drought tolerant[50]. Traditional Saami knowledge has described the influence of snow cover on the vertical distributions of lichens that live on mountain birch stems in the subarctic; *Parmelia olivacea* grows above the winter snow line, whereas *Parmeliopsis ambigua* grows below the snow line and is covered by snow for six months per year[47].

Snow accumulates debris and chemicals including plant nutrients and pollutants from the atmosphere. Some of these, such as atmospheric nitrogen[54] and seeds, accumulate over the winter and are then released or re-


Animal tracks in the snow.
Photo: Artis Rams/iStockphoto.com

A knot in the snow.
Photo: Peter Prokosch

Migratory sandpipers and snow on the Arctic tundra

Snow very much determines the distribution of Arctic birds. In the spring, 24-hour daylight and vast food supplies attract billions of waterbirds to migrate from virtually all corners of the world to breed in the Arctic. These migratory waterbirds need snow-free patches to feed and nest in the tundra.

For sandpipers breeding in Greenland and Arctic Canada, such as the knot, dunlin and sanderling, both the density and timing of breeding have been shown to be strongly related to snow cover. Successful breeding for these birds depends on finding a nesting area with the right size of snow-free patches and timing breeding so that the chick-rearing period in July coincides with the emergence of insects. Breeding too early can mean losing the clutch due to adverse weather events or due to predation by Arctic foxes, which prey more easily on nests in small snow-free patches. In Siberia, researchers found that, while patch size does not matter for the well-camouflaged ptarmigan, breeding density of passerines and sandpipers increases strongly with the size of the snow-free patches.

The highest density of breeding sandpipers is found in central-eastern Greenland, where continental climate conditions provide an ideal balance between snow-free patches and suitable vegetation. In the northern-most part of Greenland, the vegetation is thinner and fewer sandpipers breed. Further south the conditions are different again. The Atlantic climate, with more snow, allows only late breeding. Large areas in the Arctic do not harbour any sandpipers at all, due to greater snow depth and later thawing. If the current observed trend of increased snow fall continues, the best breeding areas in Greenland will shift further north and push more and more birds to the edge, with a smaller window for breeding. The most affected species are those that breed in the high Arctic. In northern Europe, most of Siberia, and Alaska, earlier thawing will mean more snow-free patches and more favourable conditions for sandpiper breeding at lower latitudes.

Sources: Meltofte 1985[51], Rysgaard and others 2003[52], Summers and Underhill 1996[53] distributed over the landscape. Snow melt provides an important source of nitrogen for tundra ecosystems and can result in a flush of moss growth in spring. However, the accumulation of chemicals by snow can have negative effects on vegetation. Although accumulations of nitrate can be potentially assimilated by mosses and related plants under the snow pack, at high concentrations characteristic of areas south of the Arctic, both nitrate and sulphate can cause physiological damage to plants under the snow[54].

Just as snow has numerous effects on vegetation, vegetation in turn exerts major effects on snow-cover dynamics[20,55,56]. Wind can remove up to 70 per cent of the snow cover in alpine areas, as well as in polar regions and on the prairies[57]. Trees and tall shrubs reduce wind speeds and thereby affect the distribution of snow on the ground[58]. The forest canopy can trap snow, especially in mountain regions with coniferous vegetation, resulting in increased snow depth underneath the vegetation[59]. Depending on the canopy characteristics of the vegetation, the opposite scenario can also occur. In dense coniferous forests, up to 60 per cent of snow fall can be intercepted[60] by the canopy and stored on the branches of the trees. This results in a decrease in snow depth underneath the vegetation, as much of the snow changes to gas (sublimates) or blows away before it falls to the ground[61]. Snow that reaches the ground has been "filtered" by the canopy and is less dense than that in open areas.

Vegetation also affects the amount of snow precipitation and the rate of snow melt. Trees and shrubs affect surface albedo – for example, black spruce can intercept up to 95 per cent of incoming radiation. Trees and shrubs thus increase local temperatures that affect snow fall, thereby indirectly moderating the amount of snow precipitation. The presence of a forest canopy generally slows the rate of snow melt (up to three fold) because it reduces net radiation and wind speeds[62], while a shrub canopy slightly increases the rate of snow melt. Snow within shrub canopies is deeper and less dense, which reduces heat transfer through the snow pack and increases winter soil temperatures by 2 °C relative to adjacent shrub-free tundra[63]. In spring when the snow starts to melt, the contrasting albedos of the vegetation and the snow enable the vegetation to transfer heat to the ground, resulting in local melt which creates holes in the snow around vegetation.

Impacts of projected snow-cover changes on ecosystems

The effect of future snow regimes on vegetation will involve complex interactions between changes in the duration of snow cover and changes in snow depth. The timing of snow cover has effects on the productivity of ecosystems. For areas of seasonal snow cover, the snow-free period in summer determines the length of the potential growing season for plants and thus ecosystem and net primary productivity[64] (Figure 4.8). The timing of the spring melt has a great impact on productivity as, in the Arctic, leaf production occurs relatively late in the season following thaw when the amount of solar radiation received is already at its maximum or declining. At an alpine site, productivity was decreased by 3 per cent for each day that snow melt was delayed[65]. In contrast, the timing of onset of winter snow has less influence on productivity as it comes at a time when solar angles are low and potential plant production is also low.

The increased snow cover that is predicted in some northern areas as temperatures rise will affect both ecosystem structure and function. Long-term experimental increases in snow cover affected species abundance, height of the vegetation, and diversity of plant functional types in the Alaskan tundra[40]. The increase in snow cover had a greater impact on vegetation than experimental summer warming, partly because insulation by increased snow in winter caused higher soil warming than increased air temperatures. In the subarctic, an experimental doubling of winter snow cover on a peat moss bog increased air and soil temperatures and strongly increased moss growth[41]. This increase in moss growth could increase the carbon sink effectiveness of northern peat lands in areas where snow depth increases.

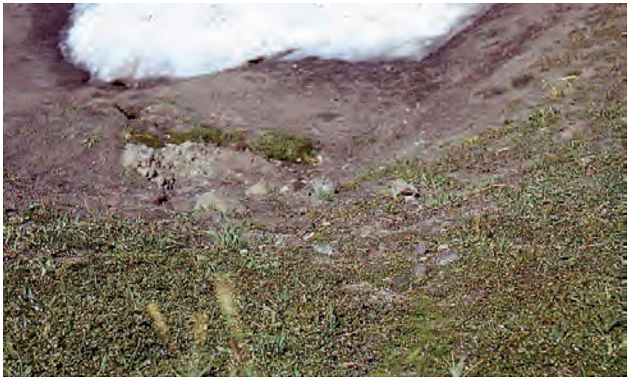


Figure 4.8: The duration of snow cover is a major determinant of the length of the growing season for plants. Shown here is a persistent snow patch in western Greenland. With increasing distance from the centre of the snow patch, the growing season becomes longer, and thus plant communities become more developed and productivity increases.
Photo: Terry Callaghan

More frequent winter thaws can also affect ecosystems. Thawing changes the mechanical properties of snow dramatically. This can reduce the insulating properties of the snow cover, with increased potential for frost penetration into the soil and root damage to certain plant species. During the brief thaw, soil microbial activity may also release greenhouse gases. This occurs at a time when plant uptake of carbon, which could offset the increase in atmospheric carbon, is not possible, and adds to atmospheric concentrations of greenhouse gases. In addition, re-freezing occurs after thawing, which forms ice layers that can be on the surface, throughout the snow cover or, if snow falls after a thawing event, under the snow in contact with the ground. Ice layers can act as a mechanical barrier, preventing herbivores such as musk oxen[66] and reindeer from digging through the snow to reach critical lichens and other forage (see box on the snow-loving deer of the Arctic). This greatly affects their health in winter and can determine their survival[67]. Ice layers may also inhibit the diffusion of organic compounds that reindeer possibly use to detect food[68]. Presence of ice layers affects the survival of other animals such as voles as well[69]. Ice layers can act as a barrier to small mammals accessing shelter, food, nests and protection from predators.

Snow cover in mountain regions is a critical source of freshwater; changes in snow cover could have indirect effects on ecosystems due to changes in availability of these water resources. One potential effect is increased intensity and size of wildfires because of moisture stress on mountain forests. There could also be impacts on anadramous fish, which require high stream flow for their migration to the ocean after hatching in fresh water.

Reindeer feeding after a heavy snowfall.
Photo: Inger Marie Gaup Eira/www.ealat.org

The snow-loving deer of the Arctic

Reindeer and caribou (*Rangifer tarandus*) have been called chionophiles, snow loving. In fact, Arctic island subspecies of *Rangifer* are associated with a snow environment for up to ten months out of the year. *Rangifer* are the most dominant large mammal species in Arctic environments. The species has specialized adaptations in order to thrive in a cold environment. Their diet is energy rich winter lichen, which they obtain mostly by digging (cratering) under the snow[70,71]. Large hooves aid in the cratering and allow *Rangifer* to better travel through snow[72–74]. *Rangifer* are the only member of the deer family in which both males and females grow antlers. Pregnant females retain their antlers until after spring-time calving, allowing them to dominate the social hierarchy in late winter. This dominance allows them to displace lower ranked animals from feeding craters, saving valuable energy[75]. The large migratory herds of *Rangifer* migrate north into regions of rapidly melting snow in spring during the calving period. The pregnant and birthing cows feed along the snow-melt line, and the newly emerged forage that they ingest is highly digestible, protein-rich and critical for milk production.

Although under normal conditions *Rangifer* are able to thrive in snow environments, snow can also severely limit the annual productivity of herds. During deep snow years, more energy is expended in digging to the lichens than is derived from eating them, so caribou limit cratering or move in search of more favourable snow conditions[75]. Under deep snow conditions, *Rangifer* severely deplete their fat and protein reserves to meet their daily energy needs. Late snow melt and deep snow stalls movement during spring migrations. Under severe conditions, calves are born before the herds arrive at the calving grounds. In such years, up to 40 per cent of calves can die before they are a month old[76]. In northwestern North America, recent warming has led to a dramatic increase in the number of days of above freezing temperatures during the *Rangifer* migration period. Thawing and subsequent re-freezing of snow results in ice layers in the snow pack which hinder travel of *Rangifer* and make it harder to crater for food[76]. There have been catastrophic declines in the Peary caribou on the Arctic islands of North America and they are now considered endangered (Figure 4.9). The formation of ice layers that prevent the caribou from accessing food has been identified as the chief cause of the declines[77,78].

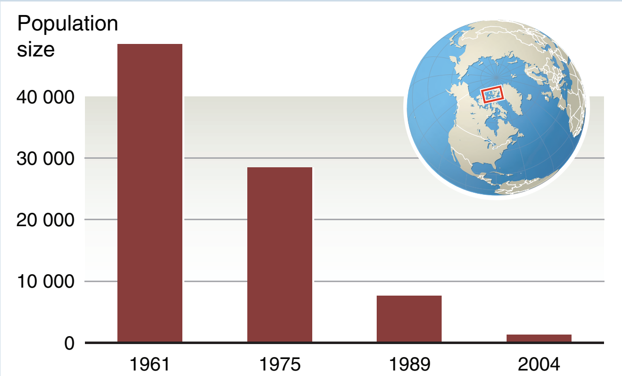


Figure 4.9: Population size of Peary caribou in the Canadian Arctic islands from 1961 to 2004, showing major declines.

Source: Based on data from D. Russell

Impacts of snow-cover changes on human economies and well-being

Impacts on water resources

One of the most dramatic impacts of changing snow cover is on water resources. Snow cover in mountain regions provides critical water supplies, serving nearly one-sixth of the global population with freshwater for domestic, agricultural and industrial uses[79]. Much of the arid American West[79] and Central Asia[80] (Figure 4.10) depends heavily (about 75–85 per cent) on snow melt to supply water for municipalities and agriculture. Snow melt driven water resources are crucial for generation of hydroelectric power, particularly in the American West, Canada, and Europe[81,82]. The declining springtime snow cover in the Pacific Northwest of the United States and rising snowlines projected for many mountain areas, noted in the 'Trends and outlook' section above, threaten these critical water supplies.

Mountain snow cover typically develops in the autumn and grows to a maximum depth in early spring (Figure 4.11). As day length and sun angles increase, so do air temperatures, causing snow cover to warm and begin to melt. Snow cover balances the availability of water in mountain environments. Where winter precipitation falls as rain, surface runoff occurs almost immediately. In contrast,

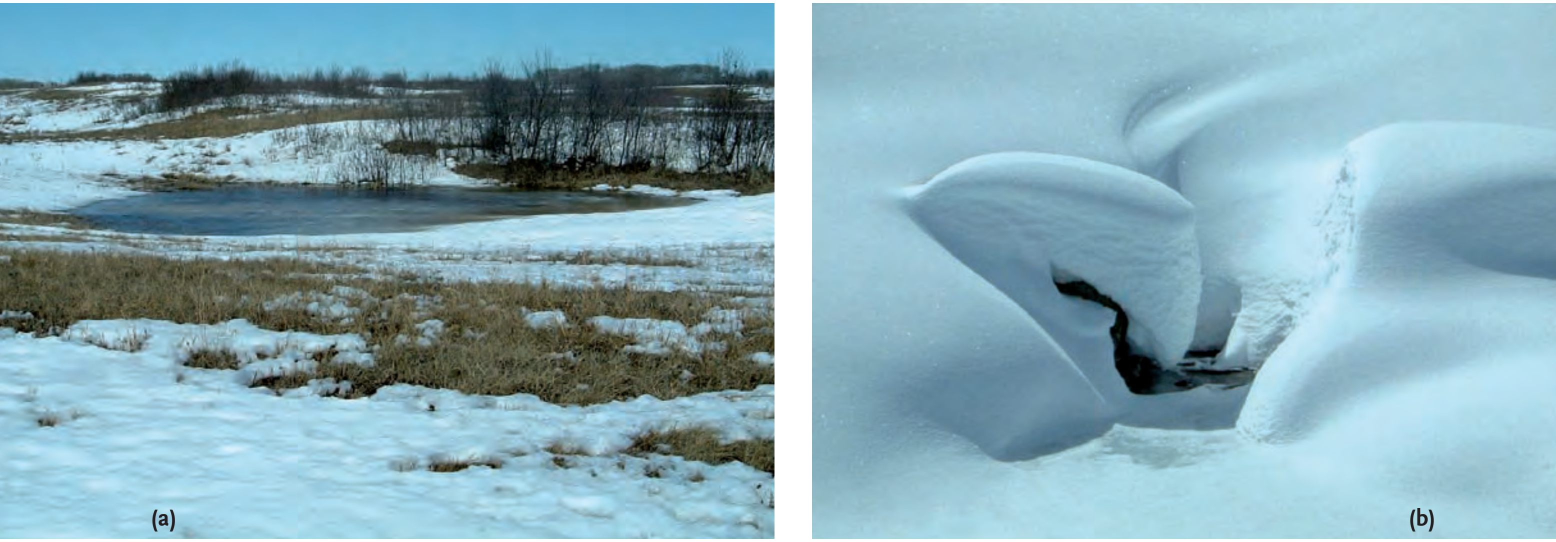


Figure 4.10: Snow cover provides critical water supplies used for many purposes.
(a) Melting of prairie snow cover, seen here in Saskatchewan, Canada, provides spring ponds that are essential for recharge of groundwater and soilwater, for farm water supplies and as spring wetlands for waterfowl migrations through what is otherwise a semi-arid environment.
(b) Melting of alpine snow cover forms a small stream in the Rocky Mountains in British Columbia, Canada. This segment of the Rocky Mountains contains the headwaters of the Columbia River, which supplies water to a large area of western Canada and north-western United States including many important irrigation and hydroelectric generation projects.
Photos: J. Pomeroy

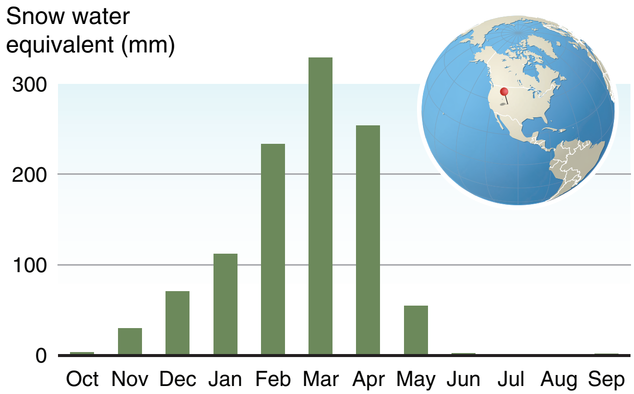


Figure 4.11: Mean monthly snow water equivalent, a common snow pack measurement, for Columbine Pass, Colorado from 1971 to 2000, showing a typical seasonal pattern in a mountain environment.

Source: Based on data from the U.S. National Resources Conservation Service

snow stores water during the winter and then melts in the spring and early summer, creating peak stream flows in the afternoon and an overall seasonal peak flow. In many semi-arid mountain environments, snow melt buffers the transition into the dry summer season. Mountain snow is also a key source of groundwater, since a significant portion of the snow melt enters the soil and drains downhill into valley sediments[83]. The timing, spatial distribution, and volume of snow melt are critical for determining how much water flows as surface runoff into rivers and lakes and how much becomes groundwater. Earlier snow melt across the western United States, for example, caused a one to four week earlier runoff for mountain rivers and longer periods of summertime low-flow[84].

Impacts on agriculture – crops and animal husbandry

The dramatic impacts of snow cover on vegetation also apply to agricultural crops. Gradual changes in snow cover, as well as incidences of extreme snow events, can have a strong impact on crops both at the start and end of the growing season. Snow typically disappears in the spring before the start of the growing season. If it occurs during the growing season, snow can insulate crops from cold air or cause damage by freezing crops or breaking off branches and stems. An early autumn snow may prevent a farmer from being able to harvest crops because snow can damage the plants, prevent

▲ Children playing in the snow.
Photo: Martha Main

◄ **Figure 4.12:** A herd of reindeer belonging to the Nenets, an indigenous people of the Russian Arctic, feed by digging under the snow in western Siberia. Reindeer herding, practiced for centuries by several Arctic peoples, is strongly impacted by snow cover.
Photo: Lars Miguel Utsi/www.ealat.org

them from ripening, or interfere with operation of machinery. In the long-term, changes in snow distributions and their impacts on the local water budget can contribute to changes in vegetation type[85,86] and change the economic cost-benefit of raising certain crops.

Changes in snow distribution can also influence animal husbandry. During extreme snow events, livestock can get lost, stressed, or fail to give birth successfully[87]. The melting of spring snow creates muddy ground conditions that, if prolonged, can lead to animal weight loss. In subsistence communities such as those across the Arctic, access to traditional hunting or herding of caribou and reindeer is strongly impacted by snow distribution[88] (Figure 4.12).

Impacts on recreational sector

Changes in snow distributions have had strong impacts on the recreational sector. Skiing is one example that is important to the economies of mountainous regions of North America, Europe, and Asia[89,90] (see text box on alpine ski resorts). Snowmobiling, used both recreationally and for transport in cold regions, is a growing pursuit and is, of course, dependent on a healthy base layer of snow. In 1985, snowmobiling contributed $300 million to the state economy of Minnesota alone[91]. Other less widespread winter sports such as dog mushing, sledding, and snowshoeing can be important to local economies, and are impacted when snow arrives anomalously late, too little, or not at all.

Making snow on the slopes of a ski resort. *Photo: UNEP/Still Pictures*

Alpine ski resorts

Winter tourism is a significant part of the economy of Alpine countries and the most important source of income in many regions. In Austria, winter tourism revenue makes up 4.5 per cent of GNP and half of the total income from tourism. Much of winter tourism is based around the ski industry, which is dependent on reliable snow conditions. Although snow fall is expected to increase at high elevations, it is winter temperatures that largely determine the depth of snow that accumulates on the mountains. The Alps are currently warming at roughly three times the global average. Climate models project an increase in winter temperatures of about 1° to 3° C from 1990 conditions by 2050, with greater warming at higher elevations. An analysis of snow cover in the Alps concluded that each increase of 1° C corresponds to a 150 m move up the mountain of the line marking the lower limit of adequate snow for ski resorts. This means that each degree of warming will result in a further decline of snow conditions to the point that more and more current ski operations will not be viable (Figure 4.13).

Adaptation measures include more artificial snow making and expanding and building ski areas at higher elevations and on north-facing slopes. As the climate warms and the snow cover declines, many low-elevation ski resorts will not be able to adapt and will be forced to switch to other types of tourism or close.

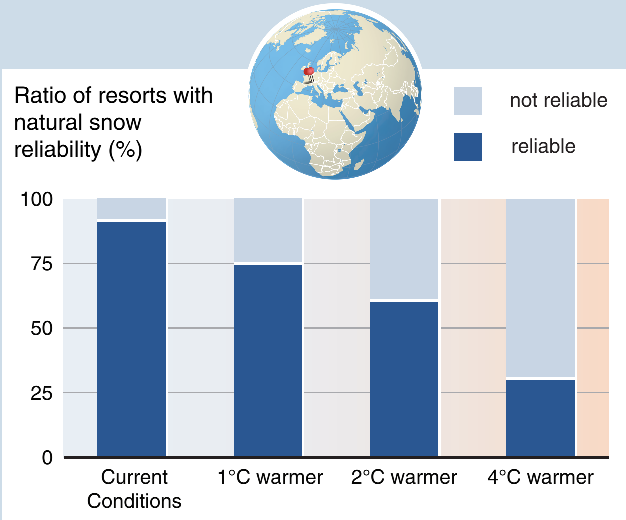


Figure 4.13: Per cent of existing ski areas in the Alps with natural snow-reliability under current conditions and warmer conditions, based on an analysis of 666 medium to large ski areas in France, Austria, Switzerland, Italy and Germany. Natural snow-reliability means on average a season of 100 days with at least 30 cm of snow on upper ski run.

Source: Based on Agrawala 2007[90]

Avalanche in the Swiss Alps.
Photo: Martin Wandel/iStock

Impacts on industry and infrastructure

Certain industries depend heavily on reliable snow cover. Oil and gas companies, for example, use ice roads in the Arctic to gain access to resource fields. In order to protect the tundra ecosystem, temperature and snow-depth criteria must be met before a company builds an ice road. Other industries benefit from less snow, as snow-removal costs can be significant for both small and large businesses. Events such as mid-winter melting or rain-on-snow can cause flooding and lead to damage of roads, bridges and homes[92].

The amount of snow per event, number of events per season, timing within the day and work week[93] all affect the economic impact of snow. The economic impact of a snow event on a region's infrastructure also depends on population density. For example, the Northeast Snow Impact Scale (referring to the northeast region of the United States) takes population density as well as snow-cover extent into account in assessing economic impacts of a snow event[94]. Expectations also play an important role in determining the economic impact of climate changes[95], including changes in snow cover. Weather model forecasts that depict weather conditions over a broad area have become important management tools for economic sectors impacted by snow. While they are not always accurate, they are the best available source of day-to-day information for most industries.

Impacts on environmental hazards

Snow avalanches, in which large quantities of snow slide down a mountainside, are major hazards in steep terrain, causing economic losses, injury and loss of life. Fatalities due to avalanches in the western United States increased to 25 per year in the 1990s[96]. In the European Alps, there was an average of 114 victims per year between 1975 and 1988, three quarters of them mountain and 'off track' skiers[97]. Factors that create high risk of avalanches are: slopes of 35–45°, new snow accumulations of 50–100 cm, and high wind speeds; the order and thickness of layers within the snow pack are also important[98]. Increasing events of rain-on-snow as in the western United States, noted in the "Trends and outlook" section above, may enhance the triggering of avalanche release. This is an increasing risk at lower elevations and in coastal mountains with rising winter temperatures.

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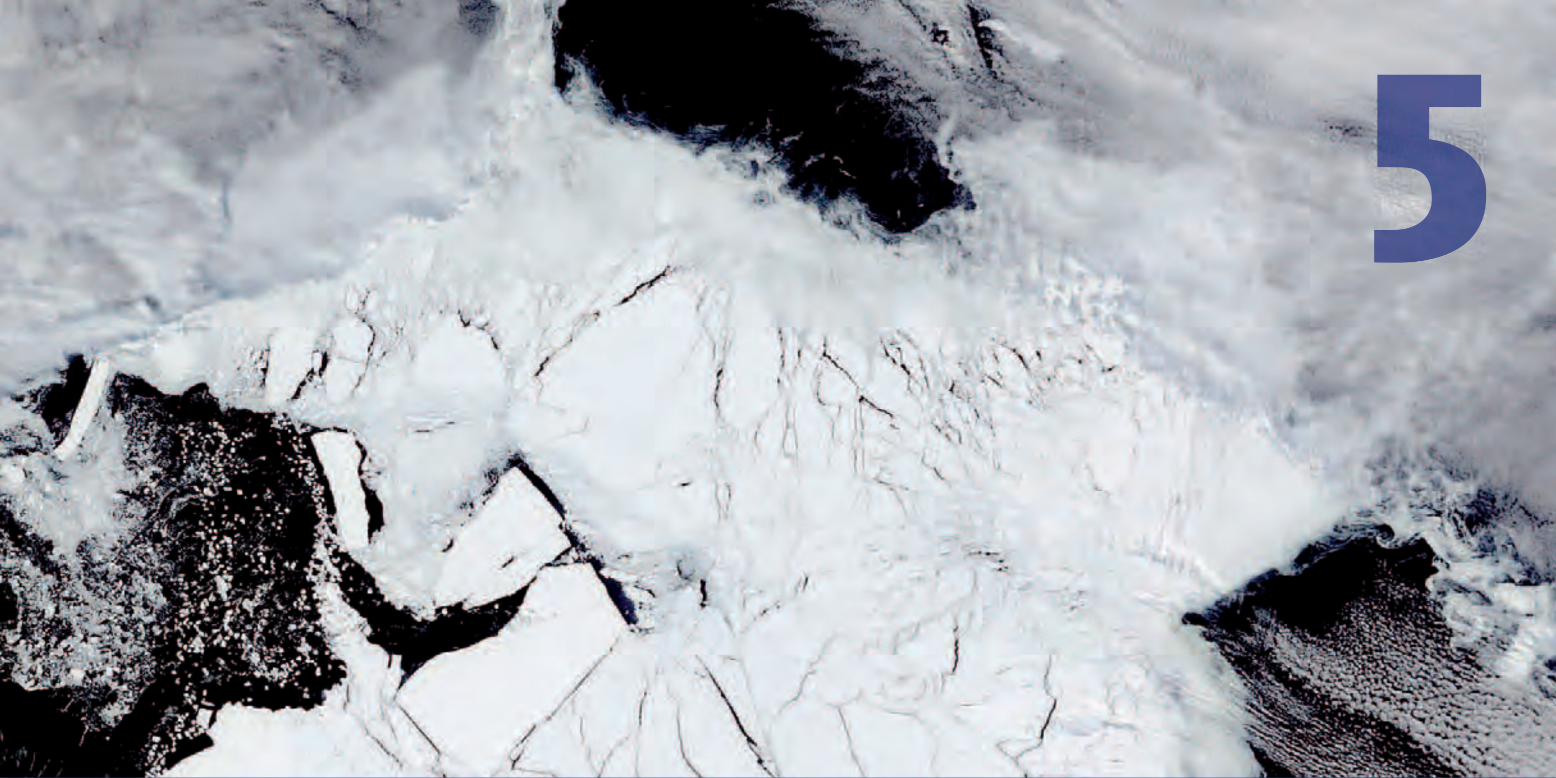

5

Ice in the Sea

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Ice in the Sea


Source: NASA

Summary

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

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

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


Annual maximum sea-ice extent in both hemispheres

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

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

Source: IPCC 2007[1a]

Introduction to sea ice

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

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

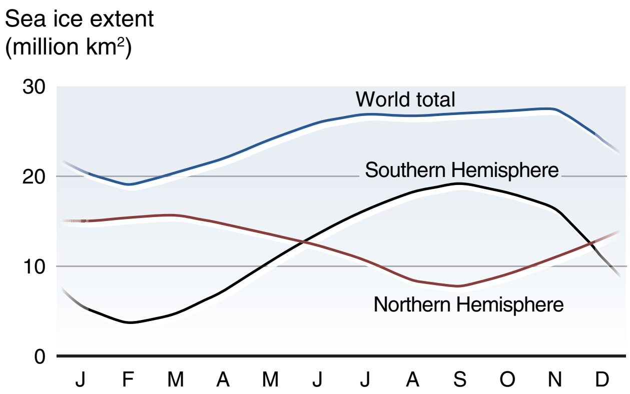


Figure 5.1: Monthly average variations in sea-ice extent in total and in both hemispheres.

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

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

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

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

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

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

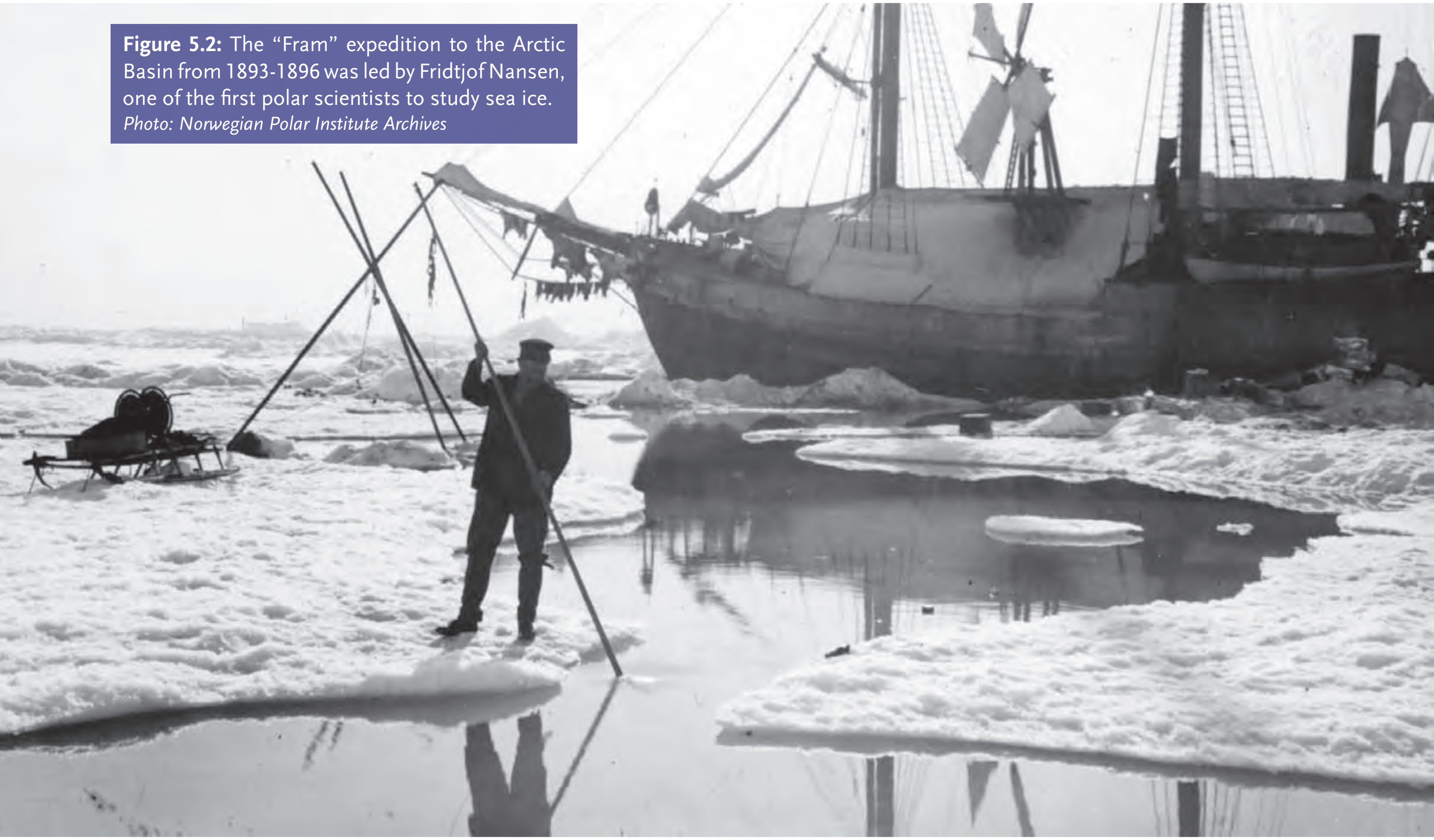


Figure 5.2: The “Fram” expedition to the Arctic Basin from 1893-1896 was led by Fridtjof Nansen, one of the first polar scientists to study sea ice.
Photo: Norwegian Polar Institute Archives

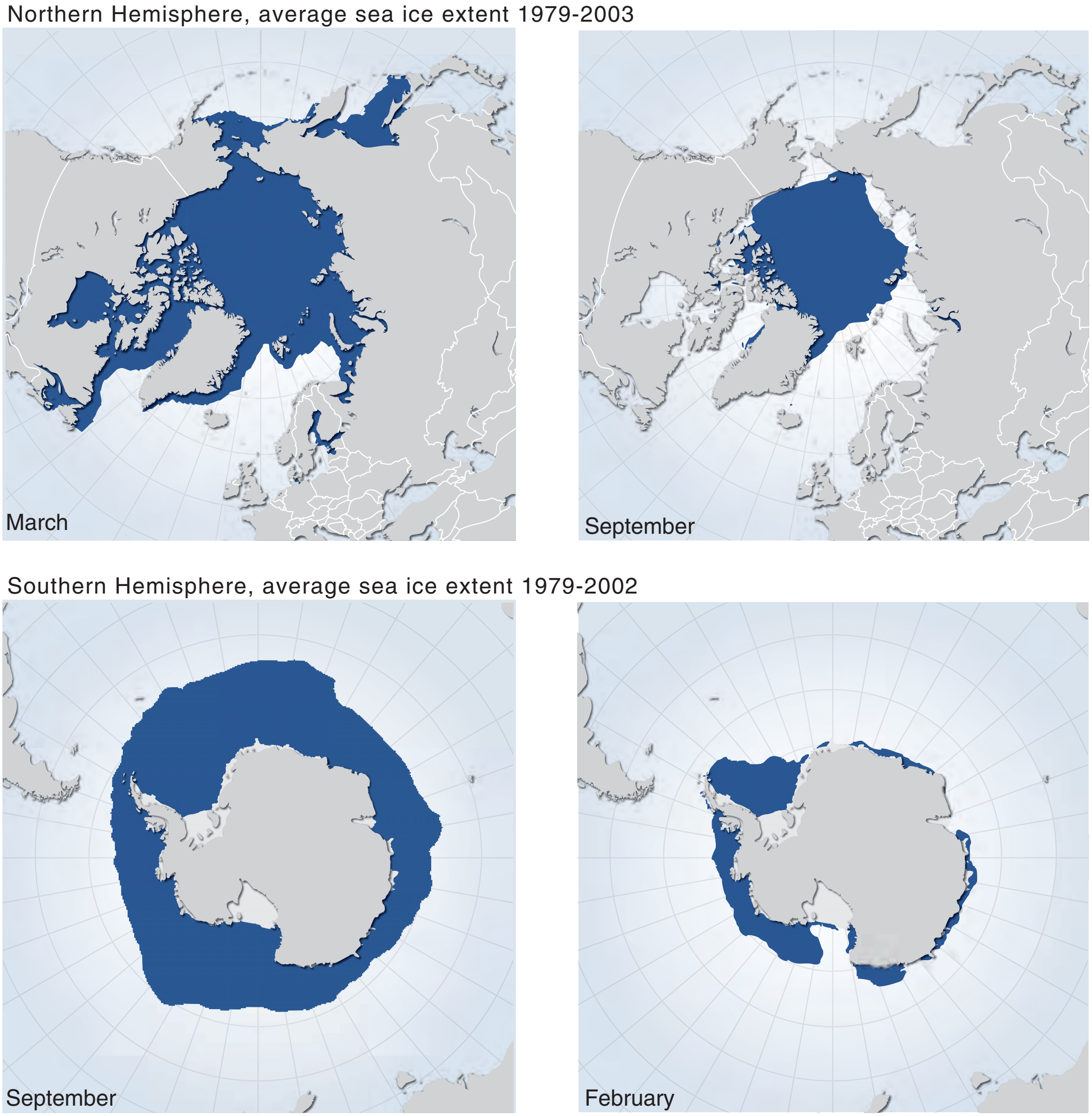


Figure 5.3: Maps of average sea-ice extent in the Arctic summer (September) and winter (March), and in the Antarctic summer (February) and winter (September). They represent average sea-ice extent from 1979 to 2002/2003, based on passive microwave satellite observations. The two polar regions are drawn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

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

Trends in sea ice

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

Northern Hemisphere trends

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

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

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

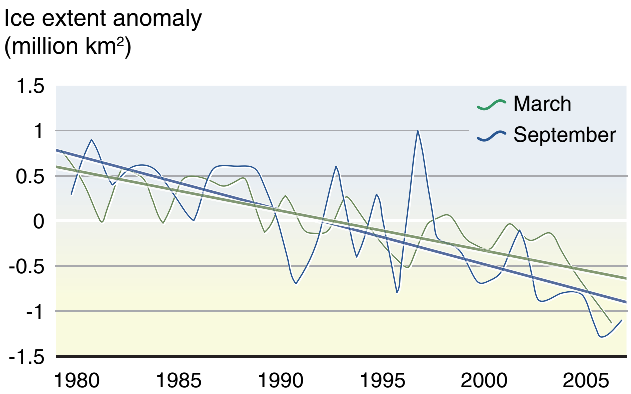


Figure 5.4: Time series of the difference in Arctic sea-ice extent in March (maximum) and September (minimum) from the mean values for the time period 1979–2006. Based on a linear least squares regression, the rate of decrease in March and September was 2.5% per decade and 8.9% per decade, respectively.

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

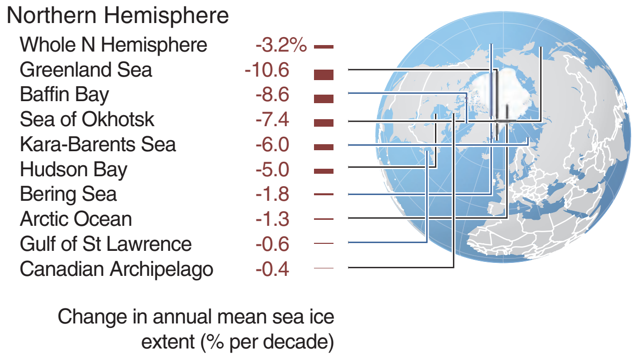


Figure 5.5: Regional changes in Arctic annual mean sea-ice extent (% per decade) for the period 1979–2004.

Source: Data courtesy of NASA 2007a[9] million km² in 1982 and only 5.6 million km² in 2005, a difference of 25 per cent. As has been observed in other recent years, the retreat of the ice cover was particularly pronounced along the Eurasian coast. Indeed, the retreat was so pronounced that at the end of the summer of 2005 the Northern Sea Route across the top of Eurasia was completely ice-free (see section below on shipping and tourism).

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

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

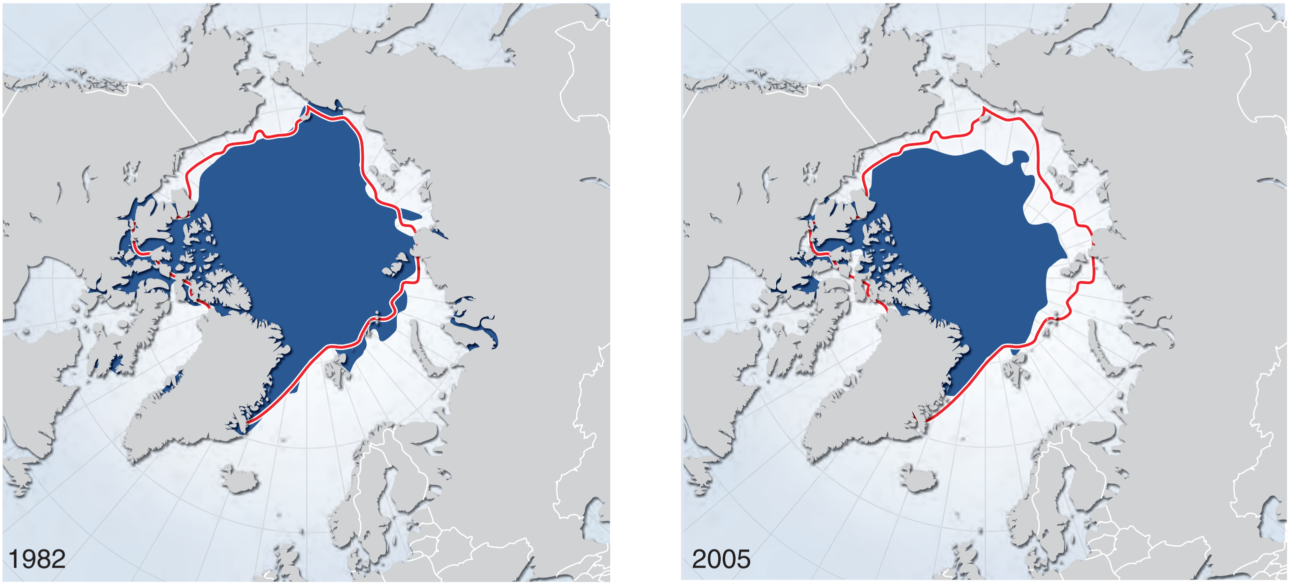
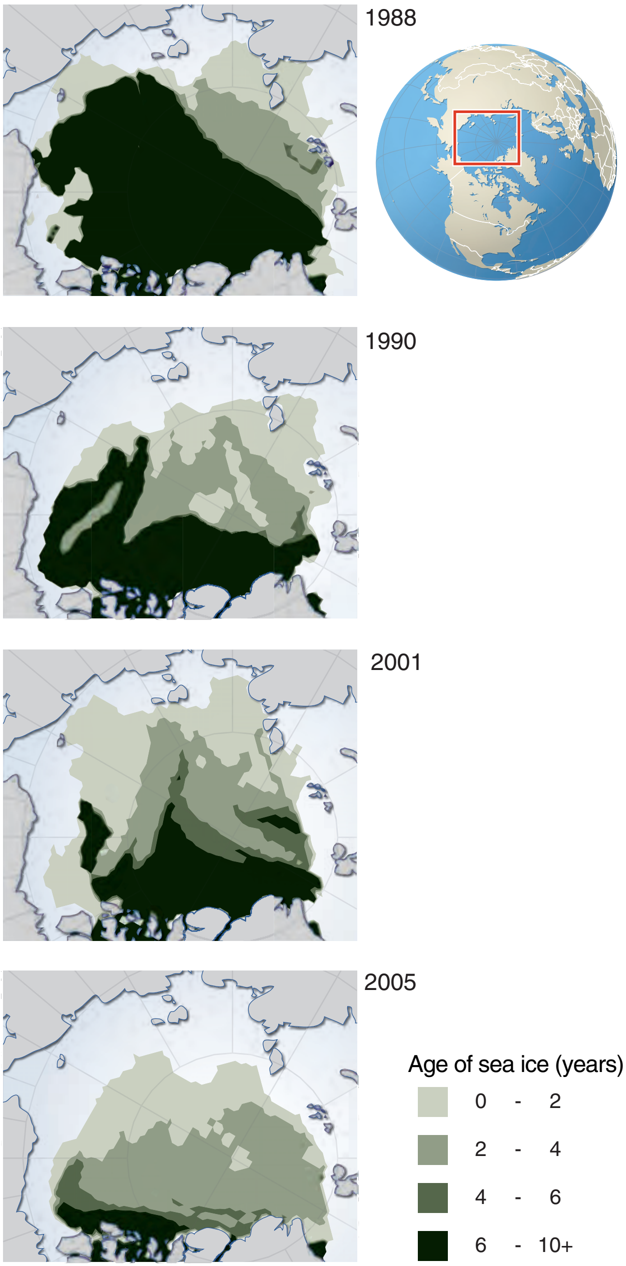


Figure 5.6: Arctic sea ice minimum extent in September 1982 and 2005. The red line indicates the median minimum extent of the ice cover for the period 1979–2000. The September 2005 extent marked a record minimum for the period 1979–2006.

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



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

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

Southern Hemisphere trends

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

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

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

Antarctic sea ice.
Photo: Mlenny/iStockphoto.com

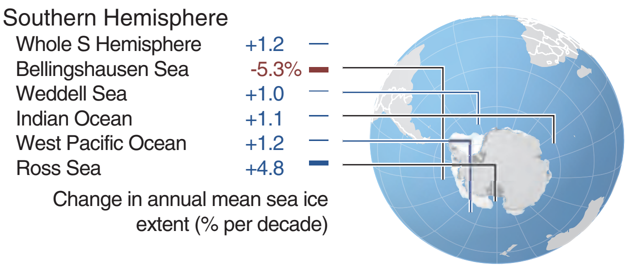


Figure 5.8: Regional changes in Antarctic annual mean sea-ice extent (% per decade) for the period 1979–2004.

Source: Data courtesy of NASA 2007a[9]

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

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

Outlook for sea ice

Northern Hemisphere

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

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

Southern Hemisphere

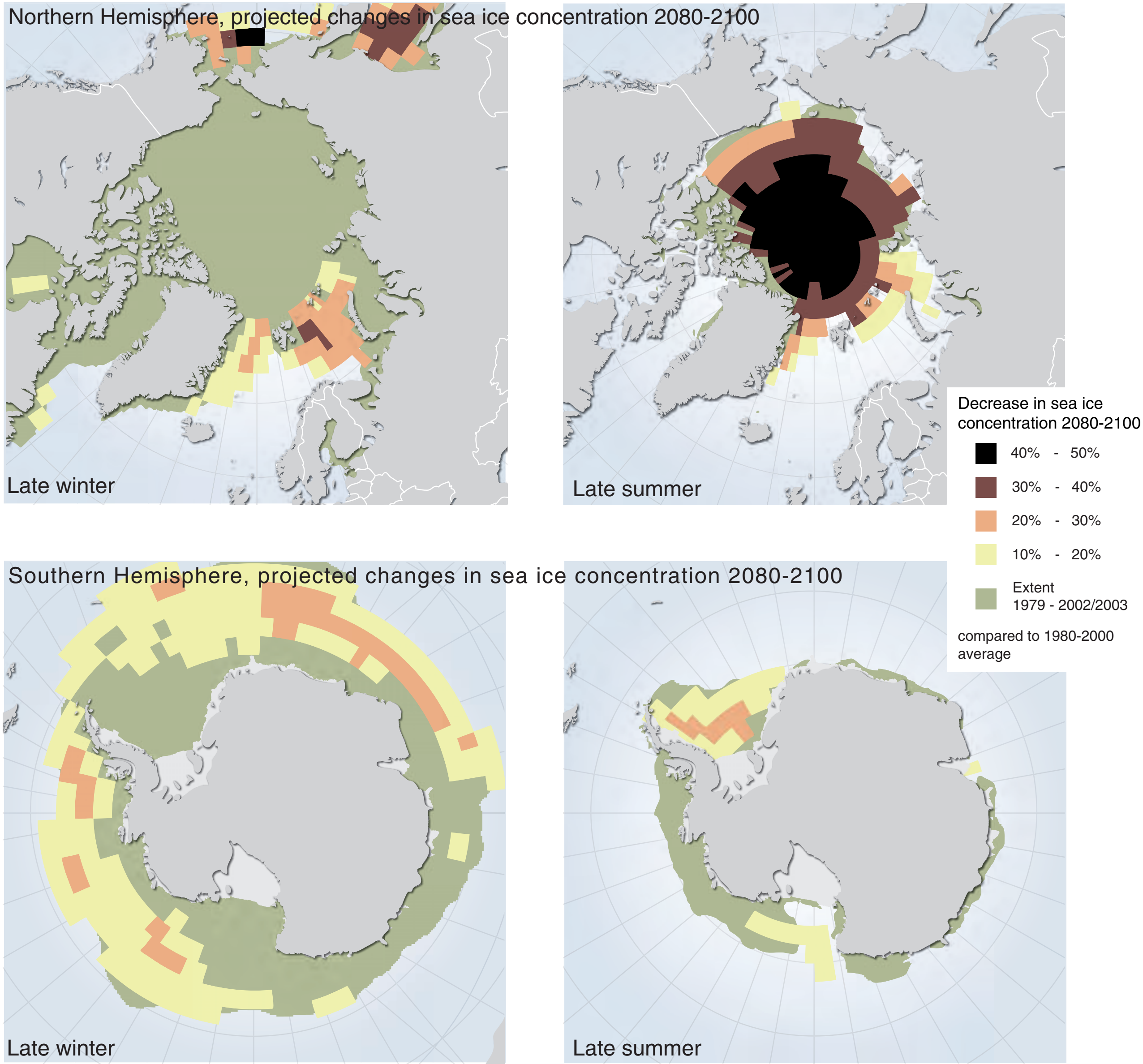
Around Antarctica the projected annual average decrease of sea-ice extent is similar to the Arctic, at around 25 per cent by 2100. Both polar regions show the largest percentage changes in late summer (Figure 5.9 upper and lower right) and an increase in the amplitude of the annual cycle. However, in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

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

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

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

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


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

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

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

Global significance of sea-ice changes

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

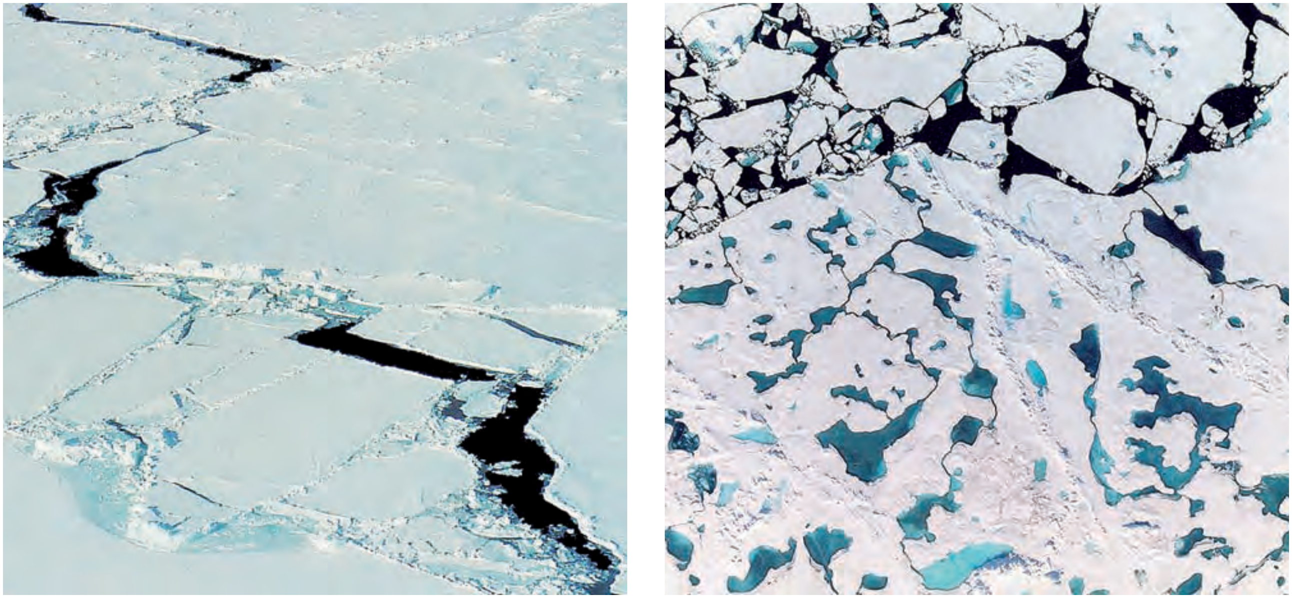


Figure 5.10: Aerial photographs of the Arctic sea-ice cover prior to melt (left) and during the summer melt season (right).
Photos: Don Perovich

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

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

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

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

Impacts of changes in sea ice

Overview

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

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

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

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

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

Sea ice as a dynamic, complex environment

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

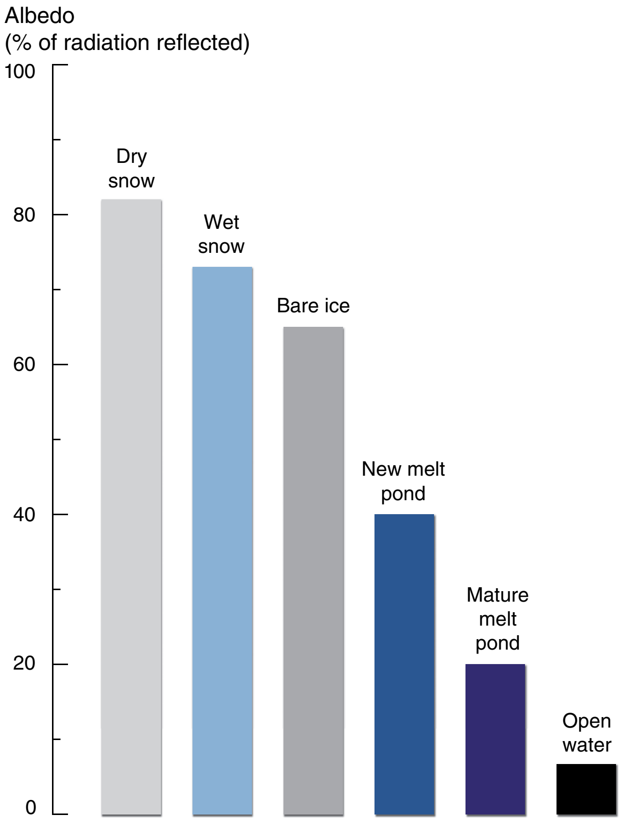


Figure 5.11a: Albedos of basic thick sea-ice surface types.

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

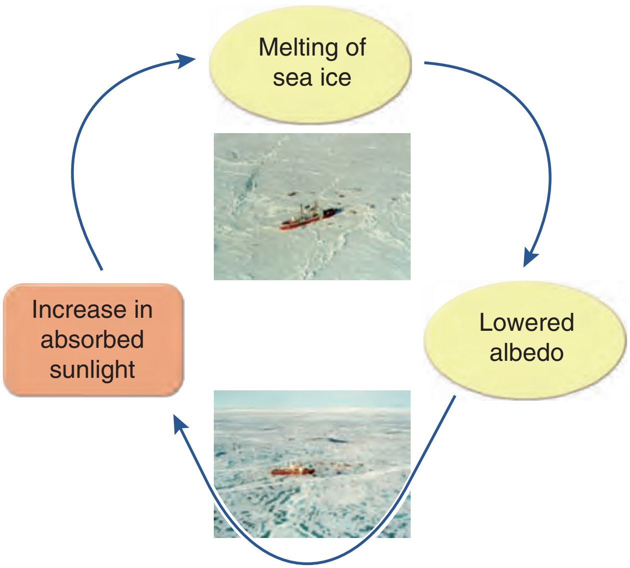


Figure 5.11b: Schematic illustrating the ice–albedo feedback. In spring, the ice is snow-covered and there is very little open water. Most sunlight is reflected, but some is absorbed. This absorbed sunlight leads to melting, which in turn reduces the ice albedo and increases the amount of open water.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

Source: Based on material from D.K. Perovich

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

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

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

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

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

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

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

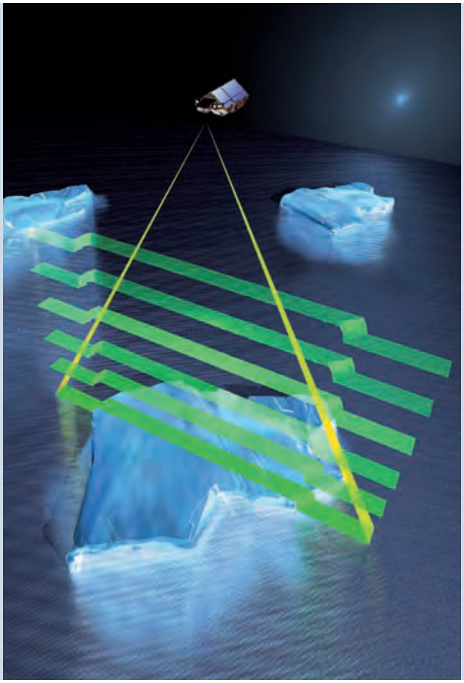


Figure 5.12: CryoSat-2, artist's impression. CryoSat-2, to be launched in 2009, will improve monitoring of ice thickness. Its altimeter measures distances to sea ice and open water and the difference between the two is used to derive ice thickness
Illustration: ESA – AOES Medialab

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

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

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

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

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

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

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

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

Marine biodiversity associated with sea ice and implications for food webs

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

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

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

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

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

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

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

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

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

Ice algae – the primary producers

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

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

Ice fauna – the secondary producers

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

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

Mammals and birds dependent on sea ice

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

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

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

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

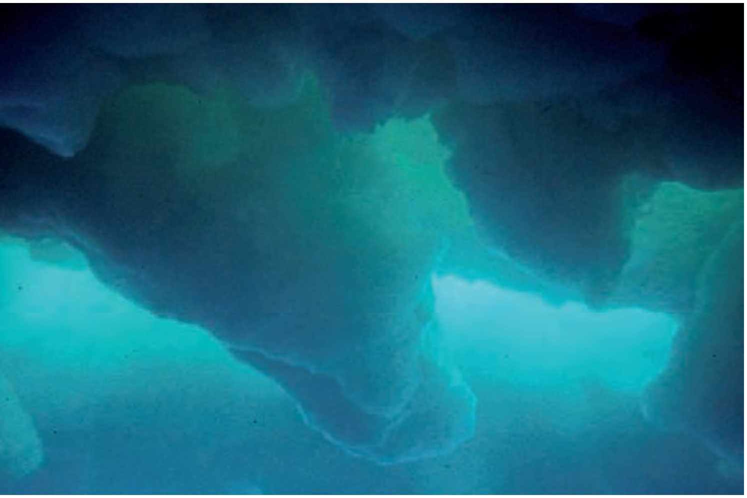


Figure 5.15a: Underside of multi-year sea ice.
Photo: Haakon Hop, Norwegian Polar Institute

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

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

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

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

Seals

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

The “classic” Arctic ice seal in a changing climate

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

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

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

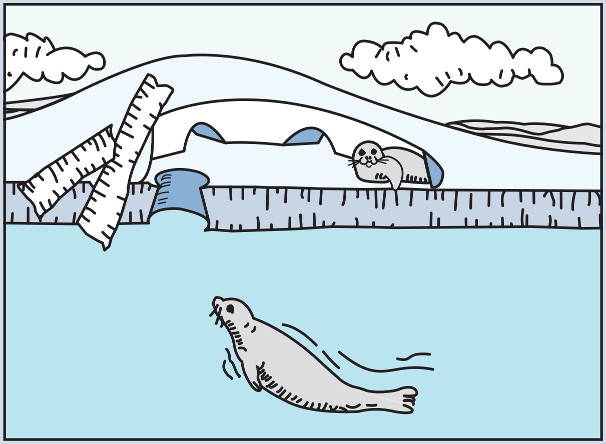


Figure 5.16: Ringed seal pupping lair, with the pup in the lair and the female approaching the haul-out hole from the water. Pups excavate the side tunnels.

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

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

Polar Bears

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

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


Photo: Jon Aars, Norwegian Polar Institute

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

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


Ivory gull.
Photo: Georg Bangjord

Whales

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

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

Seabirds

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


Photo: Bjørn Frantzen

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

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

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

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

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

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

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

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

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

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

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

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

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

Sea ice changes and economic activities

Reductions in sea-ice thickness and coverage in the Arctic will have large potential impacts on the economic activities in the region. Development of the offshore continental shelves and greater use of coastal shipping routes are likely to have significant social, political and economic consequences for all residents of Arctic coastal areas[31].

These consequences will have extended effects outside the Arctic region, as will the possible impacts of sea-ice reduction on exploration and production of oil and gas. Simultaneously, increased activity will contribute to an increased risk of environmental damage, e.g. through oil spills and other industrial accidents[91]. If the projected changes in climate and Arctic economic activities occur, they will present new challenges for trans-national cooperation and jurisdiction, for example with regard to the management of fisheries, pollution, and the establishment of a common policy for emergency response.

Arctic and Antarctic fisheries

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

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

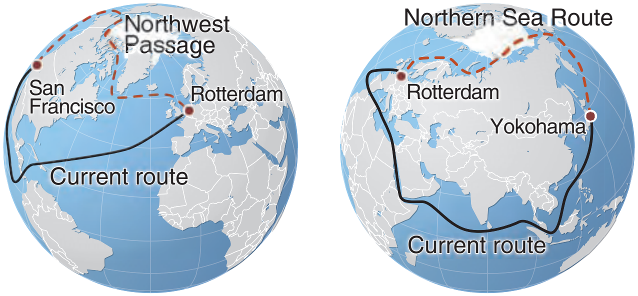


Figure 5.18: The Northern Sea Route and the Northwest Passage compared with currently used shipping routes.

Source: Based on material from Aftenposten, Norway

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

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

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

Arctic oil and gas

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

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

Shipping and tourism

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

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

The Northern Sea Route

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

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

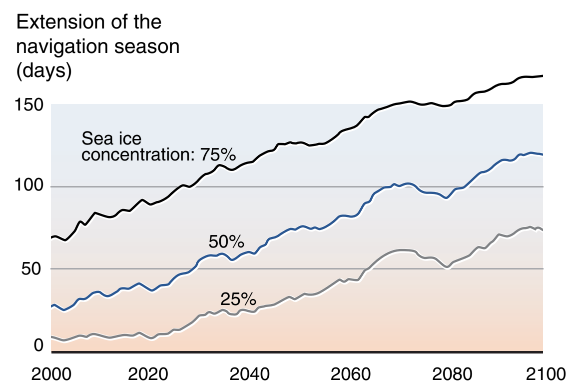


Figure 5.19: Projected increase (days) of the navigation season through the Northern Sea Route as an average of 5 ACIA model projections[91].

Source: Based on ACIA 2004[91]

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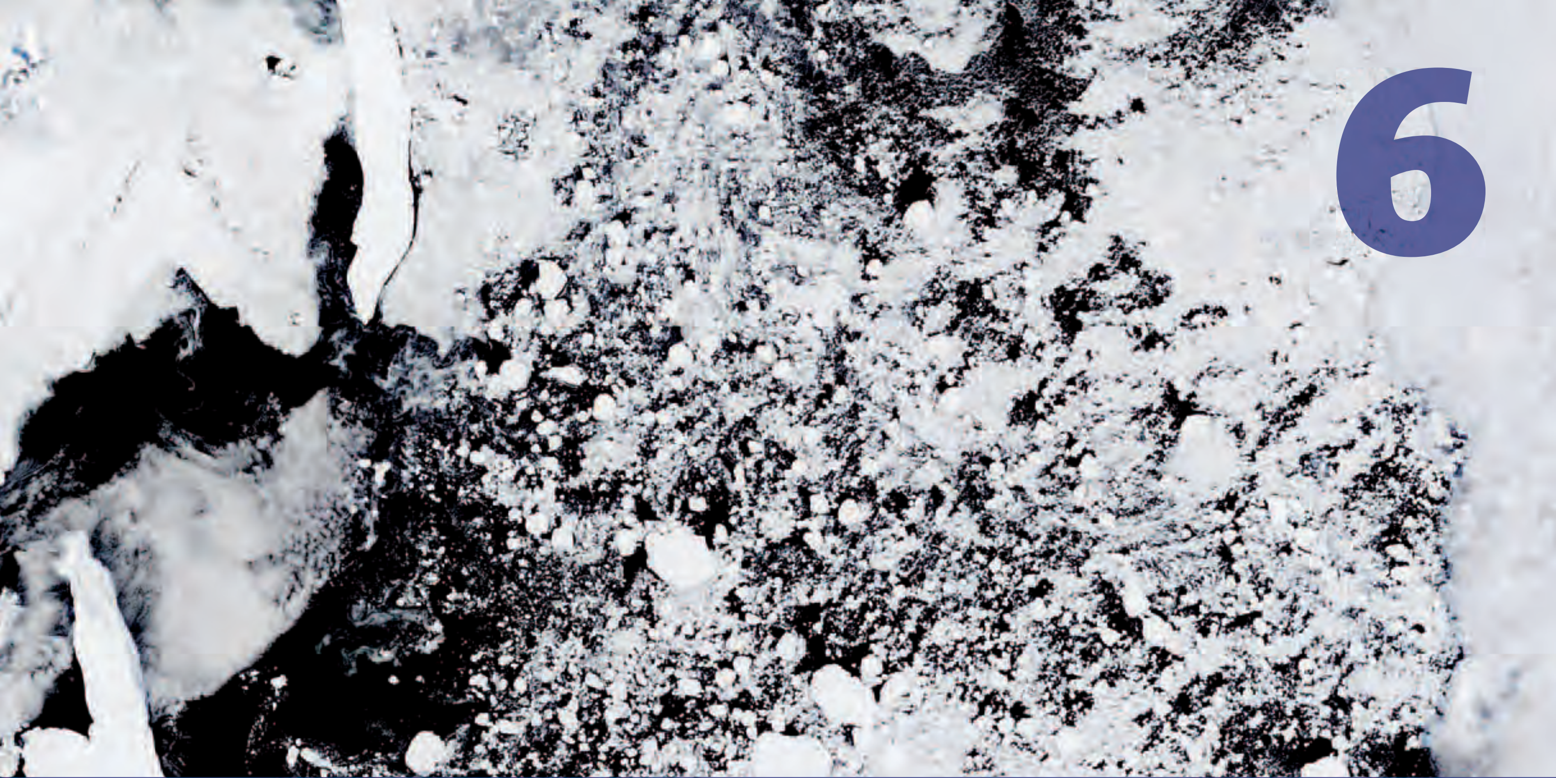


6

Ice on the Land

6A Ice Sheets
6B Glaciers and Ice Caps
6C Ice and Sea-Level Change

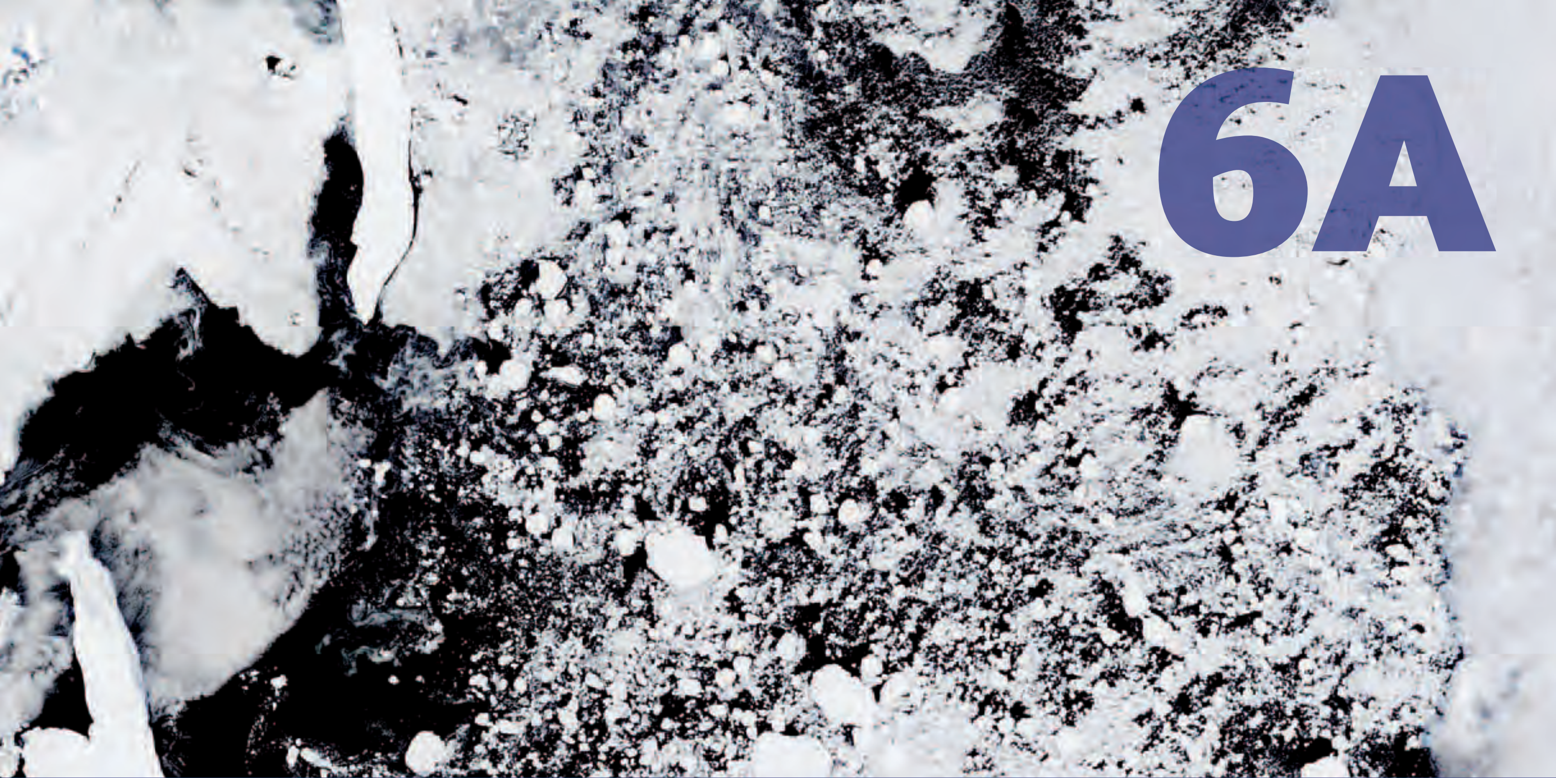
Ice on the Land

This chapter covers ice masses on land: ice sheets; glaciers and ice caps; and the impact on global sea level of the melting of land ice.

6A The two continental ice sheets, Antarctica and Greenland, make up more than half of the total amount of fresh water and around 99 per cent of the freshwater ice on Earth. The sheer size of these gigantic ice masses results in challenges for systematic research and observation. The growth and vanishing of ice sheets relates to global processes and time scales spanning ice ages. As a consequence, the ice sheets contain snowfall from hundreds of thousands of years ago, a unique record of atmospheric and climatic evolution through several ice ages (see inside back cover). Section 6A deals with the characteristics of the two continental-scale ice sheets, observations on recent changes, and the outlook for the future of Earth's ice storehouses.

6B There are glaciers and ice caps in addition to those associated with the Antarctic and Greenland ice sheets, spread all over our planet, from the poles to the tropics. Section 6B presents a global overview of these glaciers, looking at their evolution over time, recent changes, the consequences of these changes, and the outlook for the future of the world's glaciers. The final part of 6B is a world glacier tour, highlighting selected regions, mountain ranges and issues.

6C Continental ice sheets as well as glaciers and ice caps exert a strong influence on sea level, as ice that melts from land directly contributes to the rising sea level. Past changes in global sea level, the current situation of accelerating sea level rise, and the outlook for sea level are covered in 6C. The impacts of sea-level rise are, of course, global in nature. In this section we present information on the types and magnitude of these impacts on vulnerable regions, ecosystems and sectors of society.



6A

Ice Sheets

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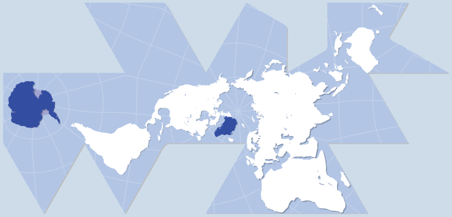
Ice Sheets

Ice sheet: a mass of land ice, continental or sub-continental in extent, and thick enough to cover most of the underlying bedrock topography. Its shape is mainly determined by the dynamics of its outward flow. There are only two ice sheets in the modern world, on Greenland and Antarctica; during glacial periods there were others.



Ice shelf: a thick, floating slab of freshwater ice extending from the coast (originating as land ice). Nearly all ice shelves are in Antarctica.

	Area Covered (million square km)	Ice Volume (million cubic km)	Potential Sea Level Rise (cm)
Ice sheets (total)	**14.0**	**27.6**	**6390**
Greenland	1.7	2.9	730
Antarctica	12.3	24.7	5660
Ice shelves	**1.5**	**0.7**	**0**

Source: IPCC 2007[35]

Summary

The vast polar ice sheets are shrinking as our climate becomes warmer. Floating ice shelves and glacier tongues are thinning and even breaking up in both Greenland and Antarctica, probably because of the combined effects of warming ocean waters and increasing summer air temperatures. Much of this floating ice fills coastal embayments, and is pushed seawards by tributary glaciers, which are observed to accelerate, as much as eightfold, following ice-shelf break-up. At the same time, warmer summers are extending the zone and intensity of summer melting to higher elevations, particularly in Greenland. This increases both meltwater runoff into the ocean and meltwater drainage to the bed, where it lubricates glacier sliding and potentially increases ice discharge into the ocean.

Together these changes have resulted in net losses from both ice sheets at rates that are increasing with time. Corresponding sea-level rise increased from about 0.2 mm per year in the early 1990s to perhaps 0.8 mm per year since 2003, contributing to the total observed rise during the 1990s of approximately 3 mm per year. Some of the thinning glaciers extend many tens to hundreds of kilometres inland, and whether or not ice losses continue to accelerate will depend partly on whether ice shelves continue to thin, and partly on how far inland the zones of glacier acceleration can extend. These questions represent a major challenge to scientists, and their answers could have a profound impact on all of us. Research planned for the International Polar Year in 2007-2008 aims to answer them.

Introduction to the ice sheets

Greenland and Antarctica contain 98–99 per cent of the freshwater ice on Earth's surface. Buried layers of ice, formed from annual snowfall, preserve records of past

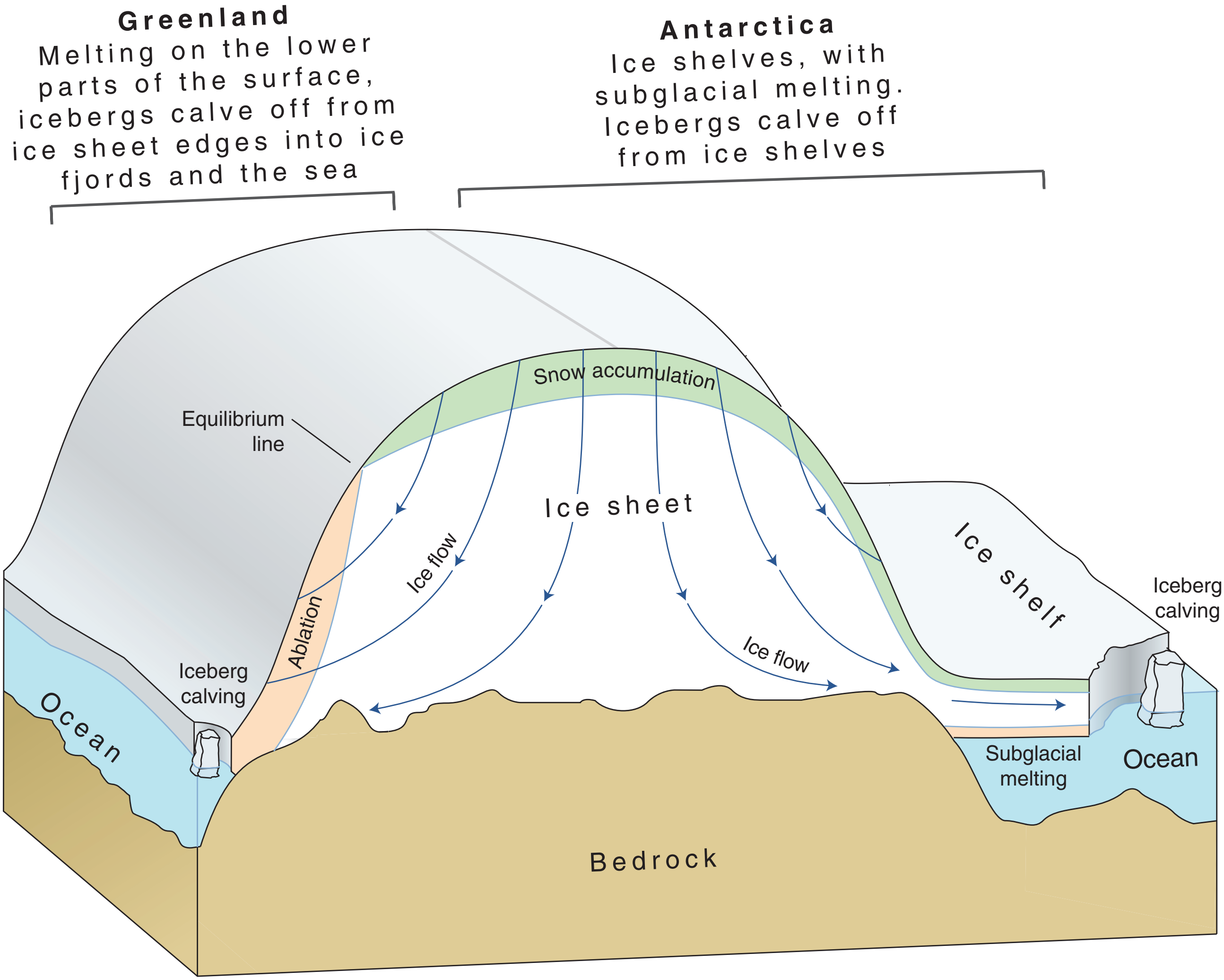


Figure 6A.1: Ice sheets.

Source: based on material provided by K. Steffen, CIRES/Univ. of Colorado

climate and air composition dating back hundreds of millennia. During glacial periods, ice sheets contained more than twice as much ice as that in Greenland and Antarctica today. Sea level would rise by about 64 m if the current mass of ice in Greenland and Antarctica were to melt completely. Although this would take many thousands of years, recent observations show a marked increase in ice-sheet contributions to sea-level rise. In addition, ice-sheet melting strongly influences ocean salinity and temperature, and also global thermohaline circulation as a consequence (see Chapter 2). Since variations in sea surface temperature also influence fluxes of heat and fresh water to the atmosphere, this forms a feedback mechanism – changes to the ocean caused by meltwater from ice sheets directly influence how much snow builds up on the ice sheets themselves. Ice sheets are thus an active and important part of an interconnected climate system.

The ice cover in Greenland and Antarctica has two components (Figure 6A.1) – thick, grounded, inland ice that rests on a more or less solid bed, and thinner floating ice shelves and glacier tongues. An ice sheet is actually a giant glacier, and like most glaciers it is nourished by the continual accumulation of snow on its surface. As successive layers of snow build up, the layers beneath are gradually compressed into solid ice. Snow input is balanced by glacial outflow, so the height of the ice sheet stays approximately constant through time. The ice is driven by gravity to slide and to flow downhill from the highest points of the interior to the coast. There it either melts or is carried away as icebergs which also eventually melt, thus returning the water to the ocean whence it came.

Outflow from the inland ice is organized into a series of drainage basins separated by ice divides that concentrate the flow of ice into either narrow mountain-bounded outlet glaciers or fast-moving ice streams surrounded by slow-moving ice rather than rock walls. In Antarctica much of this flowing ice has reached the coast and has spread over the surface of the ocean to form ice shelves that are floating on the sea but are attached to ice on land. There are ice shelves along more than half of Antarctica's coast, but very few in Greenland.

Antarctica

Antarctic inland ice ranges in thickness up to 5000 m, with an average thickness of about 2400 m, making Antarctica by far the highest of the continents. Straddling the South Pole, Antarctica is cold even during summer. Much of the continent is a cold desert with very low precipitation rates. Thus, in contrast to Greenland, only a tiny proportion of the mass loss from the Antarctic Ice Sheet occurs by melting from the surface – summertime melt from the margins of the ice sheet only occurs in the northern Antarctic Peninsula and the northernmost fringes of East Antarctica. Instead, most ice loss from Antarctica is from basal melting and iceberg calving from the vast floating ice shelves.

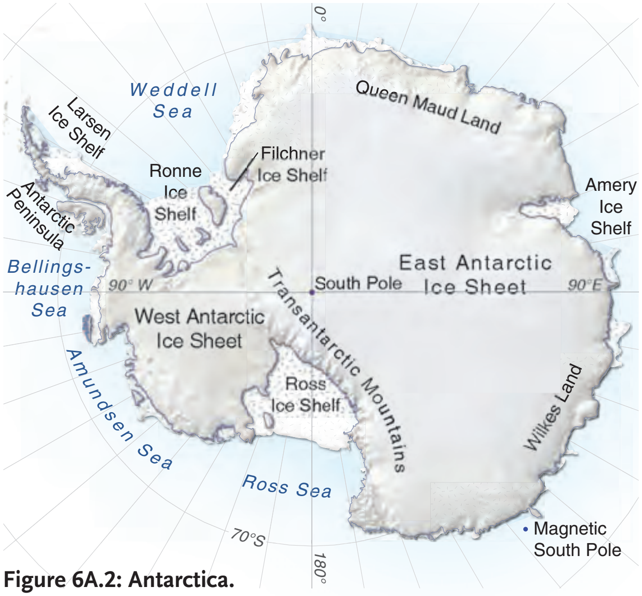


Figure 6A.2: Antarctica.

The West Antarctica Ice Sheet (WAIS) drains mostly into the Ross Ice Shelf, at the head of the Ross Sea; but also into the Filchner/Ronne Ice Shelf (two connected ice shelves), at the head of the Weddell Sea; and into small ice shelves along the Amundsen Sea coast. The Ross and Filchner/Ronne ice shelves are each about the area of Spain (see Figure 6A.2).

Glaciological interest is concentrated particularly on the WAIS because it rests on a bed far below sea level, which may make it particularly vulnerable to accelerated discharge into the ocean. If the entire WAIS were to disappear, sea level would rise by 5 or 6 meters, with major consequences (see Section 6C).

The WAIS was significantly larger during the last glacial maximum, 20 000 years ago, and retreated to near its present extent within the last several thousand years and it is probably still retreating today[1]. Several postglacial mechanisms, notably isostatic uplift (a slow rise in the level of the land) and the penetration of ice-softening warmth into the deeper layers, have long response times. The ice sheet is still reacting dynamically to the glacial-interglacial transition and to the postglacial increase in the rate of snowfall[2]. Consequently, the present Antarctic contribution to sea-level change probably reflects a long-term dynamic response of the ice sheet as well as changes in the atmospheric and oceanic climate over the last century.

Greenland

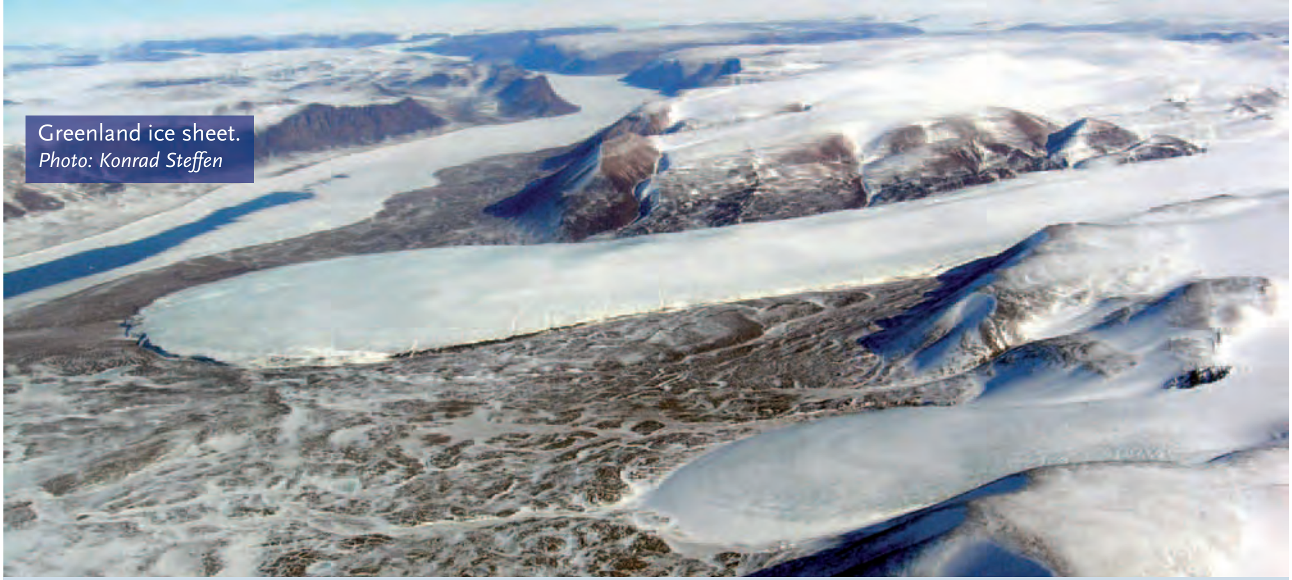
The Greenland Ice Sheet extends from 60º to 80º N, and covers an area of 1.7 million square km. With an average thickness of 1600 m, it has a total volume of about 3 million cubic km (about one ninth of the volume of the Antarctic Ice Sheet) – roughly equivalent to a sea-level rise of 7 m. It comprises a northern dome and a southern dome, with maximum surface elevations of approximately 3200 m and 2850 m respectively, linked by a long saddle with elevations around 2500 m. Bedrock beneath the central part of the ice sheet is remarkably flat and close to sea level, but the ice sheet is fringed almost completely by coastal mountains through which it is drained by many glaciers.

Greenland's climate is strongly affected by its proximity to other land masses and to the North Atlantic, leading to a proportionately higher rate of exchange of water between ice sheet and ocean than in Antarctica. Summer melting occurs over about half of the ice-sheet surface, with much of the meltwater flowing into the sea, either along channels cut into the ice surface or by draining to the bed via crevasses. The average snow accumulation rate is more than double that of Antarctica. There are only a few ice shelves and, where they do exist, basal melting rates are much higher than in Antarctica – they can exceed 10 m per year. This gives an indication of the potential effect warmer Southern Ocean temperatures would have on Antarctic ice shelves.

The Greenland Ice Sheet is particularly important to the study of sea-level change in a warming climate for two reasons. First, it is likely to respond rapidly to warmer temperatures because surface melting already occurs widely. This means that small increases in air temperatures result in large inland migrations of summer melt zones up the gentle slopes of interior parts of the ice sheet. Increasing summer melt reduces ice-sheet volume directly, by drainage into the ocean, and indirectly, by lubricating the base of outlet glaciers and increasing their total ice discharge into the ocean. Second, Greenland provides a picture of Antarctic conditions if climate warms enough to weaken or remove key ice shelves. Recent observations in Antarctica confirm the early predictions of substantial glacier acceleration following ice-shelf removal.

Recent mass balance analyses

Until recently, it was not possible to determine whether the polar ice sheets were growing or shrinking. Over the last decade, improved remote-sensing techniques combined with accurate GPS positioning have made it possible to estimate ice-sheet mass balance (see box on how to tell if an ice sheet is growing or shrinking).



Greenland ice sheet.
Photo: Konrad Steffen

How to tell if an ice sheet is growing or shrinking

The mass balance of an ice sheet, meaning the rate of change of its mass, is vitally important because changes in mass balance are transformed directly into global sea-level change. Measurement is difficult and a range of techniques has to be used to get an overall picture of change in the ice sheets. There are two basic approaches – the integrated approach and the component approach.

The integrated approach involves measuring changes in the surface height (hence volume) or gravitational attraction (hence mass) of the ice sheet using instruments mounted in satellites. These instruments include radar and laser altimeters and high-precision gravity-measuring systems. Laser altimeters can detect small surface elevation changes, but are hampered by persistent cloud cover. Satellite surveys began only in 2003. Aircraft laser measurements over Greenland began ten years earlier and, although they provide only limited coverage, flight lines can be along specified routes such as glacier flow lines. Radar altimeters have less precision, suffer errors associated with radar penetration into the ice sheet surface, and give poor results in rough or steep terrain, but their longer history is still a boon for measurements of change. The gravity-based techniques can measure changes in overall mass to an astonishing level of precision, but the accuracy of ice-sheet mass balance estimates is hampered by limited knowledge of how much mass change is caused by uplift of the rock beneath by geologic forces.

The component approach involves comparing the mass added by snowfall on the ice sheet to that lost into the surrounding ocean. Mass input is based on estimates of snow-accumulation rates from counting annual layers in snow pits and ice cores, measuring depths to well-dated radioactive fallout horizons, or weather-model simulations. Newer remote sensing methods are promising but not yet fully developed. Mass output by meltwater runoff is generally estimated from models; to that must be added the solid-ice flux, given by the product of ice flow velocity and thickness at coastal margins. Ice thickness is generally measured by radar sounding from airplanes, and ice velocity is measured by repeated GPS surveys of ice markers, tracking of crevasses and other ice features in high-resolution satellite imagery, and analysis of repeated satellite radar images. This last technique, in particular, has made it possible to measure the speed of ice movement over vast regions at high spatial resolution.

All these techniques for measuring mass balance have significant errors but because they offer independent estimates, they provide an increased level of confidence in their collective conclusions. However, interpretation of mass-balance estimates is further complicated by high natural variability that occurs on a range of time scales. Separation of long-term trends in ice mass from the effects of this variability requires observations over long time periods.

Antarctica (see Figure 6A.3)

Measurements by satellite techniques based on gravity indicate mass loss at a rate of 138 ± 73 billion tonnes per year during 2002–2005, mostly from the WAIS[6]. That is equivalent to a rise in global sea level of 0.4 ± 0.2 mm per year, or 10–30% of the global rate measured since the 1950s (see Chapter 6C), and is in good agreement with recent mass-budget estimates[10]. However, two interpretations of satellite radar altimetry pointed to a much smaller loss of about 31 billion tonnes of ice per year[8] or a net gain of about 27 billion tonnes per year[9]. The difference between these estimates from totally independent techniques reflects the uncertainties in these difficult measurements; nevertheless, on balance, they indicate a recent shift to a net loss of Antarctic ice and suggest that losses may be accelerating. Similar conclusions result from studies of Antarctic Peninsula glaciers, indicating that they are melting much faster than previously predicted and are probably already contributing significantly to sea-level rise[11].

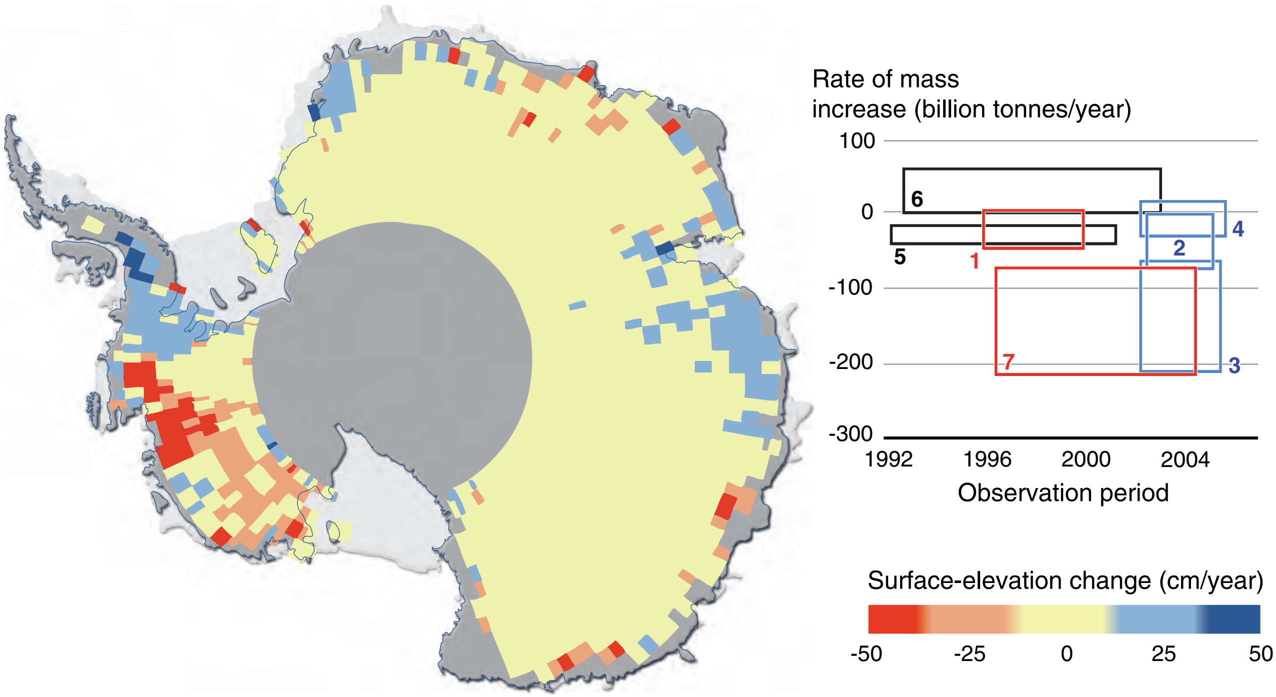


Figure 6A.3: Antarctica, showing rates of surface-elevation change derived from satellite radar-altimeter measurements[3]. The graph shows rates at which the ice-sheet mass was estimated to be changing based on radar-altimeter data (black), mass-budget calculations (red), and satellite gravity measurements (blue). Rectangles depict the time periods of observations (horizontal) and the upper and lower estimates of mass balance (vertical).

Sources (corresponding to numbers on rectangles): 1 Rignot and Thomas 2002[4]; 2 Ramillien and others 2006[5]; 3 Velicogna and Wahr 2006a[6]; 4 Chen and others 2006a[7]; 5 Zwally and others 2005[8]; 6 Wingham and others 2006a[9]; 7 Rignot and others 2007[10]

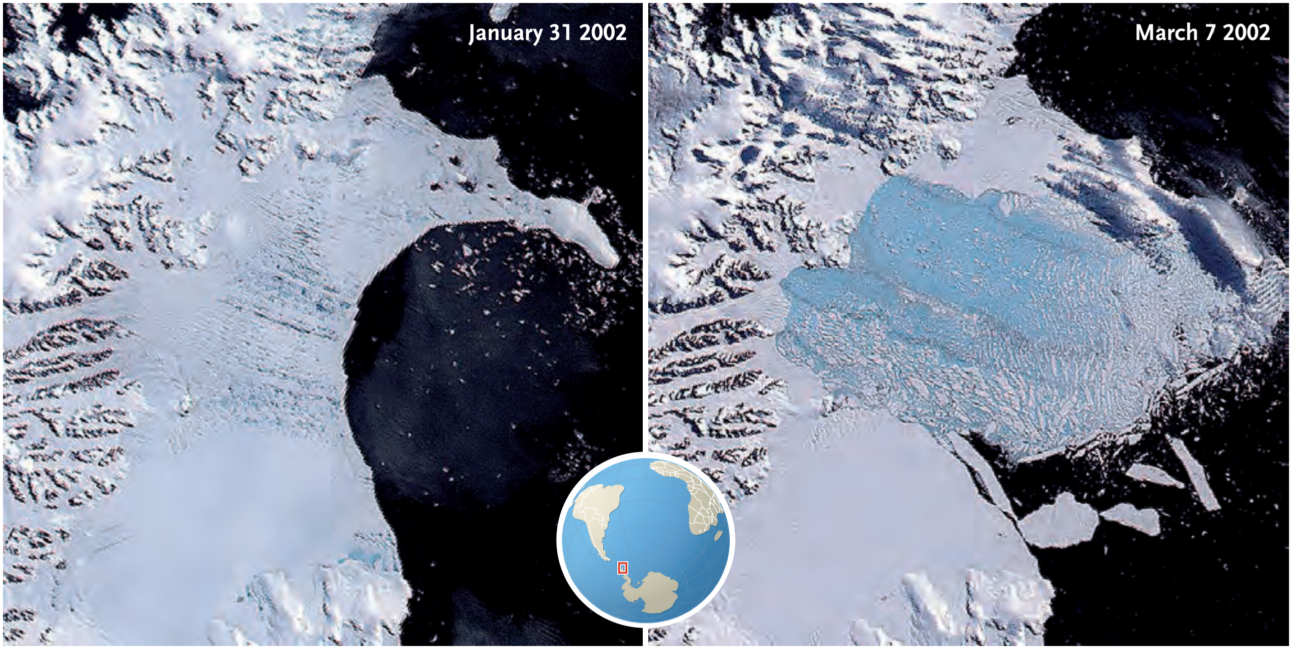


Figure 6A.4: Break-up of the Larsen B ice shelf. These are images from NASA's MODIS satellite sensor. Part of the Antarctic Peninsula is on the left. The image on the left shows the shelf in late summer, with dark bluish melt ponds on the surface. The image on the right, collected only five weeks later, shows a large part of the ice shelf collapsed, with thousands of sliver icebergs at the margins and a large blue area of ice fragments.

Images: National Snow and Ice Data Center

The questionable stability of Antarctic ice shelves in a warming climate was highlighted by the collapse of the Larsen B Ice Shelf in 2002 off the northern Antarctic Peninsula (Figure 6A.4). The significance of this event was highlighted by records from six marine sediment cores in the vicinity showing that this scale of collapse is unprecedented since the end of the last ice age. Research implies that the long-term thinning of the ice shelf has combined with the modern half-century-long warming in the Antarctic Peninsula region to cause its disintegration[12]. Moreover, nine other small ice shelves around the Antarctic Peninsula have broken up over the last 100 years.

The Larsen B collapse prompted researchers to look at the implications of ice-shelf decay for the stability of Antarctica's inland ice. Glaciers that fed the former ice shelf have speeded up by factors of two to eight following the collapse[13]. In contrast, glaciers further south did not accelerate as they are still blocked by an ice shelf. The large magnitude of the glacier changes illustrates the important influence of ice shelves on ice sheet mass balance.

Much further south, in the Amundsen Sea sector of West Antarctica, satellite radar measurements show that ice shelves have thinned by up to 5.5 meters per year over the past decade[14]. The thinning of the ice shelves, apparently from ocean currents that are on average 0.5°C warmer than freezing, is mirrored by the thinning and acceleration of their tributary glaciers[15,16]. These accelerating glaciers drain a region widely believed to be the most vulnerable portion of the WAIS because its bed is so deep below sea level. Collapse of the entire region into the sea would raise sea level by about 1 m.

Elsewhere, recent detailed high-resolution satellite imagery charted the simultaneous rise and compensating fall of a score of patches on the Antarctic Ice Sheet, reflecting extensive water movement under the ice and pointing to the potentially destabilizing effect of subglacial water[17–19]. Although the volumes of water are tiny in terms of sea-level change, the observations reveal a widespread, dynamic subglacial water system, which may exert an important control on ice flow, and hence on the mass balance of the entire ice sheet.

Greenland (see Figure 6A.5)

Mass-balance estimates for Greenland show thickening at high elevations since the early 1990s at rates that increased to about 4 cm per year after 2000, consistent with expectations of increasing snowfall in a warming climate. However, this mass gain is far exceeded by losses associated with large increases in thinning of the ice sheet near the coast.

Total loss from the ice sheet more than doubled, from a few tens of billions of tonnes per year in the early 1990s[20], to about 100 billion tonnes per year after 2000[27], with perhaps a further doubling by 2005[24]. These rapidly increasing losses result partly from more melting during warmer summers, and partly from increased discharge of ice from outlet glaciers into the ocean[22]. In particular, the speeds of three of Greenland's fastest glaciers approximately doubled since 2000[28,29], although two of them have partially slowed since[30]. The third glacier, Jakobshavn Isbrae (Figure 6A.6), increased its speed to about 14 km per year[28] after rapid thinning and break up of its floating ice tongue[31], without any signs of slowing down. The bed is very deep for several tens of kilometres inland, allowing seaward parts of the glacier to float and break up as the ice thins. By contrast, nearby glaciers with shallow beds have only small thinning rates, indicating a strong linkage between bed topography and glacier vulnerability to change.

In addition, marked increases in ice velocity occurring soon after periods of heavy surface melting suggest that meltwater draining to the base of the ice lubricates glacier sliding[32] (Figure 6A.7). This indicates that increased melting in a warmer climate could cause an almost simultaneous increase in ice-discharge rates.

Outlook for the ice sheets

For many reasons, it is not possible now to predict the future of the ice sheets, in either the short or long term, with any confidence[33]. Modeling ice sheet dynamic behaviour is seriously hampered by a paucity of observational data about the crucial, controlling conditions at the ice-sheet bed[2,34]. It is because of these uncertainties that the projections of the IPCC 4th Assessment Report, while including contributions from Greenland and Antarctica at the increased rates observed for 1993–2003, state that "larger values cannot be excluded, but understanding of these effects is too limited to assess their likelihood or provide a best estimate or an upper bound for sea level rise"[35].

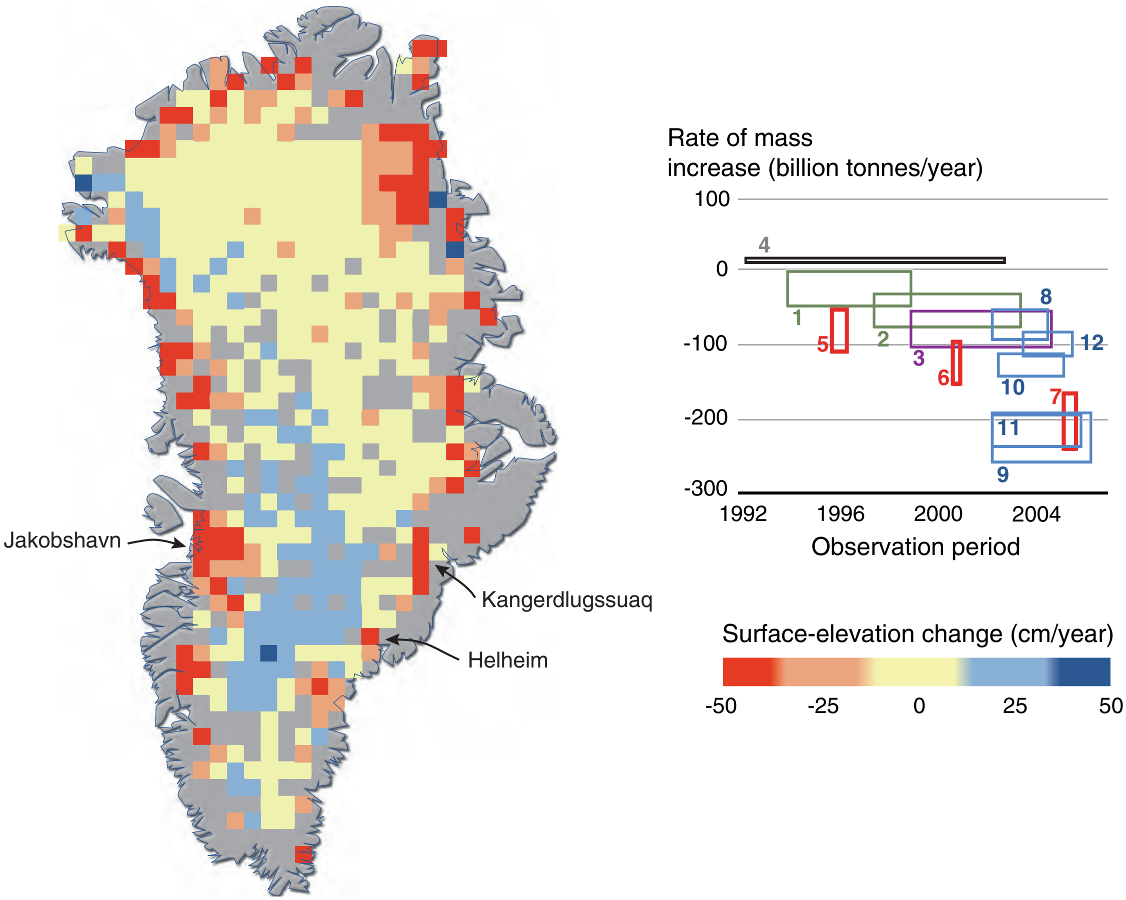
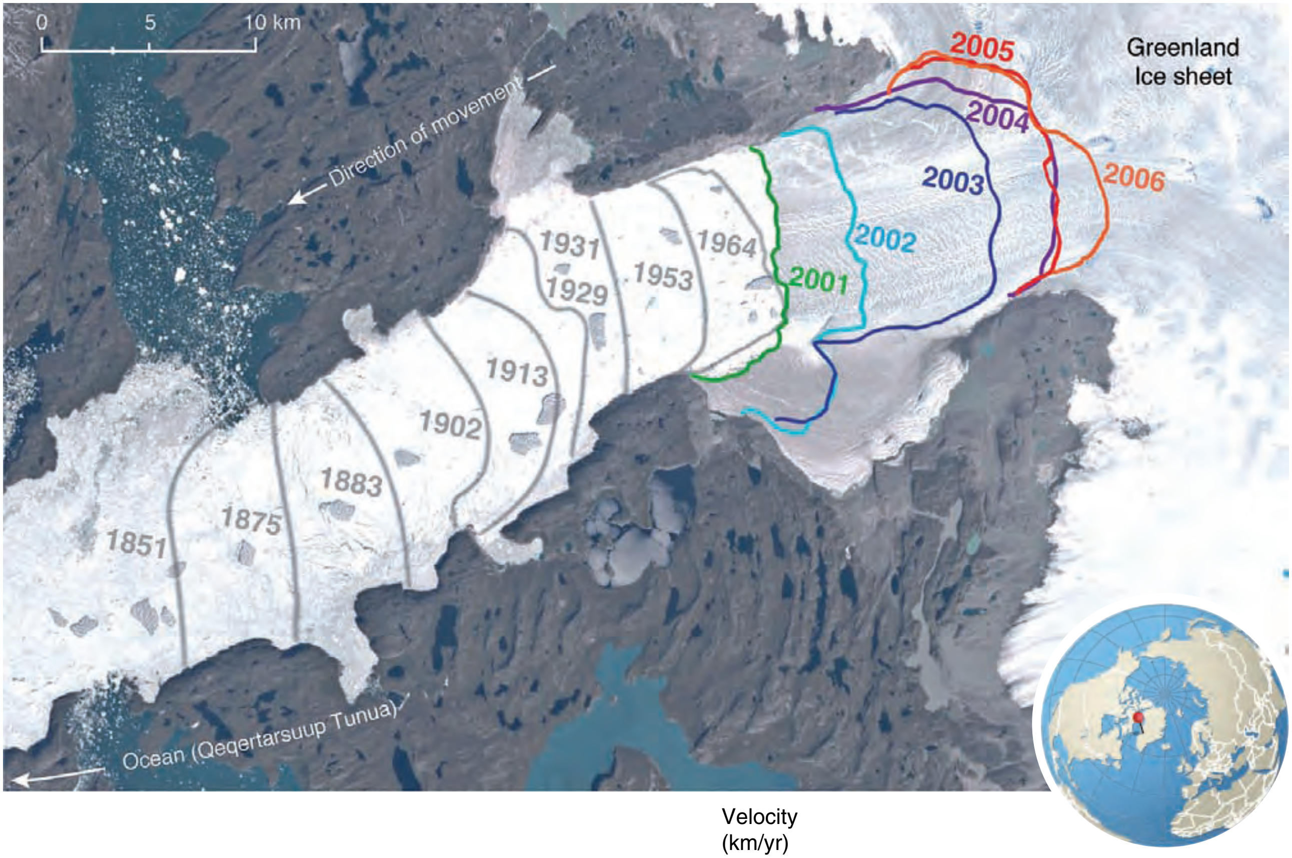


Figure 6A.5: Greenland, showing rates of surface-elevation change between the late 1990s and 2003, derived by comparing satellite and aircraft laser-altimeter surveys. The graph shows rates at which the ice-sheet mass was estimated to be changing based on satellite radar-altimeter surveys (black), airborne laser-altimeter surveys (green), airborne/satellite laser-altimeter surveys (purple), mass-budget calculations (red), temporal changes in gravity (blue). Rectangles depict the time periods of observations (horizontal) and the upper and lower estimates of mass balance (vertical). Jakobshavn, Helheim, and Kangerdlugssuaq are fast glaciers that doubled in speed recently.

Sources (corresponding to numbers on rectangles): 1 and 2 Krabill and others 2000[20] and 2004[21]; 3 Thomas and others 2006[27]; 4 Zwally and others 2005[8]; 5 to 7 Rignot and Kanagaratnam 2006[22]; 8 and 9 Velicogna and Wahr 2005[23] and 2006A[24]; 11 Chen and others 2006A[25]; 10 Ramillien and others 2006[5]; 12 Luthke and others 2006[26]



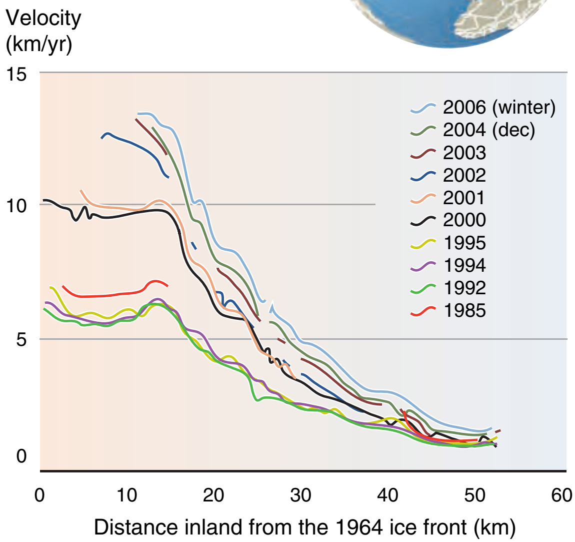


Figure 6A.6: Landsat satellite image of Jakobshavn Isbrae and its fjord, showing locations of the calving ice front in years from 1851 to 2006. The glacier extends through the Illulisat Icefjord, surrounded by mountains. Icebergs calve off from the main glacier, pile up and block the fjord before being released into Qeqertarsuup Tunua (Disko) Bay and Davis Strait. The whiter areas in the fjord are piled-up icebergs and the "real" glacier ends where the greyish striped section ends – showing that this image is from 2001.

The graph shows glacier-velocity profiles for 1985 to 2006. During this period Jakobshavn Isbrae, already the world's fastest glacier, doubled its speed to almost 14 km per year[28,29] after rapid thinning and break up of its floating ice tongue[31].

Sources: NASA/Goddard Space Flight Center Scientific Visualization Studio. Historic calving front locations courtesy of Anker Weidick and Ole Bennike
Source: based on Howatt and others 2007[30]

Figure 6A.7: Surface melting on the Greenland Ice Sheet drains down to the base of the ice sheet and lubricates its flow over the bed rock. *Photo: Roger Braithwaite/Still Pictures*

Recent signs point to accelerating loss of ice in both Greenland and Antarctica. It is becoming increasingly apparent that some changes, such as the break up of ice shelves in Antarctica, are exceptional when one looks over periods of centuries to millennia. For the ice sheets of both polar regions, some of these very fast changes are caused not by melting (included in the IPCC predictions), but by changes in glacier dynamics (not fully included in the IPCC predictions).

The slow, measured behaviour long associated with the Greenland Ice Sheet is being transformed to the rapidly changing characteristics more typical of big glaciers in Alaska and Patagonia. A zone of glacier acceleration is progressively moving northward, leaving Greenland's southern ice dome under threat from both increased summer melting near the coasts, and increased ice discharge down glaciers that extend their influence far inland. If this continues, it is quite possible that the ice dome in southern Greenland will reach a tipping point, with accelerating positive feedback causing its ever more rapid decline and an associated sea-level rise of about 85 cm. Moreover, continued northward migration of the zone of glacier acceleration would make the far larger northern dome also vulnerable.

In Antarctica, disintegration of the WAIS continues to be the primary threat. The key issue is whether the main body of the WAIS would accelerate rapidly if its ice shelves were thinned or removed by a warming climate[36,37]. There are clues. Ice-shelf break up along the Antarctic Peninsula has resulted in massive acceleration of tributary glaciers and ice-shelf thinning further south, along the Amundsen Sea, also appears to have caused glacier acceleration. Here, the acceleration is more modest, but the glaciers are far bigger, so total losses are large. No one knows how far inland the zone of glacier acceleration will spread, and no one knows why the ice shelves are breaking up. However, their thinning is almost certainly caused by increased basal melting, implicating the ocean. And final break up seems to be accelerated if there is sufficient surface meltwater to fill, and over-deepen, crevasses in the ice shelves, effectively wedging the ice shelf apart into fragments.

Observations made over the past five years have made it clear that existing ice-sheet models cannot simulate the widespread rapid glacier thinning that is occurring, and ocean models cannot simulate the changes in the ocean that are probably causing some of the dynamic ice thinning. Consequently, in its Fourth Assessment, the IPCC has taken a conservative approach by not attempting to predict the unpredictable. As a result, these projections[35] of future ice-sheet related rises in sea level should be regarded as lower bounds.

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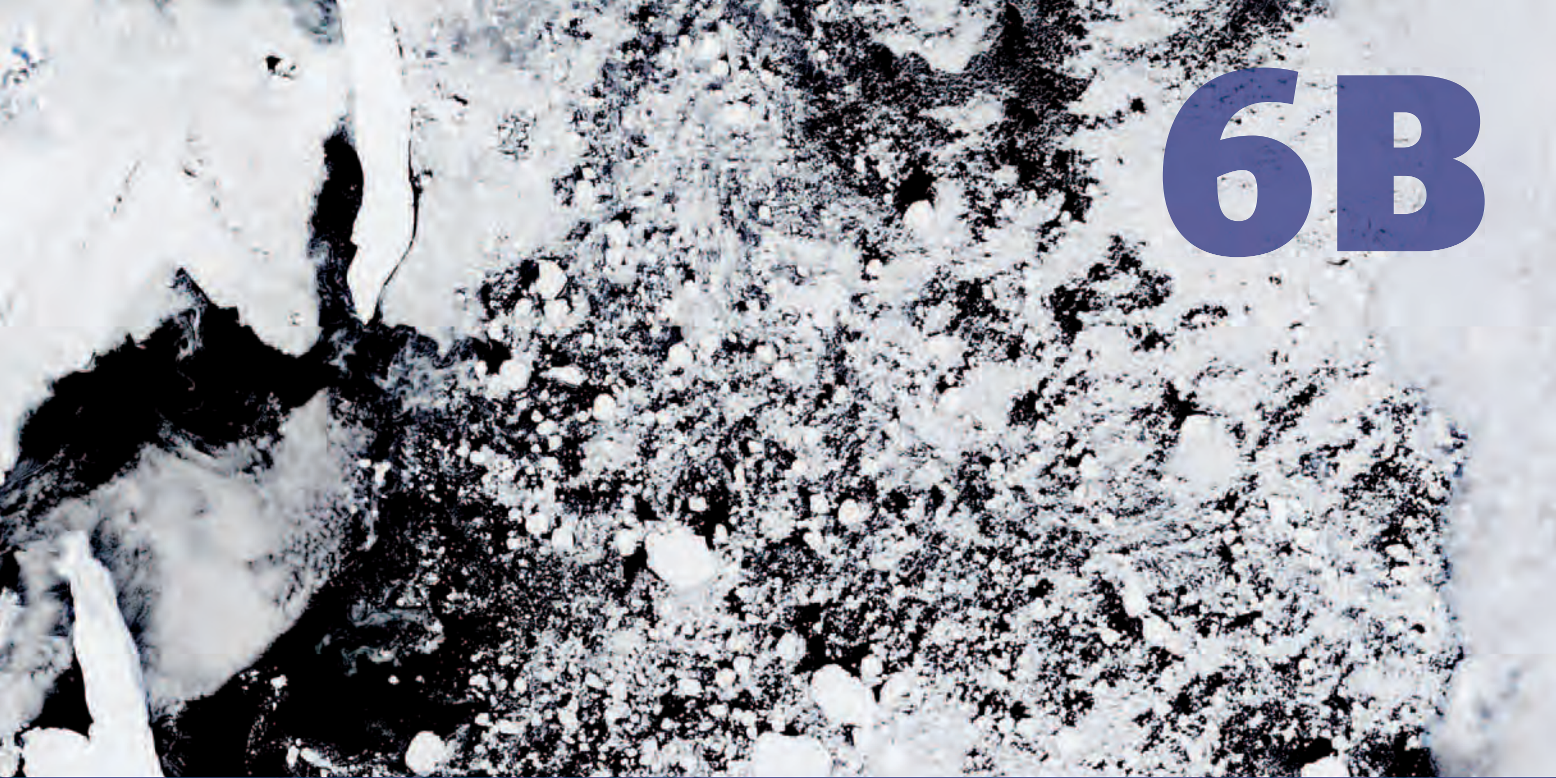

6B

Glaciers and Ice Caps

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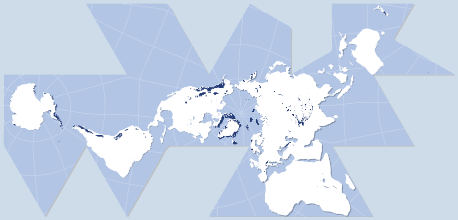
Glaciers and Ice Caps

Summary

Glaciers and ice caps are among the most fascinating elements of nature, an important freshwater resource but also a potential cause of serious natural hazards. Because they are close to the melting point and react strongly to climate change, glaciers are important indicators of global climate.

Glaciers reached their Holocene (the past 10 000 years) maximum extent towards the end of the Little Ice Age (the Little Ice Age extended from the early 14th to mid-19th century.) Since then, glaciers around the globe have been shrinking dramatically, with increasing rates of ice loss since the mid-1980s. On a time-scale of decades, glaciers in various mountain ranges have shown intermittent re-advances. However, under the present climate scenarios, the ongoing trend of worldwide and fast, if not accelerating, glacier shrinkage on the century time-scale is not a periodic change and may lead to the deglaciation of many mountain regions by the end of the 21st century.



Glacier: a mass of surface-ice on land which flows downhill under gravity and is constrained by internal stress and friction at the base and sides. In general, a glacier is formed and maintained by accumulation of snow at high altitudes, balanced by melting at low altitudes or discharge into the sea.
Ice cap: dome-shaped glacier with radial flow, usually covering a highland area. Much smaller than an ice sheet.

Glaciers and ice caps (lowest and [highest] estimates):

Area Covered (million square km)	0.51 [0.54]
Ice Volume (million cubic km)	0.05 [0.13]
Potential Sea Level Rise (cm)	15 [37]

Source: IPCC 2007[1]

Glacial retreat and melting of permafrost will shift cryospheric hazard zones. This, in combination with the increasing socio-economic development in mountain regions, will most probably lead to hazard conditions beyond historical precedence. Changes in glaciers may strongly affect the seasonal availability of freshwater, especially when the reduction of glacier runoff occurs in combination with reduced snow cover in winter and earlier snowmelt, less summer precipitation, and enhanced evaporation due to warmer temperatures. The most critical regions will be those where large populations depend mainly on water resources from glaciers during the dry season and glaciated mountain ranges that are densely populated and highly developed.

This chapter on glaciers and ice caps is divided into two parts: 1) Global Overview and Outlook, and 2) Glacier Changes around the World.

Introduction to glaciers and ice caps

Glaciers and ice caps form around the world where snow deposited during the cold/humid season does not entirely melt during warm/dry times. This seasonal snow gradually becomes denser and transforms into perennial firn (rounded, well-bonded snow that is older than one year) and finally, after the air passages connecting the grains are closed off, into ice[2]. The ice from such accumulation areas then flows under the influence of its own weight and the local slopes down to lower altitudes, where it melts again (ablation areas). Accumulation and ablation areas are separated by an equilibrium line, where the balance between gain and loss in the ice mass is exactly zero. Where glaciers form thus depends not only on air temperature and precipitation (see Figure 6B.1), but also on the terrain, which determines how much solar radiation the glacier will receive and where ice and snow will accumulate.

In humid-maritime climates the equilibrium line is at a relatively low altitude because, for ablation to take place, warm temperatures and long melting seasons are needed to melt the thick layers of snow that accumulate each year[3,4]. These landscapes are thus dominated by 'temperate' glaciers with firn and ice at melting temperatures. Temperate glaciers have a relatively rapid flow, exhibit a high mass turnover and react strongly to atmospheric warming by enhanced melt and runoff. The ice caps and valley glaciers of Patagonia and Iceland, the western Cordillera of North America, and the mountains of New Zealand and Norway are examples of this type of glacier (Figure 6B.2). The lower parts of such temperate glaciers may extend into forested valleys, where summer warmth and winter snow accumulation prevent development of permafrost.

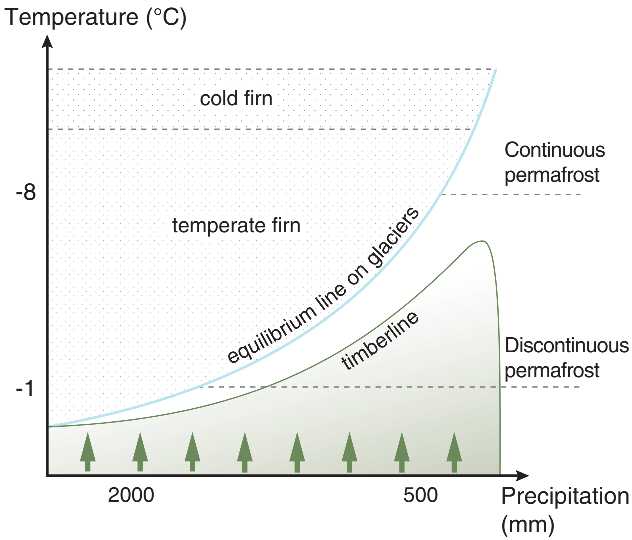


Figure 6B.1: Schematic diagram of glacier, permafrost and forest limits as a function of mean annual air temperature and average annual precipitation. Forests verge on glaciers in humid-maritime climates and grow above permafrost in dry-continental areas.

Source: Based on Shumsky 1964[3] and Haeberli and Burn 2002[4]

In dry continental areas, on the other hand, such as northern Alaska, Arctic Canada, subarctic Russia, parts of the Andes near the Atacama Desert, and many central-Asian mountain chains (Figure 6B.3), the equilibrium line is at a relatively high elevation with cold temperatures and short melting seasons. In such regions, glaciers far above the tree line can contain – or even consist entirely of – cold firn and ice well below melting temperature. These glaciers have a low mass turnover and are often surrounded by permafrost[3].

Glacier responses to climatic changes

The response of a glacier to climatic change involves a complex chain of processes[5,6]. Changes in atmospheric conditions (such as solar radiation, air temperature, precipitation, wind and cloudiness) influence the mass and energy balance at the glacier surface[7,8]. Air temperature plays a predominant role, as it is related to the radiation balance and turbulent heat exchange, and it determines whether precipitation falls as snow or rain. Over time periods of years and decades, changes in energy and mass balance cause changes in volume and thickness, which in turn affect the flow of ice through internal deformation and basal sliding.

This dynamic reaction eventually leads to changes in the length of the glacier – the advance or retreat of glacier tongues. In short, the glacier mass balance (the change in vertical thickness) is the direct signal of annual atmospheric conditions – with no delay – whereas the advance or retreat of glacier tongues (the change in horizontal length) is an indirect, delayed and filtered signal of climat-

Figure 6B.2: Franz Josef Glacier, New Zealand. This temperate glacier receives several metres of precipitation a year and its tongue extends from almost 3 000 m above sea level down to 400 m above sea level, ending in the rainforest.

Photo: Michael Hambrey, SwissEduc (www.swisseduc.ch) and Glaciers online (www.glaciers-online.net); data from the World Glacier Monitoring Service, Zurich, Switzerland

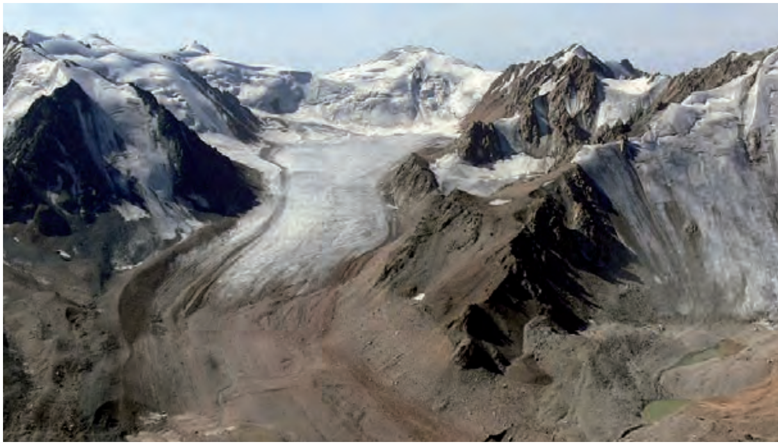


Figure 6B.3: Tsentralniy Tuyuksuyskiy Glacier, Kazhak Tien Shan in August 2006. This cold to partly temperate glacier extends from 4200 m above sea level to about 3400 m above sea level and is surrounded by continuous permafrost.

Photo: V.N. Vinokhodov; data from the World Glacier Monitoring Service, Zurich, Switzerland ic change[9]. The advance or retreat of a glacier is, though, an easily-observed and strong signal of climatic change, as long as it is observed over a long enough period. If the time interval of the analysis is longer than the time it takes a glacier to adjust to a change in climate, the complications involved with the dynamic response disappear[10,11].

Over time periods of decades, cumulative length and mass change can be directly compared. Special problems are encountered with heavily debris-covered glaciers with reduced melting and strongly limited 'retreat', glaciers that end in deep-water bodies causing enhanced melting and calving, and glaciers undergoing periodic mechanical instability and rapid advance ('surges') after extended periods of stagnation and recovery. But glaciers that are not influenced by these special problems are recognized to be among the best indicators of global climate change[12,20]. They essentially convert a small change in climate, such as a temperature change of 0.1°C per decade over a longer time period, into a pronounced length change of several hundred metres or even kilometres (Figure 6B.4) – a signal that is visible and easily understood.

Past glacier fluctuations and current trends

The Late Glacial and Holocene (the period since about 21 000 years ago)

At the time of the peak of the last ice age about 21 000 years ago, glaciers covered up to 30 per cent of the land[2]. Glacier fluctuations can be reconstructed back to that time using a variety of scientific methods. Understand-

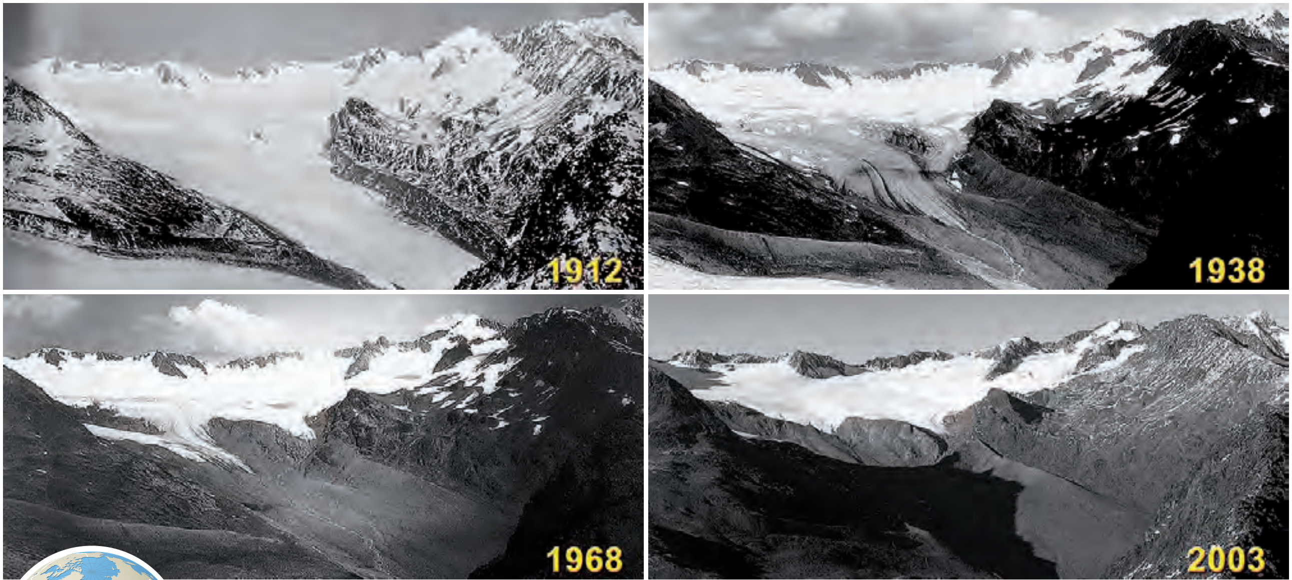


Figure 6B.4: Shrinking of Vernagtferner, Austria. This glacier in the European Alps lost almost 30% in area and more than 50% in mass between 1912 and 2003.

Source: Data and photos, taken by O. Gruber (1912), H. Schatz (1938), H. Rentsch (1968) and M. Siebers (2003), provided by the Commission for Glaciology of the Bavarian Academy of Sciences and Humanities (www.glaziologie.de) ing how glaciers have varied in the past has become central to understanding the causes and possible future of contemporary glacier change. Historical reconstruction of glaciers in the Alps, Scandinavia, Alaska, the Canadian Rockies, Patagonia, the Tropics of South America, Tibet, the Arctic and Antarctica shows that the fluctuations in the state of the glaciers are largely consistent with the reconstruction of climatic and environmental changes provided by other indicators, such as ice-cores, tree-line shifts, pollen records and lake sediments[14].

General warming during the transition from the Late Glacial period (between the Last Glacial Maximum and about 10 000 years ago) to the early Holocene (about 10 000 to 6000 years ago) led to a drastic general glacier retreat with intermittent periods of re-advances. About 11 000 to 10 000 years ago, this pronounced warming reduced the glaciers in most mountain areas to sizes comparable with conditions at the end of the 20th century[15]. In northern Europe and western North America, which were still influenced by the remnants of the great ice sheets, this process was delayed until about 6000 to 4000 years ago. Several early-Holocene re-advances, especially those in the North Atlantic and North Pacific as well as possibly in the Alps, cluster around an event about 8000 years ago, and were likely triggered by changes in the ocean thermohaline circulation and subsequent cooling resulting from the outbursts of Lake Agassiz[14].

On a timescale of hundreds of years there were periods of synchronous glacier advance around the world – peaking in the late Holocene in the Northern Hemisphere, and in the early Holocene in the Southern Hemisphere[16]. The difference in the amount of sunlight that reaches the Earth's surface in the two hemispheres[17], accounts for these differences in long-term glacier evolution[16].

Glaciers in the tropics were rather small or even absent in the early- to mid-Holocene, gradually re-advancing from about 4 000 years ago, probably as a result of increasing humidity[18]. The moraines (accumulations of unsorted, unstratified mixtures of clay, silt, sand, gravel, and boulders deposited by the glaciers) that were formed during the so-called Little Ice Age (from the early 14th to the mid 19th centuries) mark a Holocene maximum extent of glaciers in many regions of the world, although the time period for this maximum varies among the different regions.

There is evidence that mountain glaciers had retreated during various periods of the Holocene in many regions of both hemispheres at least as much as they had in the 1980s–1990s[14]. However, caution must be exercised when using glacier extent as an indicator of climate; the glacier surfaces of the European Alps today, for example, are still far larger than expected given the climatic conditions of the past decade, and are thus not in equilibrium[19].

Since the end of the Little Ice Age

There has been a general retreat of glaciers worldwide since their Holocene maximum extent towards the end of the Little Ice Age, between the 17th and the second half of the 19th century, with intermittent periods of glacier re-advance in certain regions. Direct measurements of glacier fluctuations started in the late 19th century (see box on worldwide glacier monitoring) with annual observations of glacier front variations[20]. These observations and the positions of the Little Ice Age moraines are used to measure the extent of glacier retreat. Total retreat over this time period of glacier termini (the ends of the glaciers) is commonly measured in kilometres for larger glaciers and in hundreds of metres for smaller ones[21].

Worldwide glacier monitoring

Worldwide collection of information about ongoing glacier changes was initiated in 1894 with the foundation of the International Glacier Commission at the 6th International Geological Congress in Zurich, Switzerland. Today, the World Glacier Monitoring Service continues to collect and publish standardized information on ongoing glacier changes. WGMS is a service of the Commission for the Cryospheric Sciences of the International Union of Geodesy and Geophysics (CCS/IUGG) and maintains a network of local investigators and national correspondents in all the countries involved in glacier monitoring. In addition, the WGMS is in charge of the Global Terrestrial Network for Glaciers (GTN-G) within the Global Climate/Terrestrial Observing System. GTN-G aims at combining (a) in-situ observations with remotely sensed data, (b) process understanding with global coverage and (c) traditional measurements with new technologies by using an integrated and multi-level strategy[20]. Recently, a scientific working group has been established to coordinate the monitoring and assessment of glacier and permafrost hazards in mountains[22].

To keep track of the fast changes in nature and to assess corresponding impacts on landscape evolution, fresh water supply and natural hazards, monitoring strategies will have to make use of the rapidly developing new technologies (remote sensing and geo-informatics) and relate them to the more traditional methods.

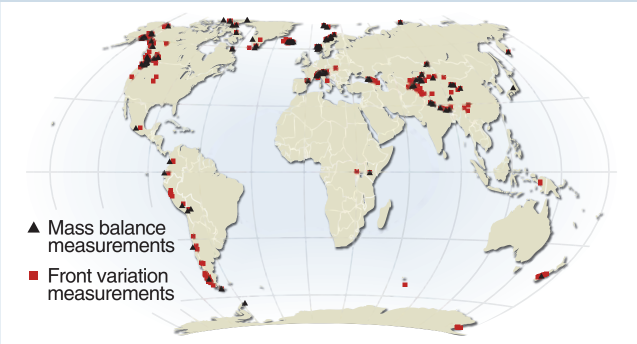


Figure 6B.5: Worldwide glacier monitoring. The locations of glaciers with available front variation and mass balance measurements are shown.

Source: Locations of glacier observations provided by the World Glacier Monitoring Service, Zurich, Switzerland; background glacier cover based on the glacier layer of the Digital Chart of the World, provided by the National Snow and Ice Data Center, Boulder, USA.

Characteristic average rates of glacier thinning (mass loss), calculated from data on changes in length over long time periods, are a few decimetres water equivalent per year for temperate glaciers in humid-maritime climates, and between a few centimetres and one decimetre water equivalent per year for glaciers in dry-continental regions with firn areas below melting temperature[21,23]. These calculated values of glacier mass loss can be compared to glacier mass balance values from direct glaciological measurements, which are available for the second half of the 20th century.

Thirty reference glaciers with almost continuous mass balance measurements since 1975 (Figure 6B.6) show an average annual mass loss of 0.58 m water equivalent for the past decade (1996–2005), which is more than twice the loss rate of the period 1986–1995 (0.25 m), and more than four times the rate of the period 1976–1985 (0.14 m). The results from these 30 continuous mass balance series correspond well to estimates based on a larger sample of more than 300 glaciers, including short and discontinuous series[24].

The mass loss of glaciers and ice caps (excluding peripheral ice bodies around the two ice sheets in Greenland and Antarctica) between 1961 and 1990 contributed 0.33 mm per year to the rising sea level, with about a doubling of this rate in the period from 1991 to 2004[24]. A step-change in climatic conditions would cause an initial mass balance change followed by a return towards zero values, due to the glacier's adaptation of its size (surface area) to the new climate. The observed trend of increasingly negative mass balances over reducing glacier surface areas thus leaves no doubt about the ongoing change in climatic conditions.

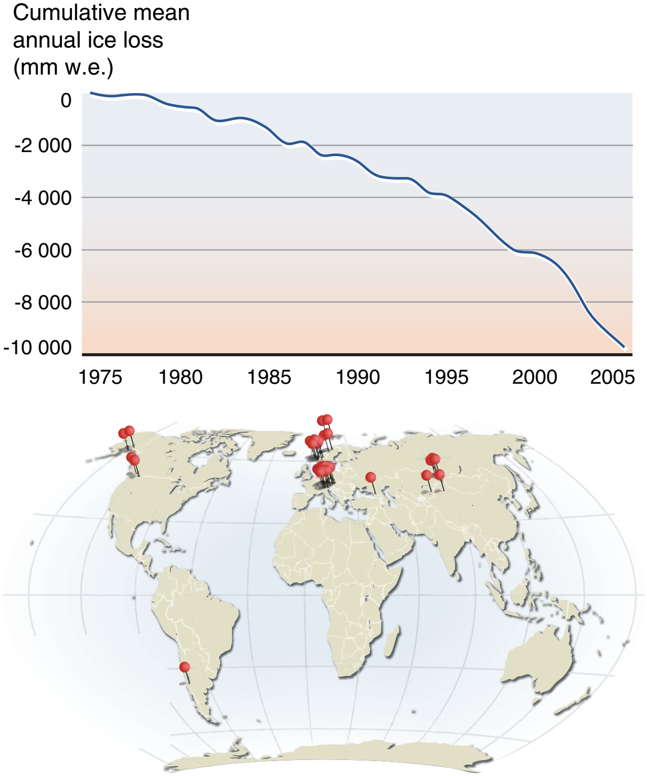


Figure 6B.6: Mass balance reference glaciers in nine mountain ranges. The 30 glaciers lost on average more than 9.5 m water equivalent in thickness over the period 1976–2005.

Source: Data from the World Glacier Monitoring Service, Zurich, Switzerland

Outlook for glaciers

The total increase of global mean air temperature of about 0.75 °C since 1850 is clearly manifested in the shrinking of glaciers and ice caps worldwide[1]. The sensitivity of glaciers in humid-maritime areas to this warming trend has been found to be much higher than that of glaciers in dry-continental areas[7,21].

According to climate scenarios for the end of the 21st century, changes in global temperature and precipitation range between +1.1 to +6.4 °C and –30 to +30 per cent, respectively[1]. Such an increase in mean air temperature will continue the already dramatic glacier changes. Cold continental-type glaciers will react in the first instance with a warming of the ice and firn temperatures, whereas glaciers with ice temperatures at the melting point will have to convert the additional energy directly into melting[7,8].

Low-latitude mountain chains like the European Alps or the Southern Alps of New Zealand, where glaciers are typically medium-sized and found in quite steep mountains, will experience rapid glacier changes in adaptation to the modified climate. A modelling study shows that the European Alps would lose about 80 per cent of their glacier cover should summer air temperatures rise by 3°C, and that a precipitation increase of 25 per cent for each 1°C would be needed to offset the glacial loss[19].

In heavily glacier-covered regions like Patagonia (Argentina, Chile) or the St. Elias Mountains (Alaska), the landscape is dominated by relatively few large and rather flat valley glaciers. Because long, flat valley glaciers have dynamic response times beyond the century scale[10,11], rapid climate change primarily causes (vertical) thinning of ice rather than (horizontal) retreat and area reduction. For such cases, conditions far beyond equilibrium stages, perhaps even run-away effects from positive feedbacks (mass balance/altitude), must be envisaged[20,25]. Downwasting or even collapse of large ice bodies could become the most likely future scenarios related to accelerating atmospheric temperature rise in these areas, and have already been documented[26,27].

Under the present climate scenarios[1], the ongoing trend of worldwide and fast, if not accelerating, glacier shrinkage on the century time scale is of a non-periodical nature and may lead to the deglaciation of large parts of many mountain regions in the coming decades.

Glacier melt water in the Caucasus mountains, Georgia.
Photo: Igor Smichkov/iStockphoto.com

Glaciers and natural hazards

Changes in glaciers may well lead to hazardous conditions, particularly in the form of avalanches and floods, and thus have dramatic impacts on human populations and activities located in glacierized mountain regions. The majority of glacier hazards affect only a limited area – often only a few square kilometres – and mostly pose a danger to densely populated mountain regions such as the European Alps. In some cases, however, glacier hazards have far-reaching effects over tens or even hundreds of kilometres and thus also affect less densely populated and developed mountain regions. The long-term average annual economic loss from glacier disasters or related mitigations costs are estimated to be in the order of several hundred million US dollars[28]. The largest disasters have killed more than 20 000 people, for instance the Huascarán rock-ice avalanches in Peru in 1970 (see box on deadly ice avalanches of Glaciar 511 in the Cordillera Blanca in Part 2 of this chapter), or the Nevado del Ruiz lahars (rapidly flowing volcanic debris flows) in Colombia in 1985.

A systematic assessment of hazards can only be achieved by identifying the physical processes involved. Generally speaking, the most important types of hazards are as follows: glacier floods, hazardous processes associated with glacier advance or retreat, ice and rock avalanches, periglacial debris flows, and ice–volcano interactions[29,30]. Particularly severe disasters have often resulted from a combination of these processes or chain reactions[13,31].

Glacier lake outburst floods represent the largest and most extensive glacial hazard, that is, the hazard with the highest potential for disaster and damage (up to 100 million m^3 break-out volume and up to 10 000 m^3 per second runoff). The Himalayas, Tien Shan and the Pamirs (see box on glacier lake outburst floods and glacier surges in Central Asia), the Andes, but also the European Alps are among those regions most severely affected by this type of hazard. Glacier floods are of particular concern in view of the rapidly retreating glaciers and the corresponding formation and growth of numerous glacier lakes[30,32–34].

In terms of hazard, ice and rock avalanches may be roughly grouped by volume. Avalanches with volumes smaller than 1 million m^3 are mostly of concern to densely populated and developed mountain regions such as the European Alps[41–43]. Avalanches with a volume of 1 to 100 million m^3 or even more have usually more far reaching effects and the potential to completely devastate mountain valleys. The most recent such disaster occurred in 2002 in the Caucasus with a 100 million m^3 ice-rock avalanche that extended more than 30 km downstream and killed more than 100 people (see box on the 2002 Caucasus ice-rock avalanche and its implications). These types of mass movements and the relationship between their magnitude and their frequency have recently have become more and more important in research because of concerns that they may become more frequent with continuing atmospheric warming, permafrost degradation and related destabilization of steep glaciers and rock walls[44].

Debris flows from periglacial areas have frequently caused damage to life and property in mountain areas[48]. Unconsolidated sediments, uncovered by glacier retreat during the recent decades, and degradation of stabilizing permafrost in debris slopes are the main sources of the largest debris flows observed in the European Alps[31,49,50].

Ice-capped volcanoes pose particularly severe hazards because large mass movements (avalanches, lahars) may result from the interactions between material that erupts from the volcanoes with ice and snow[51,52]. Alaska, the Cascades and the Andes are among the regions most affected by hazards posed by the interaction between volcanoes and glaciers[53,54].

Chain reactions and interactions between the aforementioned processes play a crucial role in determining the

Glacier lake outburst floods and glacier surges in Central Asia

Almaty (population 1.2 million) is subject to the risk of floods from torrential rainfalls and glacial lake outbursts. A glacier-induced debris flow in July 1973 in the mountains south of Almaty deposited over 4 million m^3 of debris into the safety dam, which had been specially constructed to prevent the catastrophic impacts of such floods. Before this dam was built in 1967, debris flows caused many casualties and severe destruction in 1921 and 1956[35,36].

In July 1998, a glacier lake outburst flood in the Shahimardan Valley of Kyrgyzstan and Uzbekistan killed over 100 people[37]. In August 2002, another such event in the Shakhdara Valley of the Tajik Pamir Mountains claimed 23 lives[38]. In both cases the local communities did not receive early warnings and were not prepared. These tragic lessons have prompted better cooperation between meteorological services in glacier flood hazard detection.

The increasing number of glacial and moraine lakes in Central Asian mountains is a matter of great concern[35,39]. One of the surging glaciers that poses a potential threat is the 15 km long Medvezhi (Bear) Glacier in the Pamirs mountains of Tajikistan (Figure 6B.7). Its surges have repeatedly caused lake formation, outburst and subsequent floodings. In 1963 and 1973, the surge of the glacier was so significant (1 to 2 km increase in length) that the ice dam exceeded 100 m in height and dammed a lake of over 20 million m^3 of water and debris[40]. The outburst of that lake generated a series of large flood waves. Due to early warning and monitoring, there were no victims, although infrastructural damage was significant.

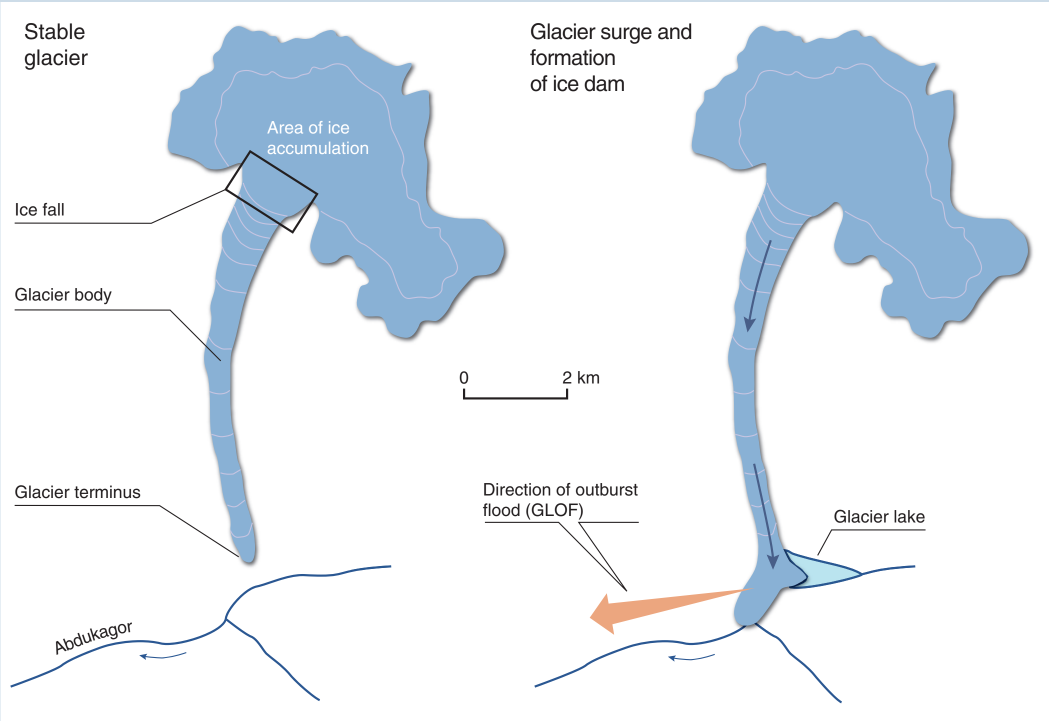


Figure 6B.7: Formation of lakes and glacier lake outburst floods (GLOFs) by Medvezhi Glacier, Pamirs.

Source: Tajik Agency on Hydrometerology

The 2002 Caucasus ice-rock avalanche and its implications

One of the largest historical glacier disasters occurred in 2002 in the Russian Republic of North Ossetia in the Caucasus. An ice-rock avalanche resulting from a slope failure in the Kazbek region and a connected instability of the Kolka glacier devastated tens of kilometres along the length of the Genaldon valley[13,45–47]. The Kolka ice-rock avalanche (Figure 6B.8) is remarkable for several reasons. The steep, high mountain wall of the initial slope failure was covered by firn and ice masses, a composition that is inherently unstable. The underlying bedrock in relatively cold permafrost conditions was influenced by deep-seated thermal anomalies induced by the overlying ice and firn through processes such as latent heat production from percolating and refreezing meltwater[13]. Increasing air temperatures can cause disturbances in such complex system, which eventually can lead to slope failure. Similar conditions as in the Caucasus exist in many glacierized mountain regions of the world. In more populated areas such as the European Alps, similarly large slope failures would cause catastrophes of even much larger dimensions.

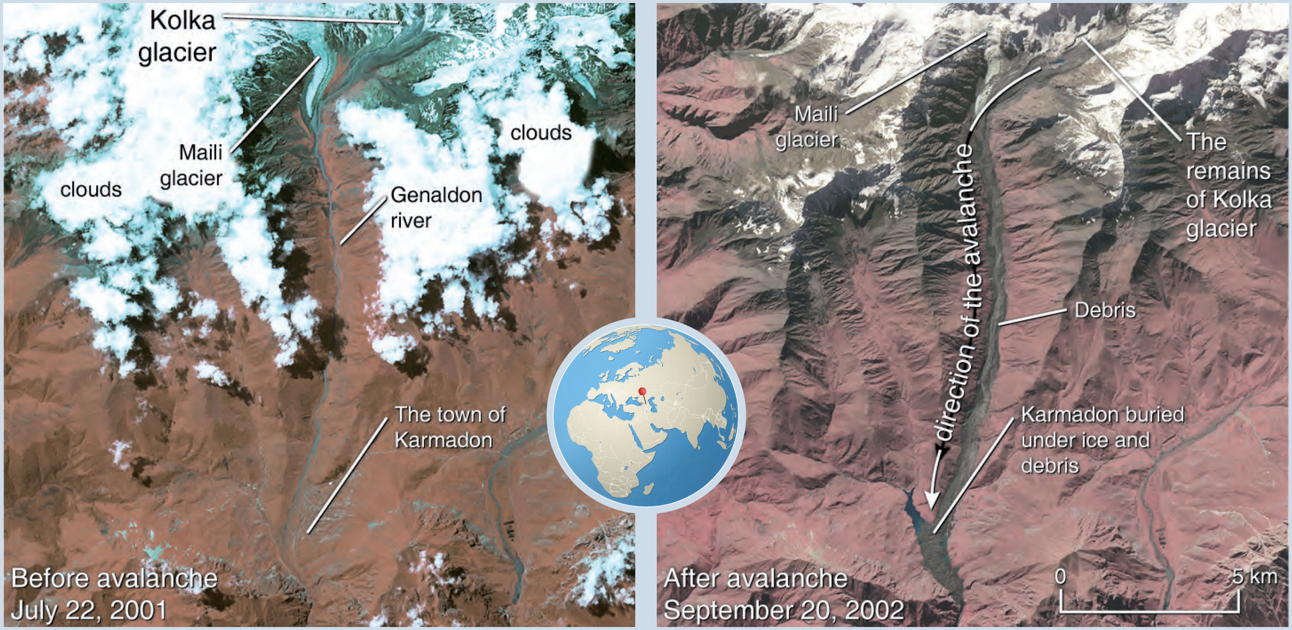


Figure 6B.8: Caucasus ice-rock avalanche in Russian Republic of North Ossetia. An ice-rock avalanche in the Kazbek region sheared off almost the entire Kolka Glacier and devastated the Genaldon valley. The satellite images show the region before (July 22, 2001) and after (October 6, 2002) the ice-rock avalanche of September 20, 2002.

Source: The ASTER scenes were provided within the framework of the Global Land Ice Measurements from Space project (GLIMS) through the EROS data center, and are courtesy of NASA/GSFC/METI/ERSDAC/JAROS and the US/Japan ASTER science team magnitude and frequency of glacier-related hazards. As one example, outbursts of naturally or artificially dammed mountain lakes were caused by impact waves from rock and ice avalanches and this led to failure of the dams[55]. Such potential process interactions have to be assessed carefully in order to predict related consequences.

Two present global developments and their regional expressions will strongly affect the potential impact of current and possible future glacier hazards: climate change and socio-economic development. First, atmospheric warming has an increasingly dramatic effect on mountain glaciers[1], and strongly influences the development of related hazards. For example, potentially unstable glacial lakes often form in glacier forefields dammed by frontal moraines which were left behind by retreating glaciers. Steep slopes of unconsolidated debris are a potential source for debris flows when they are no longer covered by glacier ice or cemented by ground ice. Fresh ice break-off zones may evolve in new places from glacier retreat, while existing danger zones may cease to be active. Atmospheric warming also affects permafrost thickness and distribution. The thickness of the active layer (that is, the layer above the permanently frozen ground that thaws during the summer) may increase, and the magnitude and frequency of rockfalls may increase or evolve at locations where such events were historically unknown. Lateral rockwalls can be destabilized by glacier retreat as a result of the stress changes induced. In general, climate change is expected to bring about a shift of the cryospheric hazard zones. It is difficult, however, to ascertain whether the frequency and/or magnitude of events have actually increased already as a consequence of recent warming trends. Nevertheless, events with no historical precedence do already occur and must also be faced in the future[29,56].

The second important change in glacier-related risks concerns the increasing economic development in most mountain regions. Human activity is increasingly encroaching upon areas prone to natural hazards. Related problems affect both developed and developing countries. The latter (such as in Central Asia, the Himalayas or the Andes), however, often lack resources for adequate hazard mitigation policies and measures. Cost-efficient, sound and robust methods are therefore needed to regularly monitor the rapid environment and land-use changes in high mountains and to identify the most vulnerable areas. This is equally important for developed countries in the European Alps. Expensive protective structures had to be built in the past to reduce the risk. Public funds increasingly struggle to keep pace with – and to ensure sufficient protection from – the rapid environmental changes and their consequences in mountain areas. Integrating climate change effects and robust process models into risk studies will help ensure that politics and planning can adapt to environmental conditions that change with increasingly high rates.

Glaciers, landscapes and the water cycle

Landscapes around many high-mountain regions but also in vast lowlands were moulded and sculpted by large ice bodies during the most recent part of Earth's history – the Ice Ages – over the last few million years[57,58]. The detection, in the first half of the 19th century, of corresponding traces from glacier erosion and of erratic boulders far from mountain chains led to the formulation of the Ice Age theory by Louis Agassiz and colleagues[59]. It was soon understood that large ice sheets had formed over North America and even entirely covered Scandinavia, lowering global sea level by more than 100 m, greatly modifying coastlines of all continents and dramatically affecting the courses of large rivers and the global ocean circulation[60,61]. This new knowledge constituted a fundamental breakthrough in our understanding of the climate system as an essential part of living conditions on Earth. Ice Age landforms have become a unique heritage, reminding us of the consequences of global temperature changes of just a few degrees.

Curiosity and romantic enthusiasm characterize many historical reports and paintings of glaciers and high mountain landscapes. Very often, glaciers are portrayed as an expression of 'wild, non-destroyable' nature, sharply contrasting with the cultivated landscape of human habitats. Glacierized mountain areas therefore became – and still are – major tourist attractions in many parts of the world. In fact, the 'clean white of the eternal snow' on high mountain peaks is often seen as a beautiful treasure and used as a precious symbol of intact environments[62]. This is why the current shrinking, decay and even complete vanishing of glaciers evokes such an emotional response.

Apart from their symbolic value, glaciers are also among the best natural indicators of climate change[12,20]. Their development can be observed by everybody – and the physical process, the melting of ice under the influence of warmer temperatures, can intuitively be understood. The impacts of accelerated atmospheric warming are thus changing the public perception of glaciers: they are increasingly recognized as a warning signal for the state of the climate system[63].

Continued atmospheric warming will inevitably lead to the deglaciation of many currently glacierized landscapes, especially in low-latitude mountain chains. In many places, lakes have already started to form. Such lakes may replace some of the lost landscape attractiveness, but their beauty may come at a dangerous price (as explained above in the section on natural hazards). On slopes, vegetation and soils take decades and even centuries or sometimes millennia to follow the retreating ice and cover the newly exposed terrain[64]. As a consequence, the zones of bare rock and loose debris will expand. Vegetation (especially forests) and ice both have a stabilizing effect on steeply inclined surfaces. During the expected long transitional period between glacier vanishing and forest immigration, erosion (including large debris flows) and instability (including large rockfalls and landslides) on slopes unprotected by ice or forest will increase substantially[65].

The perennial ice of glaciers is an important part of the water cycle in cold regions. It represents a storage component with strong effects on river discharge and fresh water supply[66,67]. Such effects indeed make high mountain chains 'water towers' for many large areas and human habitats. Climatic change will lead to pronounced changes in this system[12]. At time scales of tens and hundreds of millennia, the growth and decay of continental ice sheets, large ice caps and glaciers during periodical ice ages profoundly affect the global water cycle[61,68]. Within annual cycles of temperature and precipitation, glacial meltwater feeds rivers during the warm/dry season. In the Andes of Peru, the Argentinean Pampas or the Ganzhou Corridor of China, this contribution to river flow is the predominant source of freshwater for large regions surrounding the corresponding mountain areas[69]. Meltwater from glacierized mountain chains with rugged topography is also intensively used for hydropower generation (Figure 6B.9).

Figure 6B.9: Glaciers as source for hydropower production. A dam at Gries Glacier in Switzerland has been constructed to receive meltwater in summer for use in power generation in winter. *Photo: Jürg Alean, SwissEduc (www.swisseduc.ch)/Glaciers online (www.glaciers-online.net)*

The shrinking and even vanishing of mountain glaciers in scenarios of atmospheric temperature rise is likely to cause both small and large meltwater streams to dry out during hot and dry summers. This drying out may become more frequent at mid-latitudes, where human populations are often dense and the need for fresh water is growing. Earlier snowmelt and perhaps also reduced snow cover from wintertime could result in severe consequences for both ecosystems and related human needs: decreasing river flow, warmer water temperatures, critical conditions for fish and other aquatic forms of life, lower groundwater levels, less soil humidity, drier vegetation, more frequent forest fires, stronger needs for irrigation water, and rising demands for energy (such as air conditioning) coupled with reduced hydropower generation and less river cooling for nuclear power plants. These consequences are all likely to be interconnected and related to growing conflicts of interest.

Perhaps the most critical regions will be those where large populations depend on water from glaciers during the dry season, such as in China and other parts of Asia, including India, together forming the Himalaya-Hindu Kush region (see box on the water towers of Asia), or in the South American Andes[70] (see box on glaciers and water availability in the Andes, in Part 2 of this chapter). But it will also affect mountain ranges which are densely populated and highly developed, such as the European Alps and the regions in the vicinity of its rivers[71,72]. Glacier changes, as important and pronounced parts of climate-induced changes in mountain landscapes, are not only the clearest indication of climate change – they also have the potential of having a strong impact on the seasonal availability of fresh water for large, densely populated regions and, hence, on the fundamental basis of ecosystem stability and economic development[56,73].

The water towers of Asia

The Himalayas–Hindu Kush, Kunlun Shan, Pamir and Tien Shan mountain ranges (Figure 6B.10) function as water towers, providing water to people through much of Asia. The glacier-fed rivers originating from the mountain ranges surrounding the Tibetan Plateau comprise the largest river run-off from any single location in the world[74,75]. While the mountains are homes to some 170 million people, the rivers that drain these mountains influence the lives of about 40 per cent of the world's population[74]. The rivers provide household water, food, fisheries, power, jobs and are at the heart of cultural traditions. The rivers shape the landscape and ecosystems and are important in terms of biodiversity.

While mountains traditionally have been considered the major water sources of the region, there is great diversity in the hydrological significance of mountains and glaciers for downstream water supply, particularly between the dry north-western region and the monsoon-influenced south-eastern regions[76]. In spite of the vast water supply, seasonal water scarcity is a major issue[77].

Projections of glacier retreat in the region (based on IPCC scenarios) suggest that increases in the mean annual temperature for High Asia in the range of 1.0°C to 6.0°C (low to high estimate) by 2100 are likely to result in a decline in the current coverage of glaciers by 43 to 81 per cent[78]. The Tien Shan and Qinling Shan are likely to become entirely devoid of glaciers, and glacial cover-

Figure 6B.10: The Himalayas-Hindu Kush-Tien Shan-Tibet region.

age would be greatly diminished in the Himalayas–Hindu Kush[78]. The extent and amount of snow will also decrease as temperatures increase and the snow line moves to higher elevations. Given that some of the rivers, such as the Amu Darya and the Indus, receive nearly 90 per cent of their total water discharge from upper mountain catchments including glaciers and snow[76], the water flow in the rivers could decline perhaps by as much as 70 per cent if the glaciers disappear. In some cases, like in the Tien Shan, the rivers could become seasonal. Reduced water flow in the dry seasons will lead to more and longer periods with critical shortages of water for transportation, drinking water and irrigation, with consequences for trade, small and large-scale agriculture[74] and with increased potential for disputes over sectoral and regional allocations of this diminishing resource.

The impacts are not evenly distributed geographically or socially. High proportions of impoverished populations in the region are mountain and foothill dwellers[74,79,80]. Impoverished populations have also largely settled in areas with high flood risk, such as low-lying urban areas and deltas – because there is often no alternative[74]. The impacts are aggravated by the methods of meeting energy demands – traditional fuel sources such as fuel wood and animal dung account for 94 per cent of energy supply in some mountain areas in Nepal and Tibet[79]. Because of this dependence on fuel wood and livestock, most watersheds have experienced deforestation and overgrazing, making the hillsides much more vulnerable to land slides, either during peak snowmelt or in relation to tectonic activity[75]. Only 3 per cent of watersheds in the region are protected. High in the mountains, a rise in elevation of the snowline will lead to drying out of village grazing areas, eroding the basis of villagers' livelihoods by reducing the carrying capacity of their surrounding lands. Even slight increases in severity and frequency of land slides and flash floods may significantly reduce the ability of herders to move and transport their livestock between grazing areas and to towns for sale.

The hydrological role of mountains, glaciers and snow is particularly significant for the Tarim, Syr Darya, Amu Darya, Indus, Ganges, Brahmaputra, Yangtze and Huang He (Yellow) rivers[74,76,81] (Table 1). With increases in seasonal floods and significantly reduced overall water flow, especially during critical times of low rainfall, about 1.3 billion people could be exposed to risk of increased water shortages:

- in China up to 516 million people;
- in India and Bangladesh approximately 526 million people;
- in central Asia, including the Xinjiang province of China, about 49 million people;
- in Northern India and Pakistan as many as 178 million people.

This only includes the populations living in the watersheds, not those affected by reduced crop production from failure to secure water for irrigation, or those affected more generally from impacts on regional and national economies[82]. The result of glacier loss is therefore not only direct threats to lives, but also great risks of increased poverty, reduced trade and economic decline. This poses major political, environmental and social challenge in the coming decades.

River	Basin km^2	Total population	% cropland	% forest	% basin protected	Hydrological significance of glaciers and snow for rivers
Tarim	1 152 000	8 067 000	2	<1	21	Very high
Syr Darya	763 000	20 591 000	22	2.4	1.0	Very high
Amu Darya	535 000	20 855 000	22	0.1	0.7	Very high
Indus	1 082 000	178 483 000	30	0.4	4.4	Very high
Ganges	1 016 000	407 466 000	72	4.2	5.6	High
Brahmaputra	651 000	118 543 000	29	19	3.7	High
Yangtze	1 722 000	368 549 000	48	6.3	1.7	High
Huang He (Yellow river)	945 000	147 415 000	30	1.5	1.3	High
Salween	272 000	5 982 000	6	43	2.2	Moderate
Mekong	806 000	57 198 000	38	42	5.4	Moderate

Table 1: An overview of the major rivers in the Himalayas-Hindu Kush-Tien Shan-Tibet region.

Source: Viviroli and others 2003[76]; IUCN/WRI 2003[81]; UNEP 2004[74]

Part Two: Glacier Changes around the World

Overview

Glaciers and ice caps reached their Holocene (the past 10 000 years) maximum extent in most mountain ranges throughout the world towards the end of the Little Ice Age, between the 17th and mid-19th century. Over the past hundred years a trend of dramatic shrinking is apparent over the entire globe, especially at lower elevations and latitudes. Within this general trend, strong glacier retreat is observed in the 1930s and 1940s, followed by static conditions around the 1970s and by increasing rates of glacier wasting after the mid 1980s (Figure 6B.11). There are short-term regional deviations from this general trend and intermittent re-advances of glaciers in various mountain ranges occurred at different times.

The trend of worldwide glacier shrinking since the end of the Little Ice Age is consistent with the increase in global mean air temperature. The decline in solar radiation at the Earth's surface (global dimming) in the second half of the 20th century and the transition from decreasing to increasing solar radiation in the late 1980s may be due to the industrial pollution of the atmosphere and the more effective clean-air regulations together with the decline in the economy in Eastern European countries, respectively[83]. This might explain some of the glacier mass gains around the 1970s and the subsequent strong mass losses[84]. Significantly increased precipitation has been linked to the advance of glaciers on the west coast of New Zealand and Norway in the 1990s[85–87] and can give valuable insight into regional climate oscillations such as the El Niño/Southern Oscillation or the North Atlantic Oscillation[86,87].

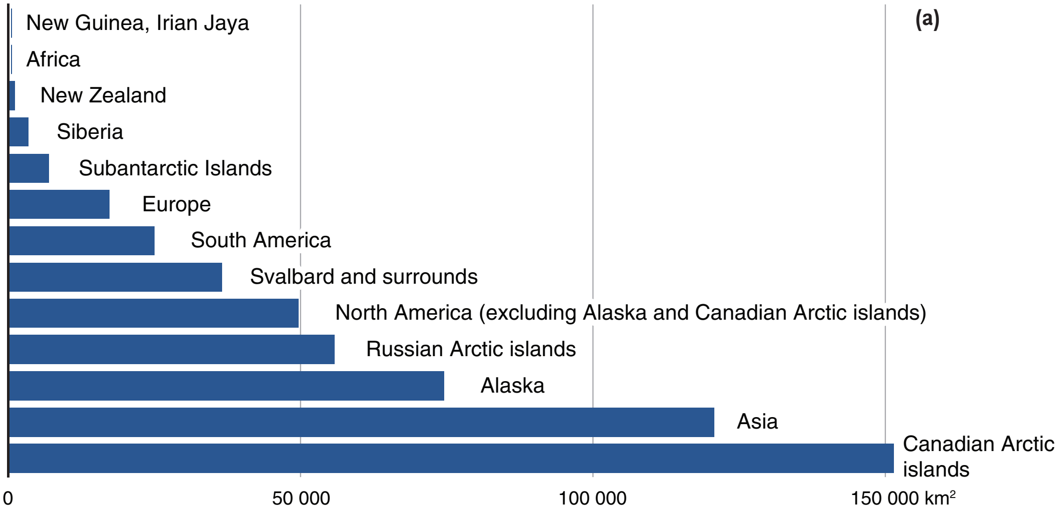
Glaciers act as vital water reservoirs maintaining river flows in many dry parts of the world. Increased melting of glaciers is providing increased flows in some areas but as glaciers continue to shrink and disappear the reservoirs will run dry, resulting in drought and hardship for many millions of people in and around regions such as the Andes, China, Central and Southern Asia, Iran and Afghanistan[70]. Increased glacial melting also results in heightened risk of flooding due to the failure and catastrophic discharge of unstable ice and detritus dams formed at the toe of receding glaciers.

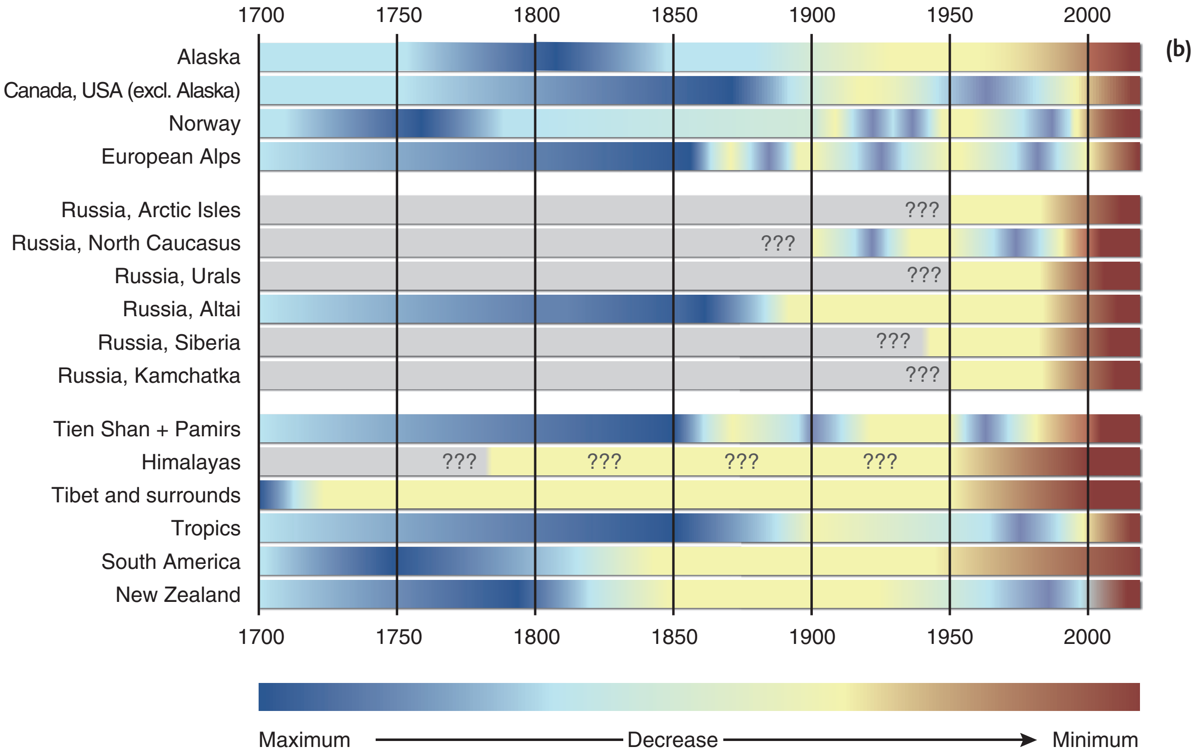
Glaciers form where snow deposited during the cold/humid season does not entirely melt during warm/dry times. These conditions are widespread in the world, so glaciers are found from the poles to the tropics. This section looks at representative mountain ranges, ordered by Northern and Southern Hemisphere from west to east. The ice sheets in Antarctica and Greenland are discussed in the previous chapter (6A). See inside front cover for a map of worldwide glacier distribution.

Figure 6B.11: Overview of world glaciers and ice caps.
(a) Glaciers and ice caps around the world. The total area of glaciers and ice caps, without the ice sheets and surrounding glaciers and ice caps in Greenland and Antarctica, sums up to 540 000 km^2.

Source: Data from Dyurgerov and Meier 2005[122]

(b) Overview on glacier changes since the end of the Little Ice Age, summarizing the regional glacier fluctuations based on the data presented in this section.


(a)
New Guinea, Irian Jaya
Africa
New Zealand
Siberia
Subantarctic Islands
Europe
South America
Svalbard and surrounds
North America (excluding Alaska and Canadian Arctic islands)
Russian Arctic islands
Alaska
Asia
Canadian Arctic islands
0
50 000
100 000
150 000 km²


(b)
1700
1750
1800
1850
1900
1950
2000
Alaska
Canada, USA (excl. Alaska)
Norway
European Alps
Russia, Arctic Isles
Russia, North Caucasus
Russia, Urals
Russia, Altai
Russia, Siberia
Russia, Kamchatka
Tien Shan + Pamirs
Himalayas
Tibet and surrounds
Tropics
South America
New Zealand
???
Maximum
Decrease
Minimum

North America

Arctic islands and mountain ranges

By far the largest area of glaciers and ice fields are found in Canada (about 201 000 km^2)[88], followed by Alaska (about 75 000 km^2)[89] with about 700 km^2 in the rest of the USA[90]. Glaciers and ice fields are concentrated in the High Arctic (Figure 6B.12) and western cordillera.

Glaciers reached their Little Ice Age maximum extent between the early 18th and late 19th century in Alaska[91] and in the mid to late 19th century in Canada and the continental USA[92]. Subsequently, a general retreat of glaciers developed, particularly at lower elevations and southern latitudes[91]. There are exceptions to this trend: southern cordilleran and Alaskan coastal glaciers slowed their retreat or advanced in response to cooler summers and heavier snowfall in the 1950s to 1970s[93,94]. Since that time the glaciers have continued to retreat and the retreat has accelerated since the 1970s. In the western cordillera they have now lost about 25 per cent of their area since the Little Ice Age[90,95]. In the northwest continental USA and southwest Canada, accelerated retreat coincided with a shift in atmospheric circulation patterns that occurred during 1976–1977[96,97].

Airborne laser altimetry studies on 67 glaciers (representing about 20 per cent of the glacierized area in Alaska and neighbouring parts of Canada) show a mean annual thickness change of –0.5 m water equivalent from the mid 1950s to the mid 1990s, and more than three times as much (–1.8 m water equivalent) from the mid 1990s to 2000–2001 based on a sub-sample of 28 glaciers[26].

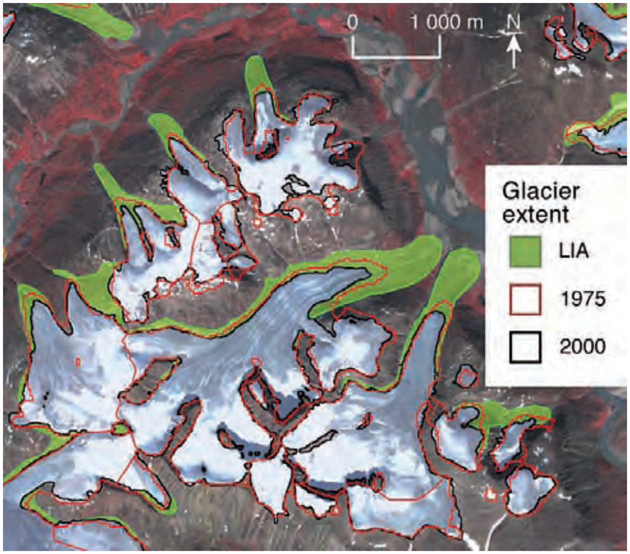


Figure 6B.12: Glacier shrinking on Cumberland Peninsula, Baffin Island, Canadian Arctic. A new glacier inventory based on satellite data shows that the glacier cover reduced by about 22 per cent between the Little Ice Age (LIA) maximum extent and 2000.

Source: Data and figure from F. Svoboda, University of Zurich, Switzerland

Norway

Mainland Norway's glacier cover is about 2600 square km[98,99]. The maximum recent extent culminated around 1750. At that time many farms and much farmland were buried by ice. Since then there has been a general retreat but with large regional variations; some areas kept the maximum extent until the late 19th century. Since 1900 glaciers have retreated but with short advances around 1910, around 1930 and in the 1990s. In contrast to glaciers in most of the world, glaciers along the western coast advanced from the 1970s to the end of the 1990s as a result of high winter snowfall. Since 2000, all glaciers have been retreating considerably[100,101].

The ice masses of the Svalbard archipelago, north of mainland Norway, cover 36 600 square km[102]. Long-term mass balance measurements from Austre Broeggerbreen and Midre Lovénbreen show a strong trend in ice loss over the past 40 years[103].

A glacier on Svalbard.
Photo: Sebastian Gerland, Norwegian Polar Institute

European Alps

Glaciers in the European Alps reached their recent maximum extent around 1850[104–106]. The overall area loss since then is estimated to be about 35 per cent until the 1970s, when the glaciers covered a total area of 2 909 km^2, and almost 50 per cent by 2000[19]. Total ice volumes in 1850, the 1970s and 2000 are estimated to be about 200 km^3, 100 km^3 and 75 km^3, respectively[19]. Observations show intermittent glacier re-advances in the 1890s, 1920s and 1970–1980s[107–109] (Figure 6B.13). After 1985 an acceleration in glacial retreat has been observed, culminating in an annual ice loss of 5–10 per cent of the remaining ice volume in the extraordinarily warm year of 2003[110]. The strong warming has made disintegration and downwasting increasingly predominant processes of glacier decline during the most recent past[111].

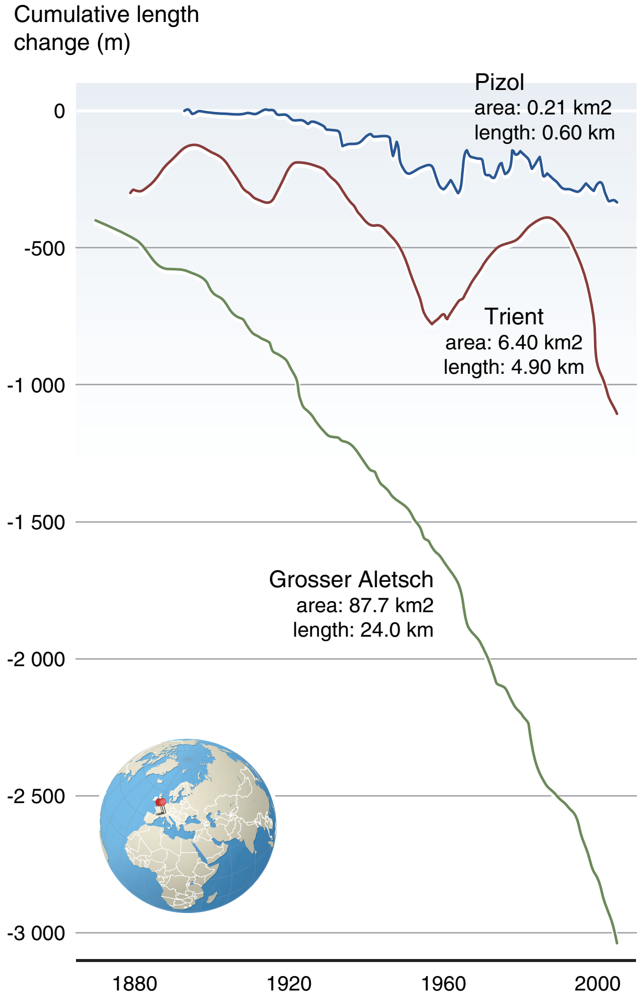


Figure 6B.13: Glacier front variations in the European Alps. Large Alpine glaciers have retreated continuously since the mid-19th century, whereas steep mid-sized glaciers reacted with re-advances in the 1890s, 1920s and between the 1970s and1980s due to the somewhat cooler and wetter periods. Small glaciers feature a high annual variability with a clear shrinking trend.

Source: Data from the World Glacier Monitoring Service, Zurich, Switzerland

Russia

Arctic islands and mountain ranges

The following details on the glacier distribution and changes in Russia are based on a monograph edited by Kotlyakov and others[112].

Russia's glaciers and ice fields are concentrated in its Arctic islands where their extent is about 56 000 km^2. Glaciers are widely dispersed on mountain ranges from the Urals to Kamchatka, with an extent of about 3600 km^2 reported in the period 1950–1970 (USSR Glacier Inventory). There is a pattern of general retreat that is mainly at lower elevations and southern latitudes that in some places is dramatic. For example, in the Arctic islands over the last 50 years there has been a reduction of only 1.3 per cent of glacierized area whereas glaciers in the North Caucasus retreated by about 50 per cent in the last century with extreme melting and abrupt decrease in area occurring in the period 1998–2001.

There has been considerable variability in the retreat of mountain glaciers, as would be expected in so large a geographic area. In the North Caucasus glacier advances were reported in the 20th century and in Kamchatka both advances and retreats have occurred on glaciers of the Avachinskaya and Klyuchevskaya groups of volcanoes, possibly connected with volcanic activity. In other parts of Kamchatka there is a general retreat with glaciers in the coastal Kronotsky peninsula being most sensitive to climate change.

Since the mid-19th century glaciers in the Altay have continuously degraded but the rate has slowed in recent years. Direct mass balance measurements at Maliy Aktru Glacier show a slightly negative mean annual mass balance (about –0.09 m water equivalent) over the period 1962–2005 (Figure 6B.14).

In some mountain ranges topographic changes have been dramatic. In the Urals some glaciers have disappeared completely and in the North Caucasus large glaciers have been reduced to separated remnants.

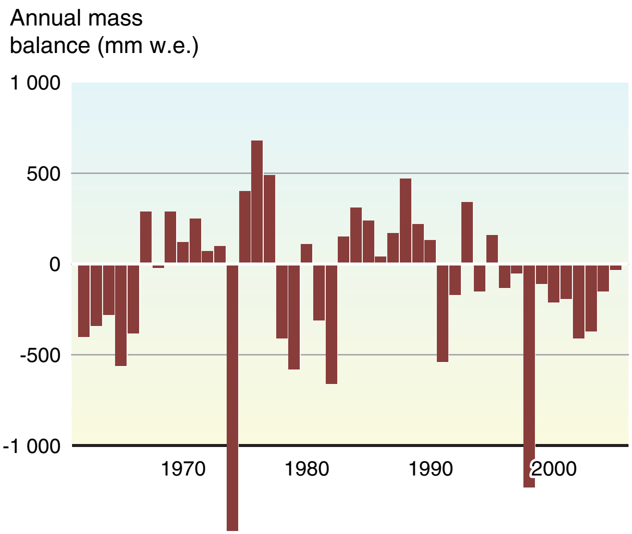


Figure 6B.14: Mass balance of Maliy Aktru Glacier, Russian Altai. Measurements on this valley-type glacier in the North Chuyskiy Range show a slightly negative annual mass balance trend culminating in an ice loss of about 4 m water equivalent over the period 1964–2005.
Photo: Y.K. Narozhniy (taken in July 1992); data from the World Glacier Monitoring Service, Zurich, Switzerland

Central Asian Tien Shan and Pamirs

Overall glacier area of Tien Shan (Central Asian republics and China) and Pamirs was estimated by Dyurgerov and Meier[122] at 15 417 km^2 and 12 260 km^2, respectively, with their maximum recent extent being between the 17th and mid 19th centuries[39,113–115].

Figure 6B.15: Shrinking of Fedchenko Glacier in the Pamirs of Tajikistan. The debris-covered glacier tongue retreated by more than 1 km since 1933 and lowered by about 50 m since 1980.
Photo: V. Novikov (taken in summer 2006); data from the Tajik Agency on Hydrometeorology

Significant loss of glaciers in Central Asia began around the 1930s, and become more dramatic in the second half of the 20th century and continue into the 21st century. Glacier area was reduced by 25–30 per cent in the Tien Shan, by 30–35 per cent in the Pamirs, including its largest Fedchenko Glacier (Figure 6B.15), and by more than 50 per cent in northern Afghanistan[39,113,115–117].

Glaciers in higher altitudes (above 4 000 m above sea level) experienced less pronounced ice losses[39,113,119]. Total retreat has reached several kilometres for many larger glaciers, some hundred metres for smaller ones, and many hundreds of small glaciers have vanished[39,113]. Glacier degradation is accompanied by increasing debris cover on many glacier termini and the formation of glacier lakes[39,113]. See also the box on glaciers and water supply in Central Asia.

Glaciers and water supply in Central Asia

On average, glacier melt contributes 10–20 per cent of the total river runoff in Central Asia[39,120]. During dry and hot years, the input of glacier water into summer river flow could be as high as 70–80 per cent, compared to 20–40 per cent in normal years. This proportion is critical for agriculture – the economic sector that consumes about 90 per cent of water resources and is highly dependent on water availability. During the severe droughts of 2000–2001 in the southern districts of Central Asia, glacier water played a vital role in sustaining agricultural production. Irrigated crops such as cotton have survived, while most rain-fed crops, especially cereals, failed. This has strongly affecting the food security of millions of people in Tajikistan, Afghanistan and Iran. It is expected that glacier recession in the long term could reduce water supply, affecting the agricultural sector and energy security, thereby destabilizing the political situation since many of the rivers are transboundary[121]. In Central Asia, the Amu Darya river basin, where input of glacier water is significant, and the densely populated Ferghana Valley, are among most vulnerable to the impacts of droughts, climate change and glacier degradation.

Himalayas

The ice extent in the Himalayas is estimated to be about 33 050 square km[122]. Observations of individual glaciers indicate annual retreat rates varying from basin to basin – in some instances showing a doubling in recent years compared to the early 1970s. An 8 per cent area loss was observed for glaciers in Bhutan between 1963 and 1993[123]. The Imja Glacier in the Dudh-Koshi basin of the Everest region retreated almost 1600 m between 1962 and 2001 and another 370 m by 2006 (Figure 6B.16). The Gangotri Glacier in Uttaranchal, India, retreated about 2 km between 1780 and 2001[124]. The glacier shrinking is accompanied by the formation of unstable glacial lakes that threaten downstream areas with outburst floods. For a discussion of the impacts of glacier shrinking on water resources, please see the box on the water towers of Asia, at the end of Part 1 of this chapter.

Figure 6B.16: Growth of Imja Tsho Lake, Himalayas. The lake started to form in 1962 at the debris-covered tongue of Imja Glacier and grew to an area of about 1 km^2 by 2006. The growing moraine-dammed lake is potentially hazardous in case of a dam failure.
Photo: Michael Hambrey, SwissEduc (www.swisseduc.ch)/Glaciers online (www.glaciers-online.net); data from the International Centre for Integrated Mountain Development, Nepal

Tibetan Plateau

The Tibetan Plateau and surrounding regions in China have a total glacier area and volume of 59 400 km^2 and 5600 km^3, respectively. Glaciers in China have been retreating with an area loss of about 20 per cent since the Little Ice Age maximum extent in the 17th century[125,126]. Retreat increased during the last century, especially during the past ten years[127,128]. Several monitored glaciers show strong retreat. About 90 per cent of glaciers are retreating, and glacier retreat increases from the continental interior to the coastal margins[127,128]. With the impact of global warming on the region[127,129,130], glacier shrinkage will be faster and pose a serious threat to water resources in this region (see box on the water towers of Asia, at the end of Part 1 of this chapter).

South America

Glaciers in South America cover an area of about 25 700 square km[131], mainly in the Patagonian Icefields, which represent 66 per cent of South America's total ice area[132]. Chile has by far most of the glaciers; Argentina has an important number of ice bodies all along the Andes; Venezuela has less than 2 km^2 of ice at Pico Bolivar[133]. Less than 10 per cent of the glacier area is located in the tropical Andes[134] (see box on tropical glaciers).

In southern Patagonia, the glacial advance appears to have peaked between the late 17th and early 19th centuries[135]. Medium and small glaciers in central Chile and Argentina have shrunk considerably. This will affect the future availability of water resources, as these glaciers can contribute up to 68 per cent of meltwater during dry seasons. (See box on glacier changes and water availability in the tropical Andes). Most of the calving glaciers in Patagonia have also experienced drastic retreat[136], contributing significantly to sea level rise[27,137]. Ice avalanches in the cordillera have resulted in many thousands of deaths (see box on the deadly avalanches of Glaciar 511 in the Cordillera Blanca).

Glacier changes and water availability in the tropical Andes

There is growing evidence that glacier retreat in the tropical Andes has accelerated in recent decades due to atmospheric warming[134]. Ongoing rapid glacier recession was found to have enhanced discharge at the expense of catchments storage[138,139]. The recent increase in runoff is not likely to last very long[140]. In the long run, changes in runoff may occur which could severely affect the availability of water resources for future generations, particularly during dry periods. Short-term increases in stream discharge with critical long-term loss of storage are likely to be widespread over the Cordillera Blanca region. Since glacier melt currently provides a very significant proportion of discharge of the Rio Santa River, the latter is also likely to diminish with continued glacier loss.

The melting of glaciers may lead to water shortages for millions of people. Among the Andean countries at risk are Bolivia, Ecuador and Peru, where glaciers feed rivers all year round. On the Pacific side of Peru, 80 per cent of the water resources originate from snow and ice melt. During the dry seasons, glacier-fed surface waters often constitute the sole water resource for domestic, agricultural (Figure 6B.17) and industrial uses, not only for rural areas but also for major cities. A reduced glacier runoff will aggravate the problems associated with the water availability, especially if a potential warming leads to earlier snow melt, regional reductions in precipitation and an increase in evaporation[1,141].

Figure 6B.17: Glaciers and irrigation. Irrigation ditches on the slopes of Huascarán, Cordillera Blanca, Peru, support extensive agriculture during the dry season. Most water comes from nearby glaciers. *Photo: Michael Hambrey, SwissEduc (www.swisseduc.ch)/Glaciers online (www.glaciers-online.net)*

Deadly ice avalanches of Glacier 511 in the Cordillera Blanca, Peru

Many disasters have been recorded from the glaciers in the Cordillera Blanca. The 1962 and 1970 events originating from Glacier 511 on the Nevados Huascarán[142] (Figure 6B.18), the highest peak of which is at 6768 m above sea level in the Peruvian Andes, were particularly severe. On 10 January 1962, an ice avalanche took place with an estimated starting volume of 10 million m^3; the avalanche travelled down 16 km and destroyed the city of Ranrahirca, where 4000 people died. On 31 May 1970, the most catastrophic rock-ice avalanche known in history was triggered at 3:23 p.m. by a strong earthquake with a magnitude of 7.7. The avalanche originated from a partially overhanging cliff at 5400 to 6500 m above sea level, where the fractured granite rock of the peak was covered by a 30 metre thick glacier. The avalanche, which had an estimated volume of 50 to 100 million m^3, travelled 16 km to Rio Santa down a vertical drop of 4 km. Along its path, the avalanche overrode a hill in the downstream area and completely destroyed the city of Yungay, claiming about 18 000 lives.

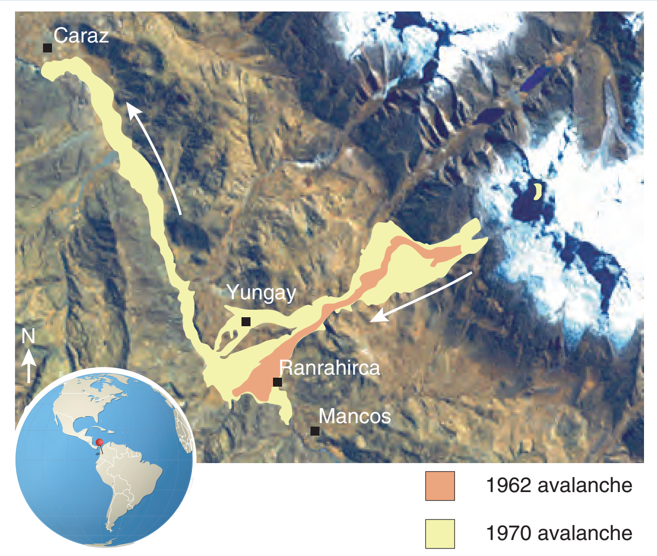


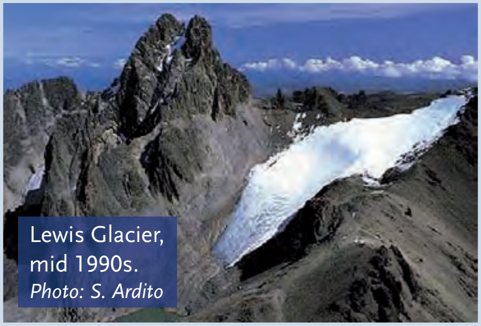
Figure 6B.18: Ice avalanches of the Nevados Huascarán in Peru. The severe events in 1962 and 1970 originated from Glacier 511 and claimed many thousands of lives.

Source: Data from the World Glacier Monitoring Service, Zurich, Switzerland and figure by UNEP's DEWA/GRID-Europe, Geneva, Switzerland

Tropical glaciers

Tropical glaciers are found in the high mountains of the Andes in Colombia (Figure 6B.19), Venezuela, Equador, Peru and Bolivia, as well as in the high mountains of East Africa (Figure 6B.20) and Irian Jaya, Indonesia. Around the period 1950–1990 they covered about 2760 km^2 with about one quarter in the Peruvian Cordillera Blanca[143]; this area had shrunk to about 2500 km^2 for the period 2000–2005[144]. The maximum extents of tropical glaciers occurred between the second half of the 17th century in Bolivia[145] and the late 19th century in East Africa[146]. From then, glacier shrinkage was more or less synchronous with the global one. Shrinkage rates were strongest in the 1940s, followed by a pause around the 1970s with several front advances. Since then, glaciers have again begun to retreat[134].

Since the publication of IPCC 2001, evidence has increased that changes in the mass balance of tropical glaciers are mainly driven by coupled changes in energy and mass fluxes related to interannual variations of regional-scale wet and dry seasons. Variations in atmospheric moisture content affect incoming solar radiation, precipitation and albedo, atmospheric longwave emission, and sublimation. At a large scale, the mass balance of tropical glaciers strongly correlates with tropical sea surface temperature anomalies and related atmospheric circulation modes[1].



Lewis Glacier, mid 1990s.
Photo: S. Ardito

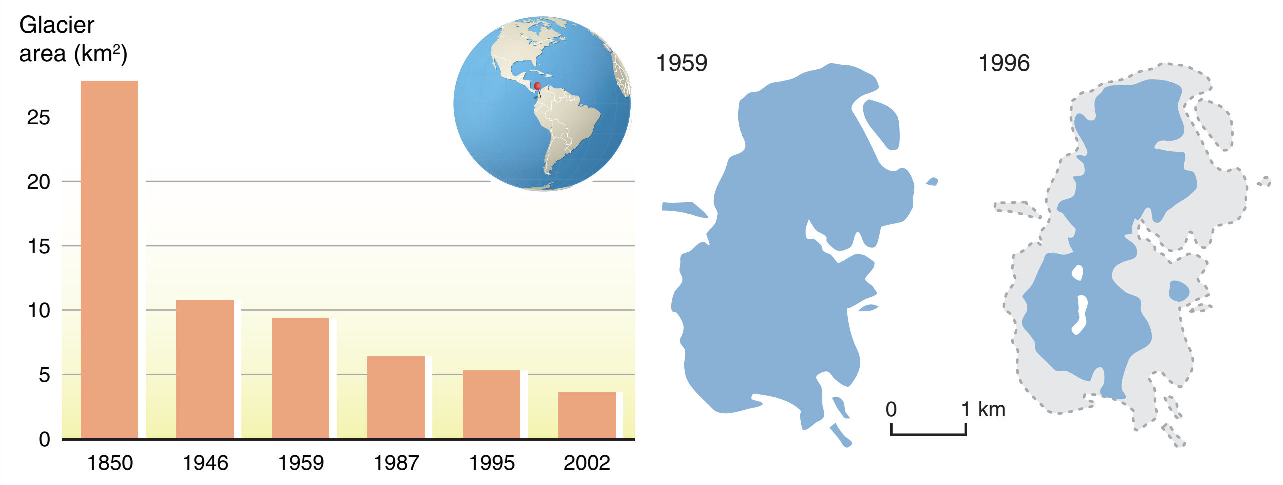
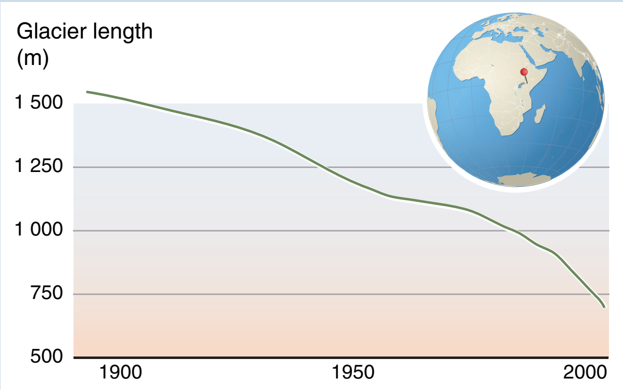


Figure 6B.19: Glacier changes on Nevado de Santa Isabel, Colombia. This inactive volcano lost about 87 per cent of its ice cover between 1850 and 2002.

Source: Data from the World Glacier Monitoring Service, Zurich, Switzerland



◀ ▲ **Figure 6B.20: Shrinking Lewis Glacier, Mount Kenya.** This tropical glacier retreated by more than 800 m between 1893 and 2004 and lost almost 16 m water equivalent of its thickness between 1979 and 1996.

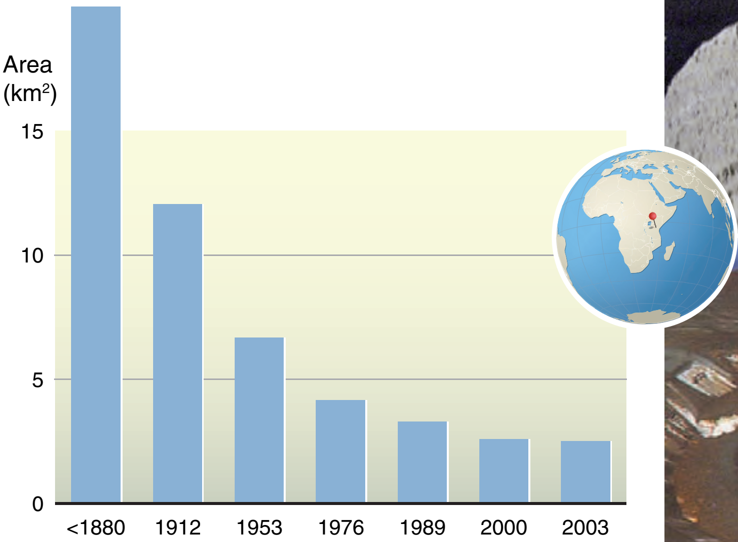
Source: Data from the World Glacier Monitoring Service, Zurich, Switzerland

Kersten glacier on Mt. Kilimanjaro.
Photo: Georg Kaser, Tropical Glacier Group, University of Innsbruck

Photo: Georg Kaser, Tropical Glacier Group, University of Innsbruck

African Mountains

Glaciers are found on three mountains in Africa: Rwenzori Mountains (5109 m above sea level), Mount Kenya (5199 m above sea level) and Kilimanjaro (5895 m above sea level) (Figure 6B.21), all located near the equator in East Africa. Recent retreat of these glaciers began around the 1880s as a result of a decrease in precipitation and an increase in solar radiation from reduced cloudiness. Later



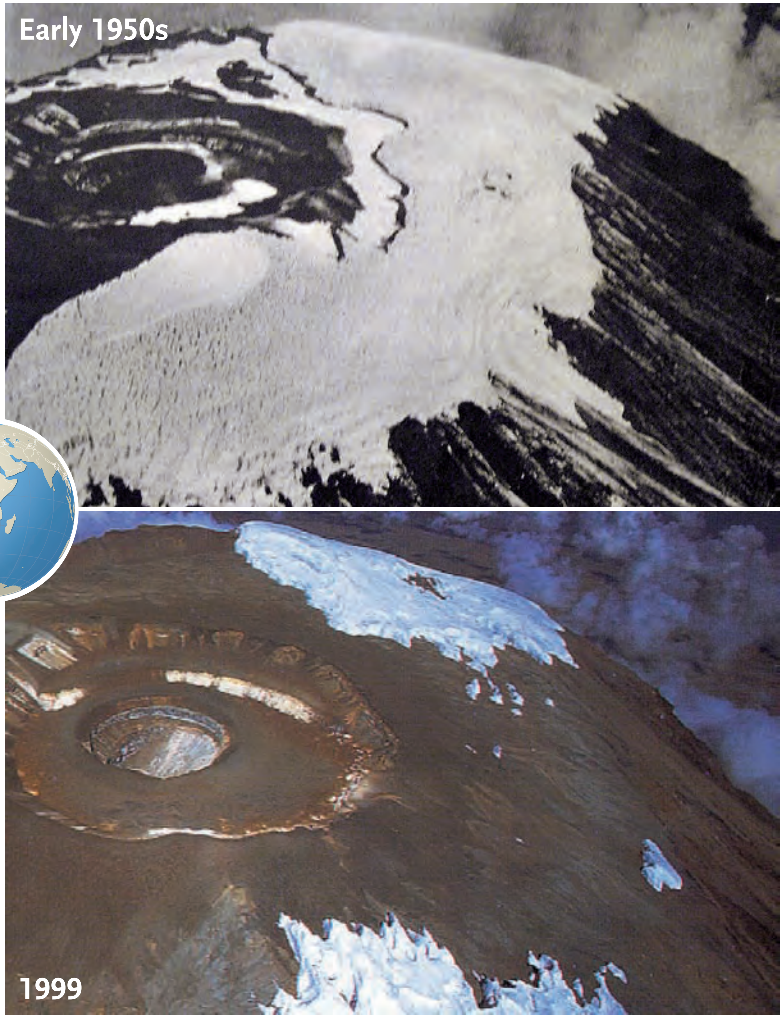


Figure 6B.21: Melting ice on Mount Kilimanjaro, East Africa. The graph shows the drastic reduction of the ice cover since the first observations in 1880, based on historical maps, aerial photographs and satellite images. The oblique photos illustrate the shrinking of the ice cover between the early 1950s and 1999. *Photos: (early 1950s) John West, (1999) Javed Jafferji. Data from Cullen and others 2006*[150] in the 20th century, increased temperature became an additional driver, although its relative importance is still debated[147–149]. Over the last century (1906–2006), these glaciers have lost an estimated 82 per cent of their area – from approximately 21 to 3.8 km^2. Close to 50 per cent of the glaciers on the Rwenzori Mountains, Mount Kenya and Kilimanjaro have disappeared, while larger glaciers – particularly on Kilimanjaro – have been fragmented[148,150,151].

The most pronounced impact of these receding glaciers is on the scenery. Unlike mountain glaciers in higher latitudes, the shrinking of the East African glaciers will have no significant impact on water resources. The hydrology on these mountains is dominated by extensive forest belts (hundreds to thousands times larger than the glaciated area) with a much higher annual rainfall. If all the glaciers on Kilimanjaro – which has the highest glacier to forest area ratio – were to melt in just one year, the resulting loss in water resources would be equivalent to only four per cent of the total annual rainfall over the forest belt[152].

New Zealand

Apart from a few glaciers on Mt. Ruapehu volcano in the North Island, the bulk of New Zealand's glaciers are located in the Southern Alps. They reached their maximum recent extent towards the end of the 18th century, with only minor retreat until the end of the 19th century[153]. Total glacier area was 1158 km^2 in 1978, with an estimated total ice volume of about 53 cubic km[154,155]. The overall estimated area and volume changes since the mid of the 19th century are –49 and –61 per cent, respectively[156]. Since the mid-1970s, the glaciers overall have experienced positive mass balances with those having short response times advancing noticeably from the mid-1980s. This period of advances appeared to be coming to an end at the beginning of the new century[157]. A recent study[85] estimates a net ice volume loss over the period 1977–2005 of 17 per cent, mainly due to calving into lakes and associated wasting at glacier tongues. Mass loss due to changes in glacier thickness, excluding that related to lake growth, has contributed only 7 per cent to the overall ice loss since 1977.

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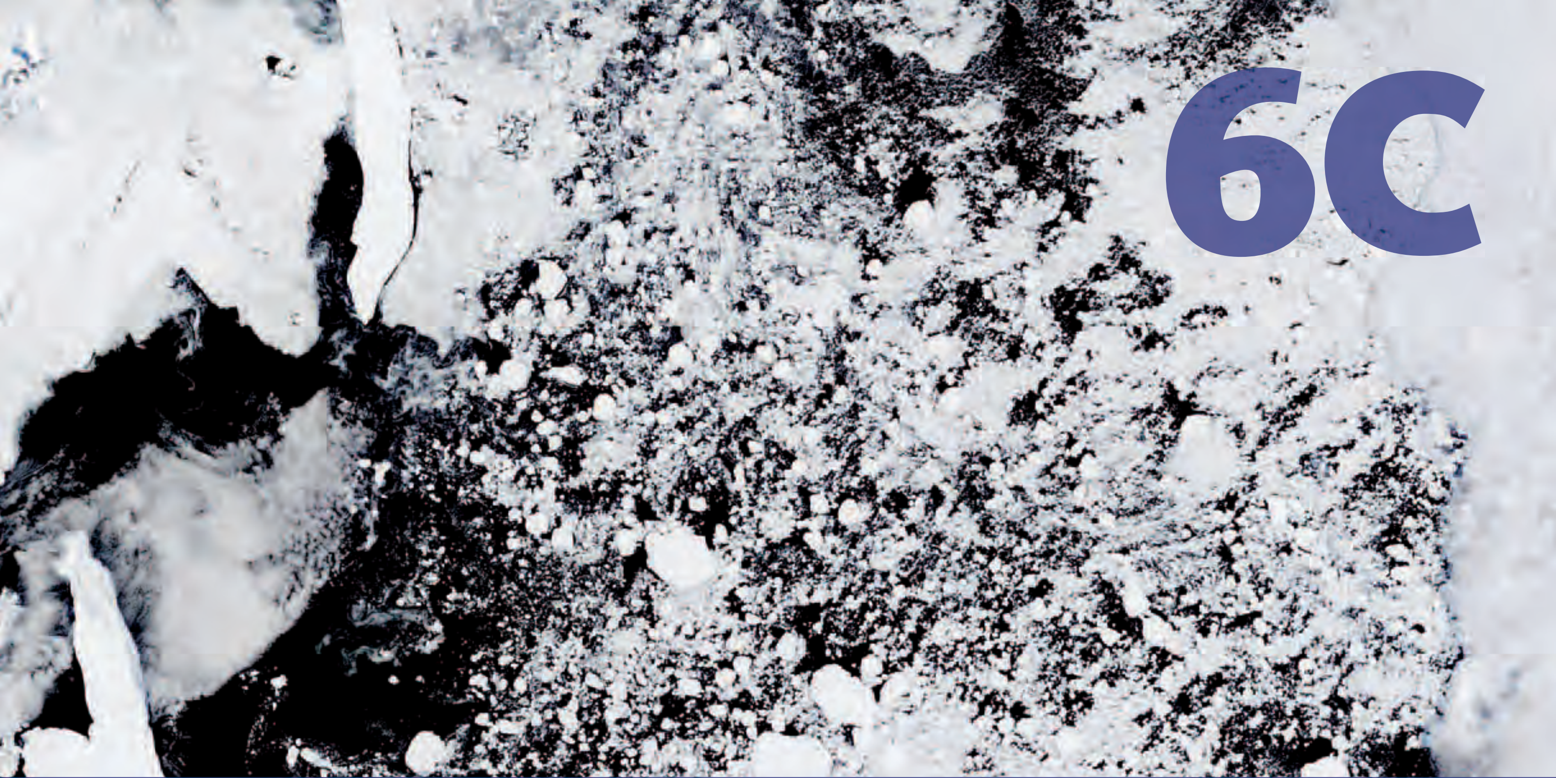

6C

Ice and Sea-level Change

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Ice and Sea-level Change

Summary

Sea-level rise is a major impact of global warming. There is clear scientific consensus that sea level is rising partly in response to past emissions of greenhouse gases from human activity. Melting glaciers and ice sheets are responsible for more than a third of the current rate of sea-level rise and the contribution of meltwater to the oceans can be expected to continue and accelerate as more land ice melts. Over the long term the ice sheets of Greenland and Antarctica have the potential to make the largest contribution to sea-level rise, but they are also the greatest source of uncertainty.

Sea level will rise during the 21st century and after and hence adaptation measures will be required during the 21st century and beyond. The rate and magnitude of sea-level rise, particularly beyond the mid 21st century, depends on future emission of greenhouse gases. Significant and urgent reductions in emissions are essential if we wish to avoid committing future generations to a sea-level rise of metres over centuries. Both adaptation and mitigation strategies need to be seriously considered, as together they can provide a more robust response to human-induced climate change than either can alone. Sea-level rise is both an international and a national issue. Preparation and implementation of adaptation and mitigation plans requires partnerships between nations, as well as between all levels of government, the private sector, researchers, non-governmental organizations and communities. Rising sea level is a mainstream issue in need of urgent and informed decision making and action.

Sea-level change: Sea level can change, both globally and locally, due to changes in the shape of the ocean basins, changes in the total mass of water in the ocean, and changes in ocean water density. Relative sea level is measured by a tide gauge with respect to the land upon which it is situated, and includes land uplift/subsidence. Mean sea level is the average sea level over a period long enough to average out effects from waves, tides and other short term fluctuations.

Components of the Cryosphere	Potential Sea-level rise (cm)
Antarctica ice sheet	5660
Greenland ice sheet	730
Glaciers and ice caps	
(lowest and [highest] estimates)	15 [37]
Permafrost (Northern Hemisphere)	~7
Snow on land (Northern Hemisphere)	
(annual minimum ~ maximum)	0.1 ~ 1
Sea ice and ice shelves	0

Source: IPCC 2007[26]

Introduction to sea level issues

Coastal regions, particularly some low-lying river deltas, have very high population densities. It is estimated that in excess of 150 million people live within 1 metre of high tide level, and 250 million within 5 metres of high tide[1,2]. Also, there are billions of dollars invested in coastal infrastructure immediately adjacent to the coast (Figure 6C.1). Sea-level rise

Figure 6C.1: Billions of dollars of coastal infrastructure has been built immediately adjacent to the coast, as shown here in Gold Coast, Australia.
Photo: Bruce Miller

Figure 6C.2: Low-lying coral atolls are particularly vulnerable to sea-level rise.
Photo: John Hay

contributes to coastal erosion and inundation of low-lying coastal regions – particularly during extreme sea-level events – and saltwater intrusion into aquifers, deltas and estuaries. These changes have impacts on coastal ecosystems, water resources, and human settlements and activities. Regions at most risk include heavily populated deltaic regions, small islands, especially atolls (islands formed of coral, Figure 6C.2), and sandy coasts backed by major coastal developments.

Sea-level rise is a central element in detecting, understanding, attributing and correctly projecting climate change. During the 20th century, the oceans have stored well over 80 per cent of the heat that has warmed the earth. The associated thermal expansion of the oceans, together with changes in glaciers and ice caps, will likely dominate 21st century sea-level rise. However, on longer time scales, the ice sheets of Greenland and Antarctica have the largest potential to contribute to significant changes in sea level.

Past sea-level change

Ice-age cycles and sea level

Sea level varied over 100 m during glacial–interglacial cycles as the major ice sheets waxed and waned as a result of changes in summer solar radiation in high northern hemisphere latitudes[3,4]. Palaeo data from corals indicate that sea level was 4 to 6 m (or more) above present day sea levels during the last interglacial period, about 125 000 years ago[5]. Climate and ice-sheet model simulations[6] indicate that Greenland was about 3° C warmer than today and that the Northern Hemisphere ice sheets contributed 2.2 to 3.4 m to the higher sea level, with the majority of the rise coming from the partial melting of the Greenland ice sheet.

During the last ice age, sea level fell to more than 120 m below present day sea level as water was stored in the

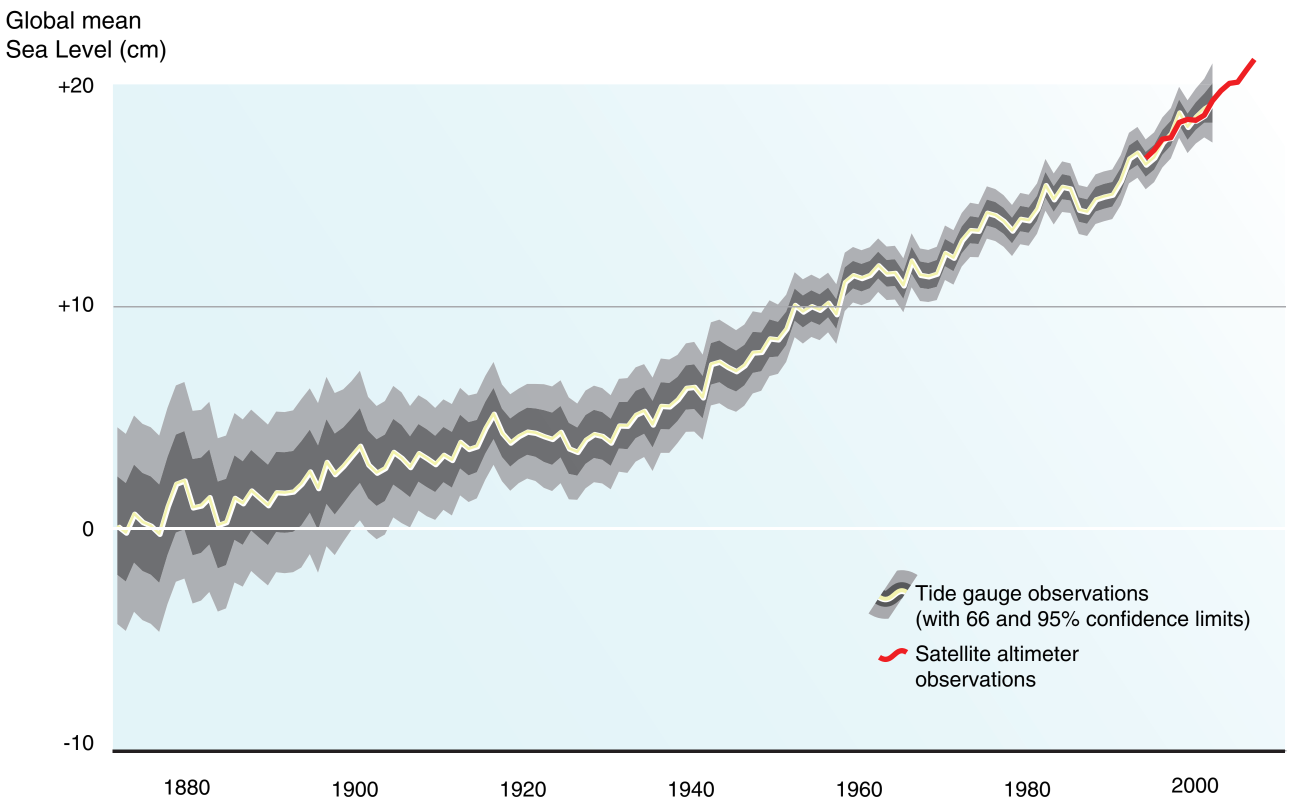

Figure 6C.3: Global averaged sea levels from 1870 to 2006 as inferred from tide-gauge data (white line, with 66% and 95% confidence limits given in dark and light shading) and satellite altimeter data (red line).

Source: Updated from Church and White 2006[13]

North American (Laurentian, Cordilleran and the Greenland), the northern European (Fennoscandia and the Barents region) and the Antarctic ice sheets[3,7]. As the ice melted, starting around 20 000 years ago, sea level rose rapidly at average rates of about 10 mm per year (1 m per century), and with peak rates of the order of 40 mm per year (4 m per century), until about 6000 years ago.

The last few thousand years

Sea level rose much more slowly over the past 6000 years. The sea level 2000 years ago can be deduced by examining fish tanks built by the ancient Romans. Because the tanks had to be at sea level for the sluice gates to function, one can precisely estimate sea level during the period of their use. Comparison of this level with historical records indicates that there has been little net change in sea level from 2000 years ago until the start of the 19th century[8].

Changes in local sea level estimated from sediment cores collected in salt marshes reveal an increase in the rate of sea-level rise in the western and eastern Atlantic Ocean during the 19th century and early 20th century[9–11], consistent with the few long tide-gauge records from Europe and North America[12].

The last few centuries

Coastal and island tide-gauge data show that sea level rose by just under 20 cm between 1870 and 2001, with an average rise of 1.7 mm per year during the 20th century and with an increase in the rate of rise over this period. This is consistent with the geological data and the few long records of sea level from coastal tide gauges[13] (Figure 6C.3). From 1993 to the end of 2006, near-global measurements of sea level (between 65°N and 65°S) made by high precision satellite altimeters indicate global average sea level has been rising at 3.1 ± 0.4 mm per year[14]. This rate is faster than the average rate of rise

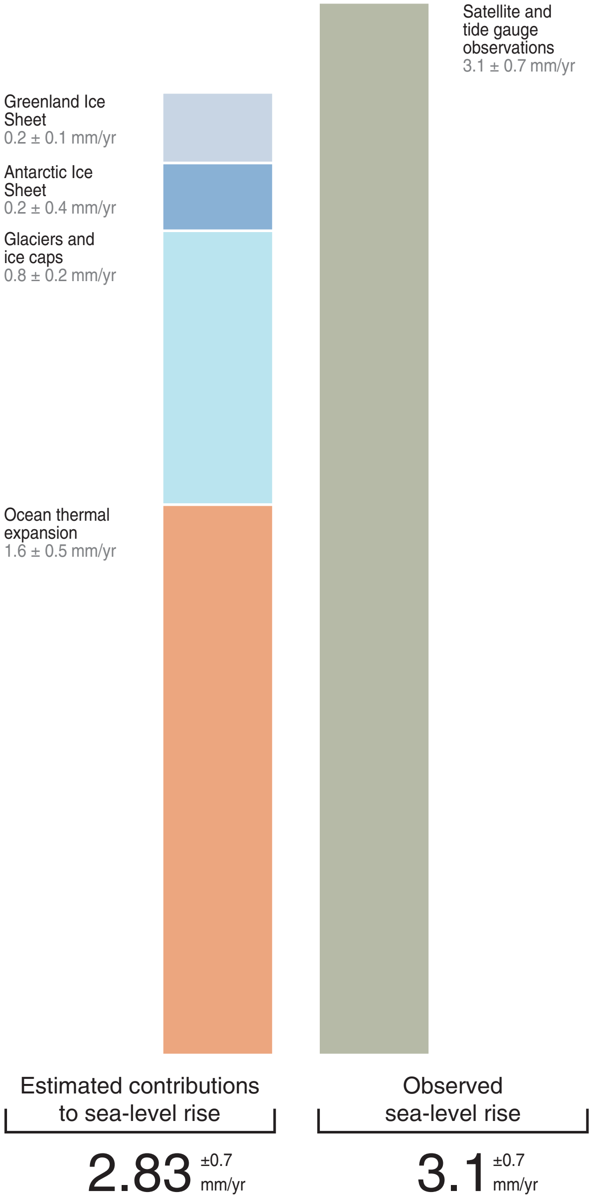

Figure 6C.4: Estimated contributions to sea-level rise from 1993 to 2003 (uncertainty intervals are 5 to 95%).

Source: Based on IPCC 2007[15]

during the 20th century which, in turn, was an order of magnitude larger than the rate of rise over the two millennia prior to the 18th century.

Contributions to sea-level change

The two main reasons for sea-level rise (Figure 6C.4) are thermal expansion of ocean waters as they warm, and increase in the ocean mass, principally from land-based sources of ice (glaciers and ice caps, and the ice sheets of Greenland and Antarctica). Global warming from increasing greenhouse gas concentrations is a significant driver of both contributions to sea-level rise.

From 1955 to 1995, ocean thermal expansion is estimated to have contributed about 0.4 mm per year to sea-level rise[16], less than 25 per cent of the observed rise over the same period. For the 1993 to 2003 decade, when the best data are available, thermal expansion is estimated to be significantly larger, at about 1.6 mm per year for the upper 750 m of the ocean alone[17], about 50 per cent of the observed sea-level rise of 3.1 mm per year. Kaser and others[18] estimate the melting of glaciers and ice caps (excluding the glaciers surrounding Greenland and Antarctica) contributed to sea-level rise by about 0.3 mm per year from 1961 to 1990 increasing to about 0.8 mm per year from 2001–2004.

The ice sheets of Greenland and Antarctica have the potential to make the largest contribution to sea-level rise, but they are also the greatest source of uncertainty (see also Section 6A). Since 1990 there has been increased snow accumulation at high elevation on the Greenland ice sheet, while at lower elevation there has been more widespread surface melting and a significant increase in the flow of outlet glaciers[19]. The net result is a decrease in the mass of the Greenland ice sheet – a posi-

Projections of 21st century sea-level rise

The Intergovernmental Panel on Climate Change (IPCC) provides the most authoritative information on projected sea-level change. The IPCC Third Assessment Report (TAR) of 2001[23] projected a global averaged sea-level rise of between 20 and 70 cm (the limits of the model projections) between 1990 and 2100 using the full range of IPCC greenhouse gas scenarios and a range of climate models. When an additional uncertainty for land-ice changes was included, the full range of projected sea-level rise was 9 to 88 cm[7]. For the IPCC's Fourth Assessment Report (AR4), 2007, the range of sea-level projections, using a much larger range of models, is 18 to 59 cm (with 90 per cent confidence limits) over the period from 1980-2000 to 2090-2100[15]. To allow a margin for the ice sheet uncertainties discussed above, the IPCC AR4 increased the upper limit of the projected sea-level rise by 10 to 20 cm above that projected by the models, but stated that "larger values cannot be excluded, but understanding of these effects is too limited to assess their likelihood or provide a best estimate or an upper bound for sea-level rise."

While the 2001 and 2007 IPCC projections are somewhat different in how they treat ice sheet uncertainties and the confidence limits quoted, a comparison of the projections (Figure 6C.5) shows the end results are similar, except that the lower limit of the 2001 projections has been raised from 9 to 18 cm.

From the start of the IPCC projections in 1990 to 2006, observed sea level has been rising more rapidly than the central range of the IPCC (2001 and 2007) model projections and is nearer to the upper end of the total range of the projections shown in Figure 6C.5[24], indicating that one or more of the model contributions to sea-level rise is underestimated. Rahmstorf[25] developed a simple statistical model that related 20th century surface temperature change to 20th century sea-level change. Using this relationship and projected surface temperature increases, estimated 21st century sea-level rise might exceed the IPCC projections and be as large as 1.4 m.

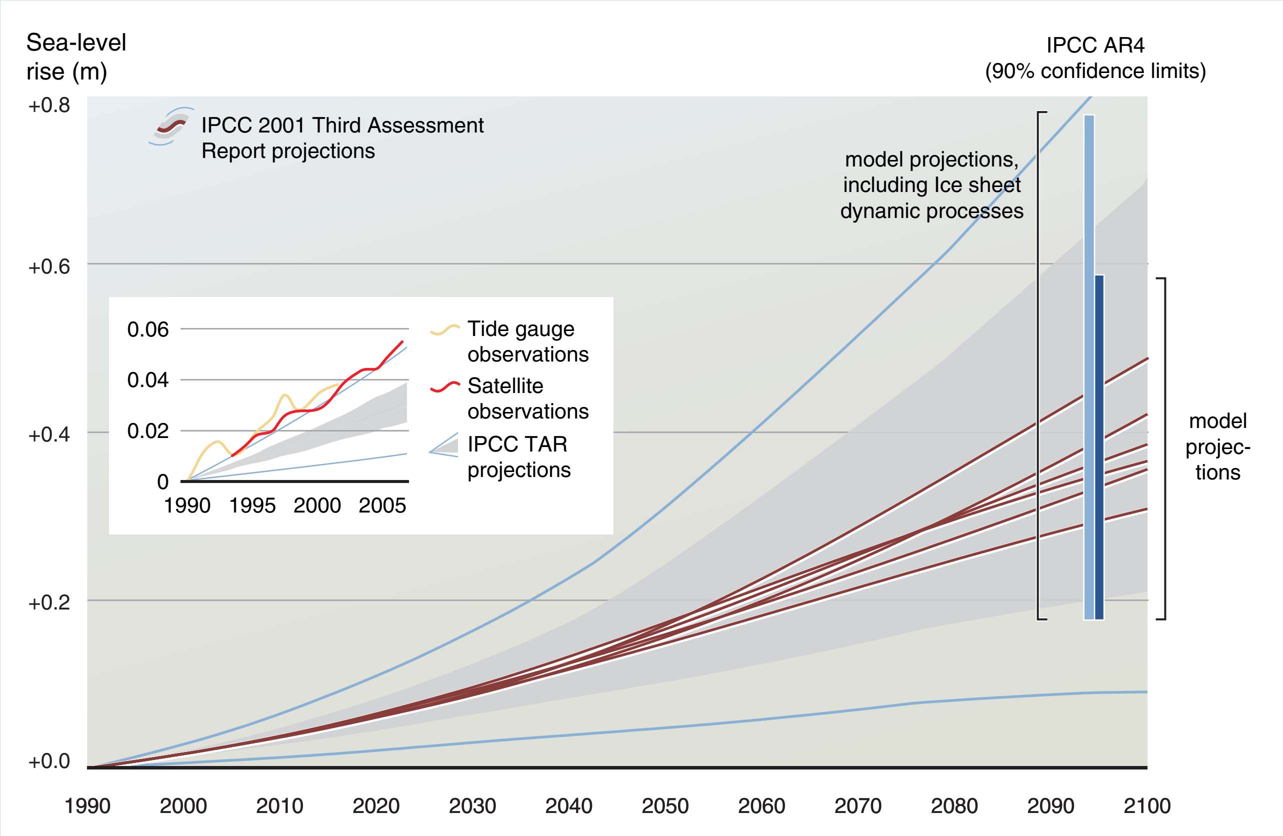

Figure 6C.5: Projected sea-level rise for the 21st century. The projected range of global averaged sea-level rise from the IPCC 2001 Assessment Report for the period 1990 to 2100 is shown by the lines and shading. The updated AR4 IPCC projections made are shown by the bars plotted at 2095, the dark blue bar is the range of model projections (90% confidence limits) and the light blue bar has the upper range extended to allow for the potential but poorly quantified additional contribution from a dynamic response of the Greenland and Antarctic ice sheets to global warming. Note that the IPCC AR4 states that "larger values cannot be excluded, but understanding of these effects is too limited to assess their likelihood or provide a best estimate or an upper bound for sea-level rise." The inset shows the observed sea levels from tide gauges (orange) and satellites (red) are tracking along the upper bound of the IPCC 2001 projections since the start of the projections in 1990.

Source: Based on Church and others 2001[7]; information added from IPCC 2007[15] and Rahmstorf and others[24] tive contribution to sea-level rise. For the Antarctic Ice Sheet, the uncertainty is greater. There are insufficient data to make direct estimates for the preceding decades. At present, the mass gain of the Antarctic Ice Sheet due to increased thickening of the East Antarctic Ice Sheet does not appear to compensate for the mass loss due to the increased glacier flow on the Antarctic Peninsula and the West Antarctic Ice Sheet[20,21]. Modelling studies suggest that the Antarctic Ice Sheet is still responding to changes since the last ice age and that this may also be contributing to sea-level rise.

The difference between the sum of the contributions to sea-level rise and the observed rise from 1993 to the present is smaller than the estimated errors. However during the 1961 to 2003 period, ocean thermal expansion along with the melting of glaciers and ice caps and a reasonable allowance for an ice sheet contribution do not adequately explain the observed rise. Possible reasons for this discrepancy include the inadequate ocean database, particularly for the deep and Southern Hemisphere oceans, leading to an underestimate of ocean thermal expansion, and inadequate measurements of the cryosphere.

Changes in the storage of water on land, including changes in lakes, building of dams (both large and small), seepage into aquifers, and mining of ground water, may also be important – but the extent of these contributions is unclear. Model studies suggest significant variability from year to year of the climate-related components of terrestrial water storage, but little long-term trend[22].

Outlook for sea-level change

During the 21st century, sea level will continue to rise due to warming from both past (20th century and earlier) and 21st century greenhouse gas emissions (see box on projections of 21st century sea-level rise). Ocean thermal expansion is likely to be the dominant contribution to 21st century sea-level rise, with the next largest contribution coming from the melting of glaciers and ice caps.

Recent estimates indicate that non-polar glaciers and ice caps may contain only enough water to raise sea level by 15 to 37 cm[26]. Melting of glaciers at lower altitude and latitude in a warming climate will eventually result in significant reduction of the sizes of the glaciers and reductions in their contribution to the rate of sea-level rise. The most important impact is from large glaciers in regions with heavy precipitation, such as the coastal mountains around the Gulf of Alaska (Figure 6C.6), or Patagonia and Tierra del Fuego in South America. Many of these glaciers flow into the sea or large lakes and melt quickly because the ice is close to melting temperature (see also Section 6B).

For Greenland, both glacier calving and surface melting contribute to mass loss. Over the last few decades surface melting has increased[27] and now dominates over increased snowfall, leading to a positive contribution to sea level during the 21st century. For the majority of Antarctica, present and projected surface temperatures during the 21st century are too cold for significant melting to occur and precipitation is balanced by glacier flow into the ocean. In climate change scenarios for the 21st century, climate models project an increase in snowfall, resulting in increased storage of ice in Antarctica, partially offsetting other contributions to sea-level rise. However, an increase in precipitation has not been observed to date[28].

In addition to these surface processes, there are suggestions of a potential dynamical response of the Greenland and Antarctic ice sheets (see also Section 6A). In Greenland, there was a significant increase in the flow rate of many of the outlet glaciers during the early 21st century[19]. One potential reason for this is increasing surface melt making its way to the base of the glaciers, lubricating their flow over the bed rock, consistent with increased glacier

Figure 6C.6: Glaciers in the Alaskan coastal mountains melt more quickly as air temperatures increase, contributing to sea-level rise. *Photo: iStockphoto* flow during the summer melt season[29] (see Figure 6A.6 in previous section). However, recent work[30] has shown the flow rate of at least two of these glaciers has recently decreased to near their earlier rates, suggesting that there is significant short-term variability in glacier flow rates.

Another potential factor is the role of ice shelves in restraining the flow of outlet glaciers. The rapid break up of the Larsen B Ice Shelf in the Antarctic Peninsula (Figure 6A.4 in previous section) was followed by a significant increase in the flow rate of the glaciers previously feeding this ice shelf[31], suggesting that the ice shelves played a role in restraining the flow of outlet glaciers. However, some modelling studies suggest this is a transient acceleration. Another important consideration is that the West Antarctic Ice sheet is grounded below current sea level. As the ice sheet thins and starts to float, warm ocean water can penetrate beneath and enhance melting at the base.

All of these dynamic ice-sheet processes, in both Greenland and West Antarctica, could lead to a greater rate of sea-level rise than in current projections. However, the processes are inadequately understood and are therefore not included in the current generation of ice-sheet and climate models. It is therefore not possible to make robust quantitative estimates of their long-term contribution to the rate of sea-level rise.

Greenland ice sheet.
Photo: Konrad Steffen

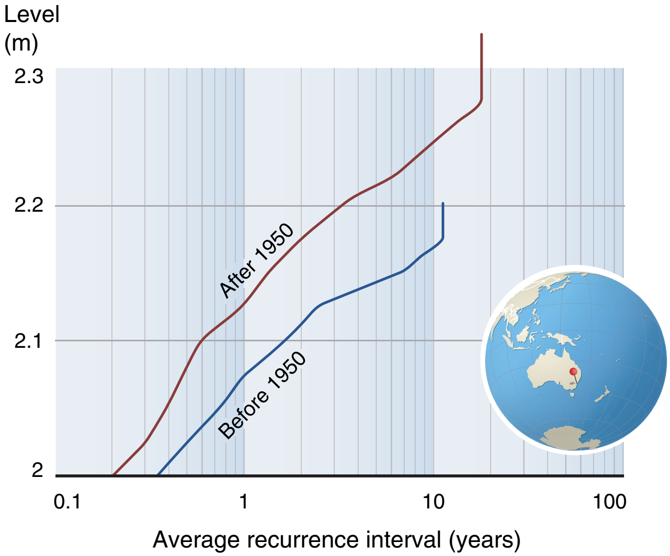

Figure 6C.7: Average Recurrence Interval for sea-level events of a given height at Sydney, Australia. For the second half of the 20th century (red line), the average recurrence interval for a sea-level height of a given value is less than half the value for the first half of the 20th century (blue line).

Sources: Based on Church and others 2006[42]

Longer-term projections

For the next few decades, the rate of sea-level rise is partly locked in by past emissions, and will not be strongly dependent on 21st century greenhouse gas emission. However, sea-level projections closer to and beyond 2100 are critically dependent on future greenhouse gas emissions, with both ocean thermal expansion and the ice sheets potentially contributing metres of sea level rise over centuries for higher greenhouse gas emissions.

For example, in the case of the Greenland Ice Sheet, if global average temperatures cross a point that is estimated to be in the range of 1.9°C to 4.6°C above pre-industrial values[32], this will lead to surface melting exceeding precipitation. The inevitable consequence of this is an ongoing shrinking of the Greenland Ice Sheet over a period of centuries and millennia[15]. This conclusion is consistent with the observation that global sea level in the last interglacial, when temperatures were in this range, was several metres higher than it is today. This threshold (of melting exceeding precipitation) could potentially be crossed late in the 21st century. In addition, dynamic responses of the Greenland and West Antarctic Ice Sheets could lead to a significantly more rapid rate of sea-level rise than from surface melting alone.

Regional patterns of sea-level rise

For the period 1993 to the present, there is a clear pattern of regional distribution of sea-level change that is also reflected in patterns of ocean heat storage[33]. This pattern primarily reflects interannual climate variability associated with the El Niño/La Niña cycle. During El Niño years sea level rises in the eastern Pacific and falls in the western Pacific whereas in La Niña years, the opposite is true. At this stage there is no agreed-upon pattern for the longer-term regional distribution of projected sea-level rise. There are, however, several features that are common to most model projections – for example a maximum in sea-level rise in the Arctic Ocean and a minimum sea-level rise in the Southern Ocean south of the Antarctic Circumpolar Current[34].

In addition, past and ongoing transfers of mass from the ice sheets to the oceans result in changes in the gravitational field and vertical land movements and thus changes in the height of the ocean relative to the land[35–37]. These large-scale changes, plus local tectonic movements, affect the regional impact of sea-level rise.

Withdrawal of groundwater and drainage of susceptible soils can cause significant subsidence. Subsidence of several metres during the 20th century has been observed for a number of coastal megacities[38]. Reduced sediment inputs to deltas are an additional factor which causes loss of land elevation relative to sea level[39].

Extreme events

Sea-level rise will be felt both through changes in mean sea level, and, perhaps more importantly, through changes in extreme sea-level events. Even if there are no changes in extreme weather conditions (for example, increases in tropical cyclone intensity), sea-level rise will result in extreme sea levels of a given value being exceeded more frequently.

This change in the frequency of extreme events has already been observed at many locations[40–43] (Figure 6C.7). The increase in frequency of extreme events will depend on local conditions, but events that currently occur once every 100 years could occur as frequently as once every few years by 2100.

Table 6C.1: The main natural system effects of relative sea-level rise, interacting factors and examples of socio-economic system adaptations. Some interacting factors (for example, sediment supply) appear twice as they can be influenced both by climate and non-climate factors. Adaptation strategies: **P** = Protection; **A** = Accommodation; **R** = Retreat.

Source: Based on Nicholls and Tol 2006[47]

Natural System Effects		Interacting Factors		Socio-economic System Adaptations
		Climate	Non-climate	
1. Inundation, flood and storm damage	a. Surge (sea)	– wave/storm climate – erosion – sediment supply	– sediment supply – flood management – erosion – land use	– dykes/surge barriers [**P**] – building codes/floodwise buildings [**A**] – land use planning/hazard delineation [**A**/**R**]
	b. Backwater effect (river)	– run-off	– catchment management – land use	
2. Wetland loss (and change)		– CO_2 fertilization – sediment supply	– sediment supply – migration space – direct destruction	– land-use planning [**A**/**R**] – managed realignment/forbid hard defences [**R**] – nourishment/sediment management [**P**]
3. Erosion (direct and indirect morphological change)		– sediment supply – wave/storm climate	– sediment supply	– coast defences [**P**] – nourishment [**P**] – building setbacks [**R**]
4. Saltwater Intrusion	a. Surface Waters	– run-off	– catchment management – land use	– saltwater intrusion barriers [**P**] – change water abstraction [**A**/**R**]
	b. Ground-water	– rainfall	– land use – aquifer use	– freshwater injection [**P**] – change water abstraction [**A**/**R**]
5. Rising water tables/impeded drainage		– rainfall – run-off	– land use – aquifer use – catchment management	– upgrade drainage systems [**P**] – polders [**P**] – change land use [**A**] – land use planning/hazard delineation [**A**/**R**]

Overview of sea-level rise impacts and adaptation

Impacts of sea-level rise are determined by the relative sea-level change, reflecting not only the global-mean trend in sea level, but also regional and local variations in sea-level change and in geological uplift and subsidence[44]. Areas that are subsiding are more threatened. The most significant impacts may be associated with changes in interannual variability and changes in extreme sea levels resulting from storms. Given that more intense storms are expected both in the tropics and outside of the tropics[45], extreme sea level scenarios due to changing storm characteristics need to be considered along with mean sea-level rise scenarios, although this information is presently much less developed for most coastal areas[46].

Maintaining and restoring native coastal vegetation in response to sea-level rise

Without stable shorelines, the integrity of infrastructure such as roads, airports, buildings, and residences may be threatened. In addition, significant amounts of salt water may infiltrate the groundwater and degrade drinking-water sources, wetlands, and agriculture.

Intact native vegetation is ideal for stabilizing shorelines. For example, plants indigenous to tropical islands have evolved to tolerate high temperatures and humidity, salt water, extreme sunlight and storms. These vegetation communities function as soil binders and as effective filters, thus maintaining coastal berms and forests. They are part of the dynamic coastal system, well adapted to shifting shorelines. In contrast, seawalls are static, immobile objects that do not conform to the advance and retreat of shorelines. When shorelines shift, sea walls may become undermined and no longer function (Figure 6C.8(a)). Furthermore, seawalls and other similar construction activities often disrupt or displace native vegetation communities. Preserving and restoring this vegetation helps maintain shoreline integrity in the face of rising sea level (Figure 6C.8(b)).

Figure 6C.8: Shoreline integrity in the Fijian village of Yadua.
(a) Part of the degraded seawall protecting the village – storm waves penetrate into the land behind the damaged sea wall and erode the coastal flat on which the village lies.
(b) Mangrove nursery and recent foreshore plantings.
Photos: Patrick Nunn

Relative sea-level rise has a wide range of effects on coastal systems, summarized in Table 6C.1. The immediate effect is submergence and increased flooding of coastal land, as well as saltwater intrusion into surface waters. Longer-term effects also occur as the coast adjusts to the new environmental conditions, including increased erosion, ecosystem changes, and saltwater intrusion into groundwater. These longer-term changes interact with the immediate effects of sea-level rise and often exacerbate them. For instance coastal erosion, which on sandy coastlines occurs at tens to hundreds of times the rate of sea-level rise, will tend to degrade or remove protective coastal features such as sand dunes and vegetation, thereby increasing the risk of coastal flooding (see box on maintaining and restoring coastal vegetation).

Sea-level rise does not happen in isolation (see Table 6C.1 for interacting factors) and it is only one of a number of changes that are affecting the world's coasts. For instance, under a positive sediment budget, coasts may be stable or even grow, while under a negative sediment budget, sea-level rise is exacerbating a situation that is already prone to erosion. Due to increasing human activity in coastal zones and their catchments, sea-level rise impacts are more often exacerbating an adverse situation than not. This emphasizes the need to analyse the impacts of sea-level rise within a framework which addresses multiple stresses.

These natural system changes have many important direct socio-economic impacts on a range of sectors. For instance, flooding can damage key coastal infrastructure, the built environment, and agricultural areas, while erosion can lead to a loss of buildings with adverse consequences on coastal communities and on sectors such as tourism and recreation. As well as these direct impacts, indirect impacts are also apparent, including impacts on human health. For example, mental health problems increase after a flood. Thus, sea-level rise has the potential to produce a cascade of direct and indirect impacts through the socio-economic system. The uncertainties around the actual socio-economic impacts are also large, as impacts will depend on the magnitude of changes to natural systems and on society's ability to adapt to these changes.

Most existing studies examine exposure or potential impacts – few consider the potential impacts while taking into account realistic assumptions about adaptation. This is a complex issue to analyse as it requires integration across the natural, engineering and social sciences. The available analyses all suggest that the high value of many coastal areas would make widespread adaptation to sea-level rise an economically rational response in cost-benefit terms[47,48]. Following this logic, actual impacts would be greatly reduced through adaptation, but

this would require significant investment and planning. Measures instituted to protect human safety may also exacerbate ecosystem impacts, and this needs to be taken into account. For example, building dykes can result in the loss of salt marshes and mudflats[49]. Delivering effective adaptation will be challenging, especially in the poorer countries – and disasters can still occur in rich countries, as shown by Hurricane Katrina in 2005.

◀ Mangrove on Erakor Island, Vanuatu.
Photo: Topham Picturepoint/TopFoto.co.uk

▼ **Figure 6C.9:** Male, Maldives.
Photo: Bruce Richmond, USGS

Vulnerable sectors, systems and localities

Small islands and low-lying coastal areas, such as deltas, have long been considered amongst the areas most vulnerable to sea-level rise[39,50–53]. Low elevation and close proximity to a rising ocean are important collective contributors to this vulnerability. But such a view is overly simplistic. While the interiors of many small islands rise to high elevations, settlements, infrastructure and facilities are usually concentrated around the coastal perimeter. In low-lying areas (such as coastal Bangladesh) the adverse consequences of a rising sea level will be felt at least 100 km inland[54]. Variations in relative sea-level rise also need to be considered, especially in large, geologically-complex features, such as deltas.

In the context of small islands and low-lying areas, the following discussion identifies some of the sectors, systems and localities that are especially vulnerable to sea-level rise. Vulnerability is influenced not only by the nature of the impacts, but also by the capacity to adapt.

Vulnerability of coastal wetlands, mangroves and biodiversity

Since coastal vegetated wetlands are intimately linked to sea level, these ecosystems are sensitive to long-term sea-level change. Modelling of coastal wetlands (excluding sea grasses) suggests that 33 per cent of global wetlands would be lost with a 36 cm rise in sea level from 2000 to 2080 and 44 per cent would be lost with a 72 cm rise in sea level over this period[55]. Losses would be most severe on the Atlantic and Gulf of Mexico coasts of North and Central America, the Caribbean, the Mediterranean, the Baltic and most small island regions, largely reflecting their low tidal range.

A global assessment of mangrove accretion rates[56] indicates that the rate at which mangroves grow in height is variable but commonly approaches 5 mm per year. This is greater than recent, and even many projected, rates of increase in global mean sea level. However, many mangrove shorelines are subsiding and thus experiencing a more rapid relative sea-level rise[57]. Sea-level rise could reduce the current half-million hectares of mangroves in 16 Pacific Island countries and territories by as much as 13 per cent by 2100[58].

Higher relative coastal water levels, and the associated increasing salinity of estuarine systems, will encourage the inland migration of coastal plant and animal communities. However, if such migration is blocked by natural or human-built barriers it will be difficult for these plant and animal communities to survive as sea level rises. Moreover, impacts on one or more 'leverage species' can result in sweeping community-level changes[59].

Vulnerability of sediment processes and coastal zones

Accelerated sea-level rise will exacerbate the problems of coastal erosion which are already widespread globally. But there is not a simple relationship between sea-level rise and the retreat of low-lying coasts[60]. For example, large amounts of sand from the neighbouring open coast can be transported into estuaries and lagoons due to sea level rise. As a result, local erosion rates for these coasts can be an order of magnitude greater than simple equilibrium models would suggest[61].

Changes in sediment supply can influence atoll island morphology to at least the same extent as sea-level rise[62,63]. This is consistent with the view that uninhabited islands of the Maldives are morphologically resilient while those that have been subject to substantial human modification (Figure 6C.9) are inherently more vulnerable[64,65].

Vulnerability of coral reefs

Healthy coral reefs have kept pace with rapid postglacial sea-level rise, suggesting that the projected rates of sea-level rise are unlikely to threaten these reef ecosystems, at least over the next few decades[66]. Some Indo-Pacific reef flats are currently exposed at low tide. Anticipated increases in sea level might well result in their submergence and subsequent recolonization by corals[67]. However, other climate stresses, especially rising sea surface temperature threaten many coral reefs worldwide[46].

Vulnerability of water resources

The water resources of small islands and low-lying coastal areas are very susceptible to sea-level rise. Figure 6C.10 illustrates the direct impacts on the water resources sector, as well as the plethora of higher-order impacts which affect not only that sector but most, if not all, other sectors including health, transport and agriculture.

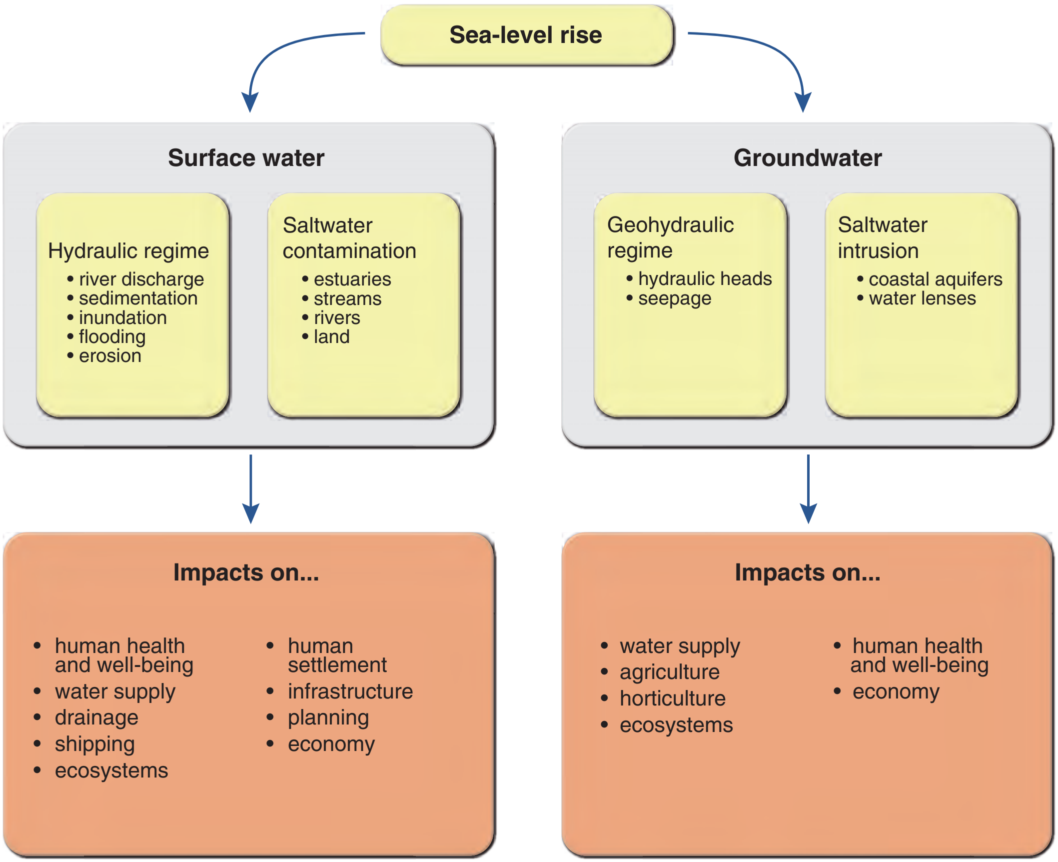

Figure 6C.10: Effects of sea-level rise on water resources of small islands and low-lying coastal areas.

Source: Based on Hay and Mimura 2006[68]

The magnitude of impacts from sea-level rise

Even for today's socio-economic conditions, both regionally and globally, large numbers of people and significant economic activity are exposed to sea-level rise (Figure 6C.11).

With no additional coastal protection a 40 cm rise in sea level by the 2080s (see Figure 6C.5) would result in more than 100 million people being flooded annually, regardless of which socio-economic scenario is adopted (Figure 6C.12). Under this adaptation scenario of no additional protection response, most of these people might be forced to move to higher locations. Upgraded coastal defences can reduce the impacts substantially: in many cases to levels lower than estimated for the baseline (in 1990).

The densely populated megadeltas are especially vulnerable to sea-level rise. More than 1 million people living in the Ganges-Brahmaputra, Mekong and Nile deltas will be directly affected simply if current rates of sea-level rise continue to 2050 and there is no adaptation. More than 50 000 people are likely to be directly impacted in each of a further nine deltas, and more than 5000 in each of a further 12 deltas[39]. Some 75 per cent of the population affected live on the Asian megadeltas and deltas, with a large proportion of the remainder living on deltas in Africa. These impacts would increase dramatically with accelerated sea-level rise.

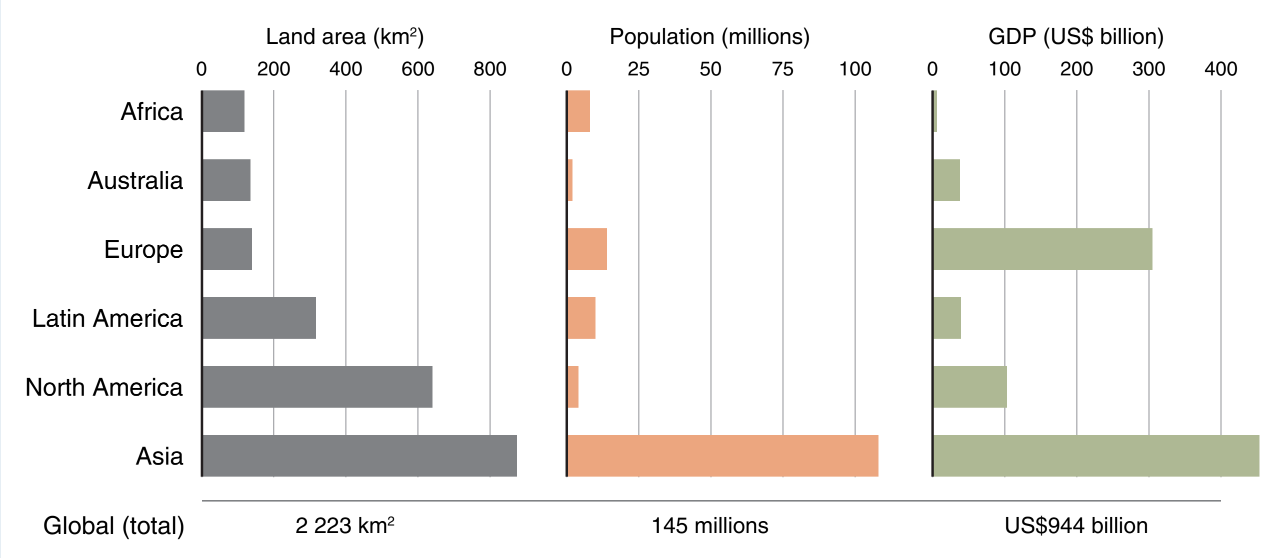

Figure 6C.11: Indicative estimates of regional and global exposure to a uniform 1 m rise in sea level based on today's population and economy.

Source: Based on Anthoff and others 2006[1]

A one-metre rise in sea level would potentially affect more land, people, and value of economic activity in Asia than in any other continent.
Photo: Veer.com

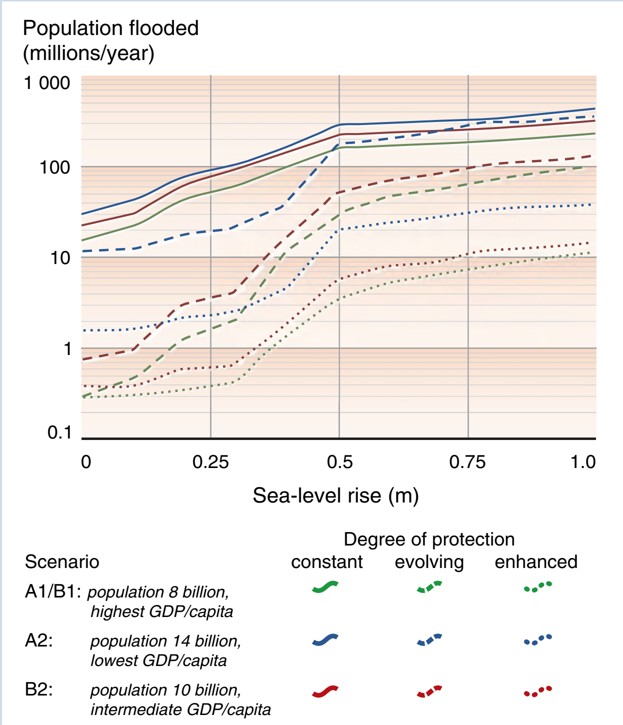

Figure 6C.12: Estimates of people flooded in coastal areas in the 2080s as a result of sea-level rise and for given socio-economic scenarios and protection responses. The lines represent IPCC Special Report on Emissions Scenarios (SRES) based on different world views. The differences in impacts between the SRES scenarios for the same amount of sea-level rise and protection response reflect differences in exposure (population) and ability to adapt (wealth). The solid lines represent a level of 'constant' (no additional) protection response. The dashed and dotted lines represent the addition of protection response to different degrees.

Source: Based on Nicholls and Lowe 2006[69]*; Nicholls and Tol 2006*[47]

The direct influence of sea-level rise on water resources comes principally from:

- new or accelerated erosion of coastal wetlands;
- more extensive coastal inundation and higher-levels of sea flooding (see box on the magnitude of impacts from sea-level rise);
- increases in the landward reach of sea waves and storm-surges;
- seawater intrusion into surface waters and coastal aquifers (contaminating fresh water); and
- further encroachment of tidal waters into estuaries and coastal river systems.

Sea-level rise, on its own, will not result in seawater contaminating a fresh groundwater lens – it merely raises the height of the interface between the saline and fresh water. But frequently, when one or more of the other direct impacts occurs, seawater will penetrate further into coastal aquifers, including those of small islands. Higher sea levels will, in most cases, result in a local rise in the water table.

The distance inland that a water table will be affected by sea-level rise depends on a range of factors, including elevation and subsurface permeability. In some locations, particularly in deltas such as those in Bangladesh, rising water tables can occur as far as several tens of kilometres inland. Thus, for small islands and even for depressions that are some distance from the coast, sea-level rise may lead to an expansion of the standing body of fresh and brackish water. Drainage and productive use of these and adjacent low-lying areas will often be impeded.

Vulnerability of deltas

Rates of relative sea-level rise can greatly exceed the global average in many heavily populated deltaic areas[39]. This is due to natural subsidence from compaction of sediment under its own weight and human-induced subsidence from water extraction and drainage.

Bangladesh consists almost entirely of the densely populated deltaic plains of the Ganges, Brahmaputra, and Meghna rivers. Here accelerated relative sea-level rise will likely be further compounded by increasing extreme water levels associated with more intense storm surges and monsoon rains. These are in turn related to rising water temperatures in the Bay of Bengal. The vulnerability of Bangladesh is exacerbated by the expansion of aquaculture, involving the conversion of mangroves which provide natural coastal defences[53]. Thus sea-level rise poses a particular threat to deltaic environments, especially with the synergistic effects of other climate and human pressures[70].

Vulnerability of human settlements and activities

Human settlements and activities are preferentially concentrated close to the coasts of both small islands and low-lying areas[71] (Figure 6C.13). This places them at risk from high sea levels, be they associated with extreme events such as storm surges, or increases over the longer term[72]. A few examples:

- The sustainability of island tourism resorts in Malaysia is expected to be compromised by rising sea level causing both beach erosion and saline contamination of the coastal wells that are a major source of water supply for the resorts[73].
- The number of annual rice crops possible in the Mekong delta will decline dramatically with a relative sea-level rise of 20 to 40 cm[74].
- In Hawaii numerous electrical power plants and substations, petroleum and gas storage facilities and lifeline infrastructure such as communications, telephone

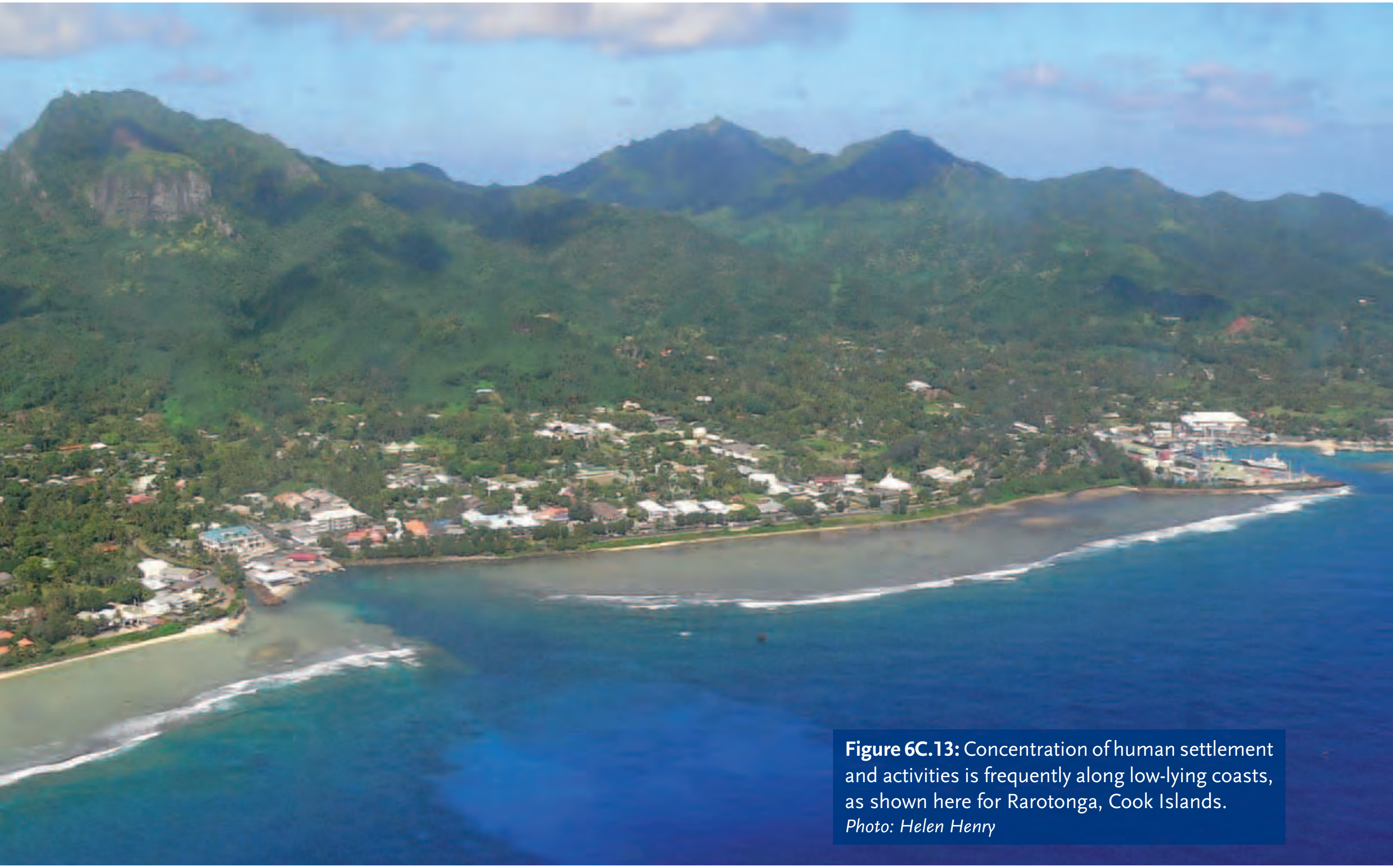

Figure 6C.13: Concentration of human settlement and activities is frequently along low-lying coasts, as shown here for Rarotonga, Cook Islands. *Photo: Helen Henry*

offices, fire and police stations are mostly located within coastal inundation zones[75].

- The port facilities at Suva, Fiji and Apia, Samoa would experience overtopping, damage to wharves and flooding of the hinterland if there was a 0.5 m rise in sea level combined with waves associated with a 1 in 50 year cyclone[76].

In addition, most of the world's megacities are in vulnerable coastal regions, some are located on sinking deltaic regions, and are subject to flooding from storm surges as so graphically illustrated by the New Orleans experience of Hurricane Katrina in 2005. See the box on New York City for a case study on vulnerability of megacities to sea-level rise.

Vulnerability of megacities: case study of New York City

New York City faces increasing vulnerability to flooding and storm surges as sea level rises, with extensive damage to infrastructure and buildings, beach erosion, and loss of wetlands. Within the last 45 years, at least three coastal storms have produced widespread inundation and disruption of area transportation systems. Major portions of the city's transportation infrastructure lie at elevations of 3 m or less and have been flooded by severe storms in the past. Regional beaches and coastal wetlands, which provide recreation areas and buffer zones against destructive storm surges, have been eroding, due in part to historic sea-level rise and to the presence of "hard" engineering structures.

Regional 20th century rates of relative sea-level rise (2.1 to 3.8 mm per year) lie above the global mean trend as a result of subsidence caused by ongoing glacial isostatic adjustments. Recent projections of sea-level rise range between 29 and 53 cm for New York City by the 2080s, depending on model and emission scenarios used[77]. Increased ice sheet melting or break up would augment these model projections.

Even modest increases in sea level can exacerbate flood risks. An earlier study found that by the 2080s flood heights of today's 100-year storm (including both hurricanes and powerful nor'easters) would be more likely to recur, on average, as often as once in 60 to once in every 4 years, and that beach erosion rates could increase several-fold, with associated sand replenishment needs increasing 26 per cent by volume[78,79].

New York City is especially vulnerable to major hurricanes that travel northward along a track slightly to its west, since the strongest, most destructive winds to the right of the hurricane's eye would pass directly over the city. Furthermore, the surge would be funnelled toward the near right-angle bend between the New Jersey and Long Island coasts into the New York City harbour. The city and surrounding areas have experienced at least three Category 3 hurricanes during the 20th century. Adding as little as 47 cm of sea-level rise by the 2050s to the surge for a Category 3 hurricane on a worst-case storm track would cause extensive flooding in many parts of the city[80] (Figure 6C.14).

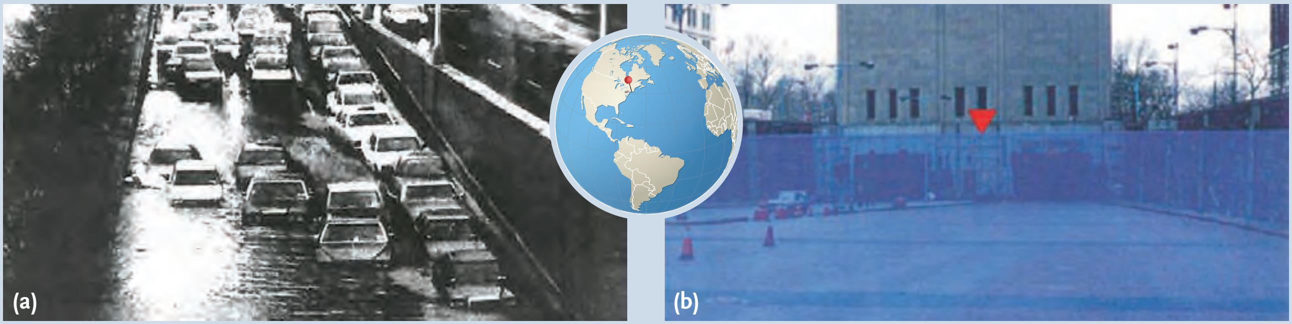

Figure 6C.14: New York City, storms and flooding.
(a) Flooding on the FDR Drive and 80th Street, Manhattan, looking north, during the December 13 1992 extra-tropical cyclone.
(b) Calculated potential surge height (with present day sea level) for a Category 1 (Saffir-Simpson scale) hurricane at Brooklyn-Battery Tunnel Manhattan entrance.

Source: (a) The Queens Borough Public Library, Long Island Division, New York Herald-Tribune Photo Morgue; (b) Rosenzweig and Solecki 2001[79]

Adaptive capacity in small islands and low-lying coastal areas

Adaptive capacity is the ability of a system to adjust to climate change (including variability and extremes), to moderate potential damages, to take advantage of opportunities, or to cope with the consequences[46]. Natural systems have an inherently high ability to adapt to sea-level rise. But this capacity is frequently compromised by human activities stressing or constraining these coastal ecosystems.

The vulnerability of human systems to sea-level rise is strongly influenced by economic, social, political, environmental, institutional and cultural factors[81]. But even a high adaptive capacity may not result in effective adaptation if there is no commitment to sustained action[82]. Importantly, in small island countries such as the Maldives, Kiribati and Tuvalu there is a shortage of the data and local expertise required to assess risks related to sea-level rise. The low level of economic activity also makes it difficult to cover the costs of adaptation[52]. Traditional knowledge is an additional resource to adaptation in such settings and should be carefully evaluated within adaptation planning[76].

Over the years many climate change-related projects have been undertaken in coastal and other low-lying areas. But in most cases these have focused on assessments of vulnerability and on the building of human and institutional capacity. A community-level adaptation project implemented in the Pacific region[83] was one of the first projects world-wide that went beyond the planning and capacity-building stages and included measures to facilitate adequate adaptation. This illustrates that the scale of adaptation for sea-level rise that is required is much larger than the current level of activity.

Need for adaptation

Even if atmospheric concentrations of greenhouse gases could be held constant at today's levels, sea level would continue to rise for decades to centuries. This means adaptation will be required in order to live with the sea-level rise occurring during the 21st century and beyond. Strategies include[84]:

1) **Accommodation** through forward planning and appropriate use of low-lying coastal regions (for example, to ensure escape and emergency routes are available for future flooding events and to increase the resilience of coastal developments and communities). Example: the construction of cyclone storm-surge shelters in Bangladesh, combined with effective warning systems, which has saved many lives.
2) **Protection** via hard measures such as sea walls (Figure 6C.15) for valuable locations and soft measures such as increased beach nourishment. Example: the construction of major dykes and levees to protect the 10 million people who live below sea level in the Netherlands.
3) **(Planned) Retreat** through spatial planning, such as implementation of no-build areas or building setbacks for areas susceptible to flooding and erosion. Example: building setback distances in South Australia that take into account the 100-year erosional trend and the effect of a 0.3 m rise in sea level by 2050.

Adaptation plans must not only consider modern urban development but also allow for the protection of historical sites (such as Venice, Italy or Jamestown, Virginia, USA) and sensitive environmental areas and ecosystems – developing management policies that simultaneously address these potentially conflicting goals presents a major challenge. With proactive planning we can substantially lessen the impact of 21st century sea-level rise.

Figure 6C.15: Examples of accommodation and protection measures.
(a) Sea wall protecting road in the atoll of South Tarawa, Kiribati. The elevated building in background is also a protection measure.
(b) The Thames Barrier. Built 25 years ago, the barrier and associated defences require significant upgrading to protect the City of London from higher sea levels and storm surges, at a probable cost of billions of pounds[85,86].
Photos: (a) John Hay; (b) The Environment Agency

Need for mitigation

The rate and magnitude of sea-level rise, particularly later in the 21st century and beyond, depends on future emissions of greenhouse gases. Indeed, 21st century greenhouse gas emissions could commit the world to a sea-level rise of several metres over hundreds of years as a result of ongoing ocean thermal expansion and contributions from the Greenland and West Antarctic Ice Sheets, as experienced during the last interglacial period. Such a sea-level rise would put huge pressures on society and could result in many millions of environmental refugees[1,87,88].

If we are to avoid these large rises in sea level, a significant reduction in greenhouse gas emissions is essential. Achieving the necessary reduction in emissions will be challenging and requires urgent and sustained commitment.

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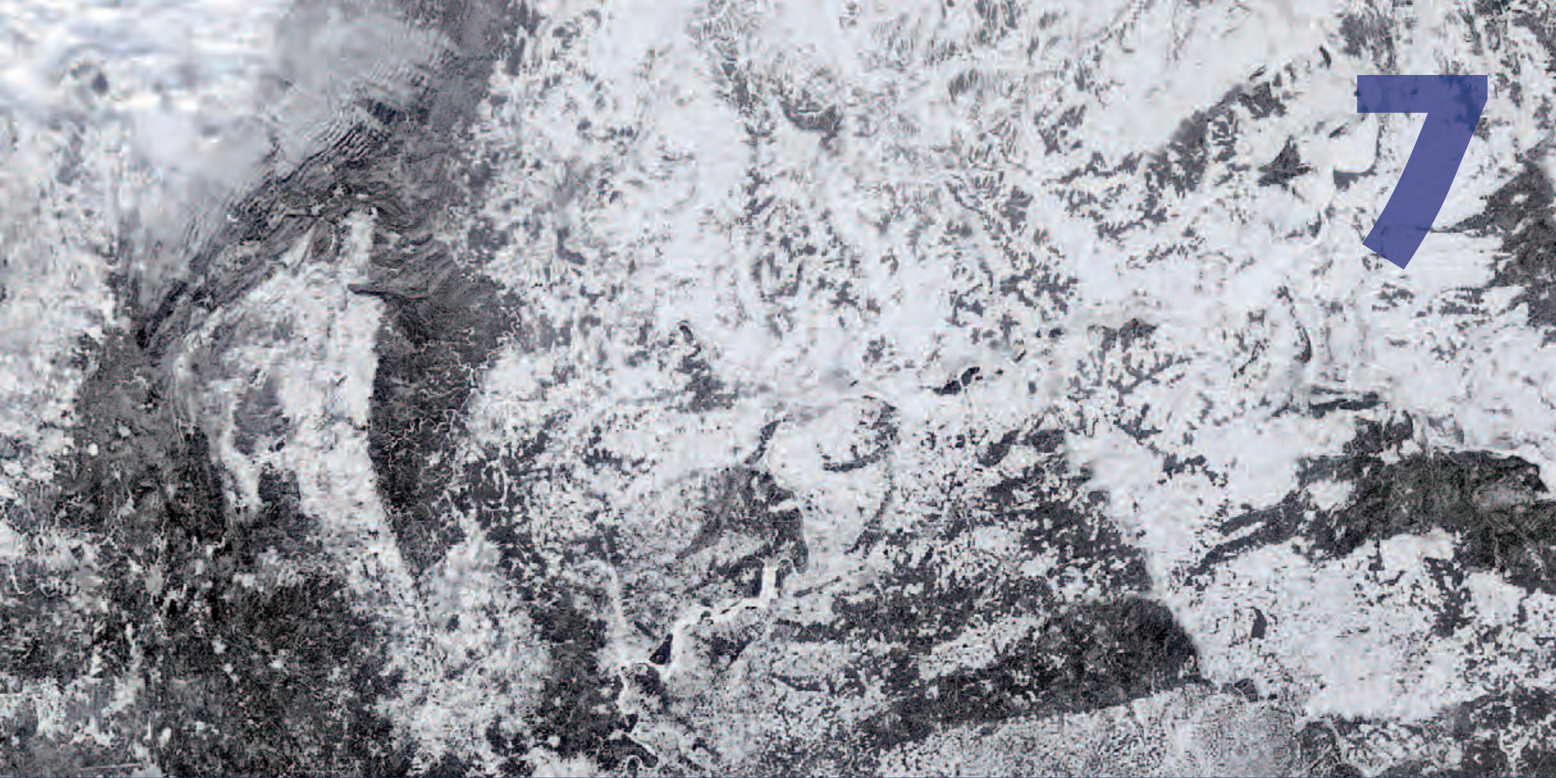

7

Frozen Ground

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Frozen Ground

Summary

Permafrost temperatures have increased during the last 20–30 years in almost all areas of the Northern Hemisphere. An increase in the depth of the active layer above the permafrost, which thaws in the summer, is less certain. Further increases in air temperatures predicted for the 21st century are projected to initiate widespread permafrost thawing in the subarctic and in mountain regions in both hemispheres. Widespread thawing of permafrost will speed up the decomposition of organic material previously held frozen in permafrost, emitting large amounts of greenhouse gases into the atmosphere. Thawing of ice-rich permafrost may also have serious consequences for ecosystems and infrastructure, and in mountain regions, may reduce the stability of slopes and increase the danger of rock falls and landslides.

Introduction to permafrost

Permafrost zones occupy up to 24 per cent of the exposed land area of the Northern Hemisphere[1] (Figure 7.1). Permafrost is also common within the vast continental shelves of the Arctic Ocean. This subsea permafrost formed during the last glacial period when global sea levels were more than 100 m lower than at present and the shelves were exposed to very harsh climate conditions. Subsea permafrost is slowly thawing at many locations. Permafrost of various temperatures and continuity also exists in mountainous areas, due to the cold climate at high elevations. Permafrost exists throughout ice-free areas of the Antarctic, as well as underneath some areas of the Antarctic Ice Sheet[2].

Permafrost extent within the exposed land areas of the Arctic and Antarctic

Permafrost: perennially frozen ground – rock, sediment or any other earth material with a temperature that remains below 0°C for two or more years.

Permafrost (Northern Hemisphere):	
Area Covered (million square km)	22.8
Ice Volume (million cubic km)	4.5
Potential Sea Level Rise (cm)	~7

Source: IPCC 2007[1a]

There are two permafrost zones: continuous permafrost and discontinuous permafrost (Figure 7.1). In the continuous permafrost zone, permafrost lies beneath the entire surface except beneath large rivers and deep lakes. Most continuous permafrost formed during or before the last glacial period. In the discontinuous permafrost zone, permafrost lies beneath 10 to 90 per cent of the surface. Most discontinuous permafrost is much younger and formed within the last several thousand years. Permafrost ranges from very cold (–10° C and lower) and very thick (from 500 to 1400 metres) in the Arctic, to warm (one or two degrees below the melting point) and thin (from several metres or less to 150 metres) in the subarctic.

The main feature that distinguishes permafrost from unfrozen ground is the presence of ground ice. The amount of ground ice in permafrost varies from a few tenths of a per cent to 80 or 90 per cent of the total permafrost volume. The mechanical strength of frozen soil with ice in it is close to the strength of bedrock, while the strength of unfrozen soil is much lower. The stability of ecosystems in permafrost regions depends on the stability of the ground ice; loss of permafrost means a loss of system stability.

Current measurements and climate model projections show that areas in which permafrost occurs are currently and will continue to be among the areas of the world with the largest changes in climate. Current climatic changes and those predicted for the future will inevitably affect the stability of permafrost. The changes that affect permafrost most are increases in air temperature and changes in the hydrological cycle. Ground ice will begin to melt, triggering changes in ecosystems that will make them very vulnerable to natural and anthropogenic influences. The thawing of permafrost will thus alter, if not destroy, ecosystems. These effects of permafrost thaw have already been seen in the mountain areas of Europe, Central Asia, China, and the Andes, where permafrost is generally warm and contains less ice.

Figure 7.1. Permafrost extent in the Northern Hemisphere.

Source: Based on Brown and others 1997[3]

Trends and outlook for high latitude (Arctic) permafrost

There has been a general increase in permafrost temperatures during the last several decades in Alaska[4–6], northwest Canada[7–9], Siberia[10–13], and northern Europe[14,15].

Permafrost temperature records have been obtained uninterrupted for more than 20 years along the International Geosphere-Biosphere Programme Alaskan transect, which spans the entire continuous permafrost zone in the Alaskan Arctic. Records from all locations along the transect show a substantial warming during this period. The permafrost typically warmed by 0.5 to 2°C, depending on location (Figure 7.2). Similar warming trends were observed in the North Slope region of Alaska from long-term monitoring sites[16].

Temperature monitoring in Canada indicates a warming of shallow permafrost over the last two to three decades. Since the mid-1980s, shallow permafrost (upper 20-30 m) has generally warmed in the Mackenzie Valley[7,17,18]. The greatest increases in temperature were 0.3 to 1°C per decade in the cold and thick permafrost of the central and northern valley (Figure 7.3). In the southern Mackenzie Valley, where permafrost is thin and close to 0°C, no significant trend in permafrost temperature is observed[7] (Figure 7.3). This absence of a trend is probably due to the fact that this permafrost is ice-rich; a lot of heat is absorbed to melt the ice before an actual temperature change occurs.

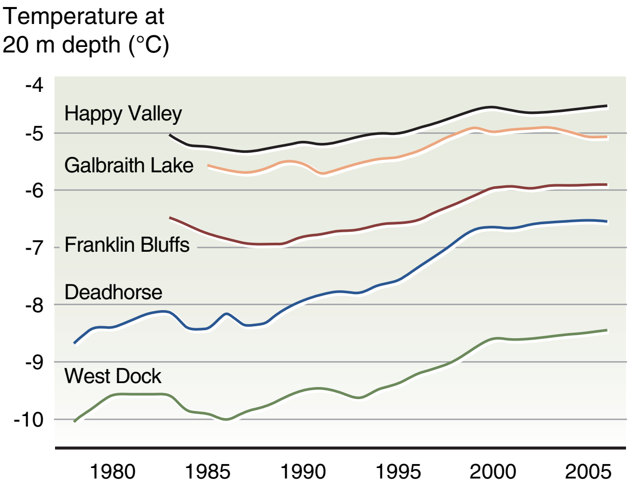


Figure 7.2: Changes in permafrost temperatures during the last 23 to 28 years in northern Alaska. Temperatures are measured at 20 m depth, at which there is no seasonal temperature variation in the permafrost.

Source: V.E. Romanovsky; updated from Osterkamp 2003[5]

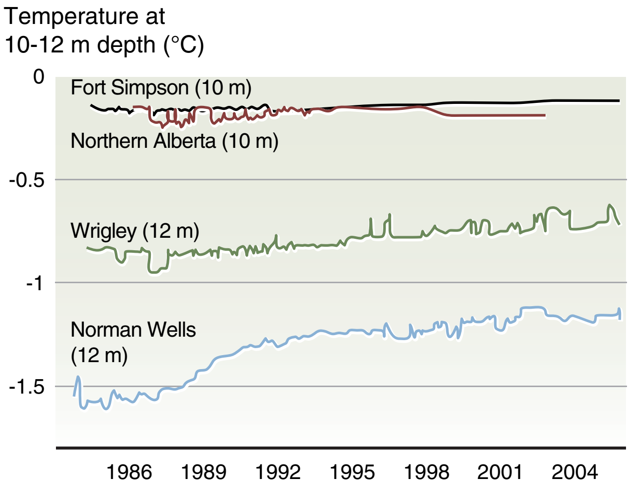


Figure 7.3: Ground temperatures at depths of 10 or 12 m between 1984 and 2006 in the central (Norman Wells and Wrigley) **and southern** (Fort Simpson and Northern Alberta) **Mackenzie Valley,** showing increases of up to 0.3°C per decade.

Source: S. Smith; updated from Smith and others 2005[7]

A similar lack of temperature trend is found for warm and thin permafrost in the southern Yukon Territory[19,20].

Warming of permafrost is also observed in the eastern and high Canadian Arctic but this appears to have mainly occurred in the late 1990s. At Alert, Nunavut, a warming of 0.15°C per year occurred between 1995 and 2001 at a depth of 15 m and warming of about 0.06°C per year has occurred since 1996 at a depth of about 30 m[8]. At another high Arctic site, shallow permafrost (upper 2.5 m) temperatures increased by 1°C between 1994 and 2000[21]. At Iqaluit in the eastern Arctic, permafrost cooled between the late 1980s to the early 1990s at a depth of 5 m and warmed by 0.4°C per year between 1993 and 2000[7]. A similar trend was observed in northern Quebec[22,23].

In environments containing permafrost, the top layer (active layer) of soil thaws during the summer and freezes again in the autumn and winter. Trends in the depth of this active layer are less conclusive than trends in permafrost temperature. In the North American Arctic, the depth of the active layer varies strongly from year to year[24–26]. An increase in active-layer thickness was reported for the Mackenzie Valley in Canada[27]. However, after 1998 the active layer began decreasing in thickness at most of the same sites[28]. An increase in thickness of more than 20 cm between the mid-1950s and 1990 was reported for the continuous permafrost regions of the Russian Arctic[29,30]. At the same time, reports from central Yakutia show no significant changes in active-layer thickness[31,32].

Thawing permafrost along the bank of the Kolyma River in Siberia.
Photo: V. Romanovsky

Outlook

Permafrost warming has not yet resulted in widespread permafrost thawing on a landscape or regional scale. Long-term thawing of permafrost starts when the active layer of soil above the permafrost, which thaws during the summer, does not refreeze completely even during the most severe winter. Year-round decomposition of organic matter can then occur, and permafrost continues to thaw from the top down. Predicted further changes in climate will eventually force high latitude natural systems to cross this very important threshold.

When permafrost starts to thaw from the top down, many processes, some of them very destructive, can be triggered or intensified. These changes may impact ecosystems, infrastructure, hydrology and the carbon cycle, with the largest impacts in areas where permafrost is rich in ground ice. One of the most significant consequences of ice-rich permafrost degradation is the formation of thermokarst, land forms in which parts of the ground surface have subsided[33]. Thermokarst forms when ground ice melts, the resulting water drains and the remaining soil collapses into the space previously occupied by ice. In addition to its impacts on ecosystems and infrastructure, thermokarst often leads to the formation of lakes and to surface erosion, both of which can significantly accelerate permafrost degradation.

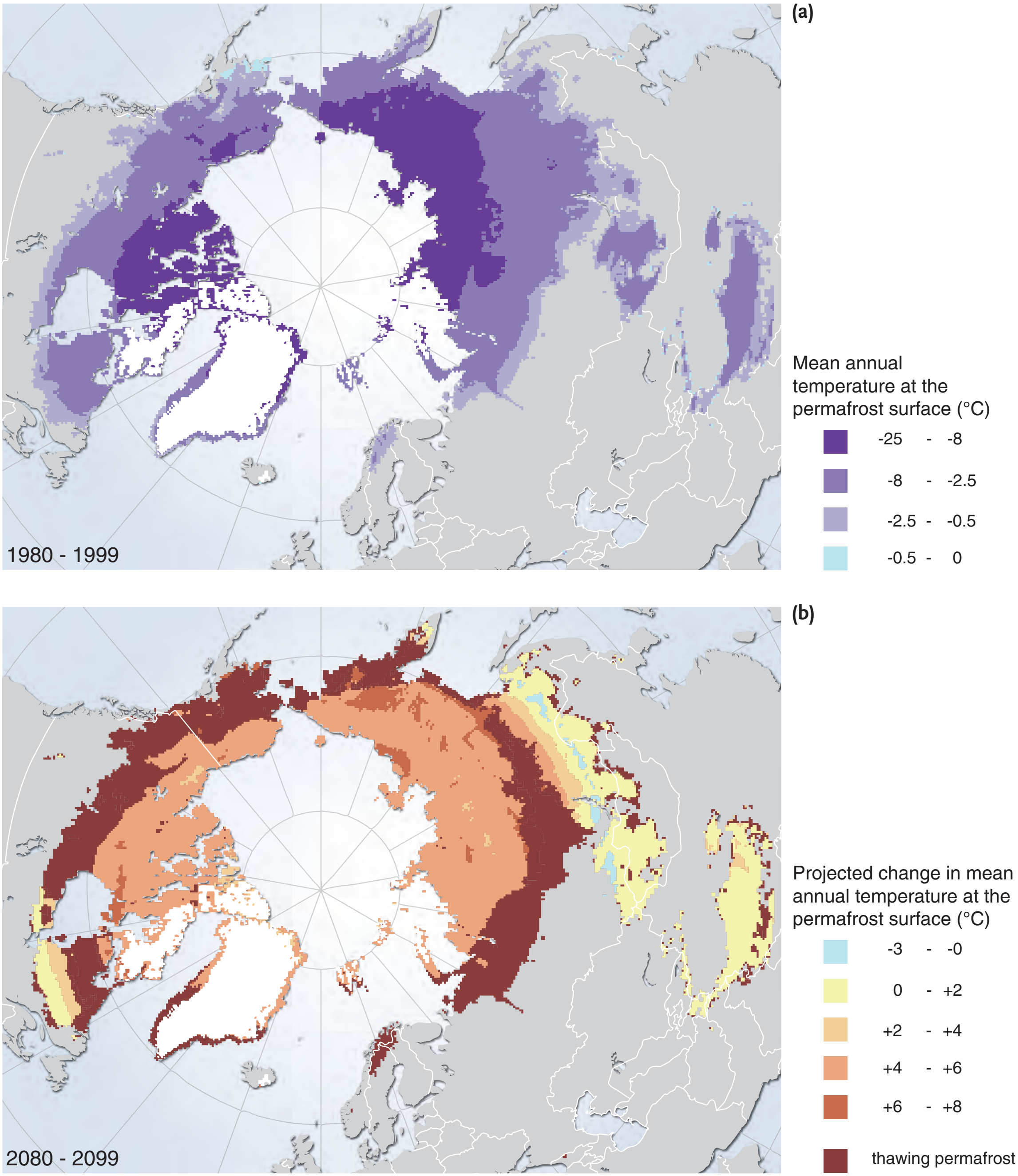
Effects of thermokarst on a railway track.
Photo: US Geological Survey

The form and rate of permafrost degradation will differ between regions, depending on geographical location and on specific environmental settings. On the Arctic tundra, the ground temperatures are generally cold and no widespread permafrost thawing is expected during the 21st century, with the possible exception of the European tundra where temperatures are closer to zero. However, location of ground ice close to the surface makes the Arctic tundra surfaces extremely sensitive to thawing, as only a small amount of thawing can lead to development of thermokarst. In contrast, in boreal forests ground ice is typically located at a greater depth below the surface. Thus, although warming of permafrost will soon lead to extensive permafrost thawing because of the relatively high temperature of permafrost in boreal forests, the thawing will not immediately lead to destructive processes.

Future changes in permafrost will be driven by changes in climate (primarily by air temperature and precipitation changes), changes in surface vegetation and changes in surface and subsurface hydrology. At present, there is no coupled climate model that takes into account all of these driving forces. However, by choosing a future climate scenario and assuming certain changes in vegetation and/or hydrology, it is possible to specify and apply an equivalent forcing to a permafrost model in order to project future permafrost dynamics on a regional or

Figure 7.4: Modelled permafrost temperatures (mean annual temperature at the permafrost surface) for the Northern Hemisphere, derived by applying climatic conditions to a spatially distributed permafrost model[34,35].
(a) Present-day: temperatures averaged over the years 1980–1999. Present-day climatic conditions were based on the CRU2 data set with 0.5° x 0.5° latitude/longitude resolution[36].
(b) Future: projected changes in temperatures in comparison with 1980–1999, averaged over the years 2080–2099. Future climate conditions were derived from the MIT 2D climate model output for the 21st century[37].

Source: Permafrost Laboratory of the Geophysical Institute, University of Alaska Fairbanks


(a)
1980 - 1999
Mean annual temperature at the permafrost surface (°C)
-25 - -8
-8 - -2.5
-2.5 - -0.5
-0.5 - 0
(b)
2080 - 2099
Projected change in mean annual temperature at the permafrost surface (°C)
-3 - -0
0 - +2
+2 - +4
+4 - +6
+6 - +8
thawing permafrost

even circumpolar scale. Figure 7.4 shows a projection of future permafrost temperatures for the entire Northern Hemisphere. According to this model, by the end of the 21st century permafrost that is presently discontinuous with temperatures between 0 and –2.5° C will have crossed the threshold and will thus be actively thawing. The most significant permafrost degradation is expected in North America, where permafrost will be thawing in practically all areas south of the Brooks Range in Alaska and in most of subarctic Canada. This is probably due to the fact that permafrost within continental North America is generally warmer and thinner than in Siberia. In Russia the most severe permafrost degradation is projected for northwest Siberia and the European North.

Methane emissions from thermokarst lakes

Depressions in the irregular thermokarst topography caused by thawing of ice-rich permafrost are usually occupied by lakes called thermokarst lakes, as meltwater cannot drain away due to the underlying permafrost. Active thawing of the permafrost beneath these lakes releases organic matter into the oxygen-deficient lake bottoms, which produces methane as it decomposes. Ninety-five per cent of the methane emitted from these lakes is released through bubbling[46]. Many of these methane-rich bubbles become trapped in lake ice in the winter as the lake surfaces freeze. Extremely high rates of bubbling from distinct points in lake sediments, known as bubbling hotspots, can maintain open holes in lake ice even during winter, releasing methane to the atmosphere year-round. Recently, scientists quantified methane emissions from thermokarst lakes in Siberia by studying the pattern of bubbles in the lake ice, and found that the amount of methane emission from lakes in this region may be five times higher than previously estimated[46] (Figure 7.5). The methane emitted from the thawing edges of the lakes in this region was 36 000–43 000 years old, showing that organic matter previously stored in permafrost for tens of thousands of years is now contributing to methane emissions when permafrost thaws[46]. High rates of methane production and emission have also been observed in thermokarst lakes in other regions of the Arctic. The formation of new thermokarst lakes and expansion of existing ones observed during recent decades has increased methane emissions in Siberia[46,47]. If significant permafrost warming and thawing occurs as projected, tens of thousands of teragrams of methane could be emitted from lakes, an amount that greatly exceeds the 4850 teragrams[48] of methane currently in the atmosphere[49].

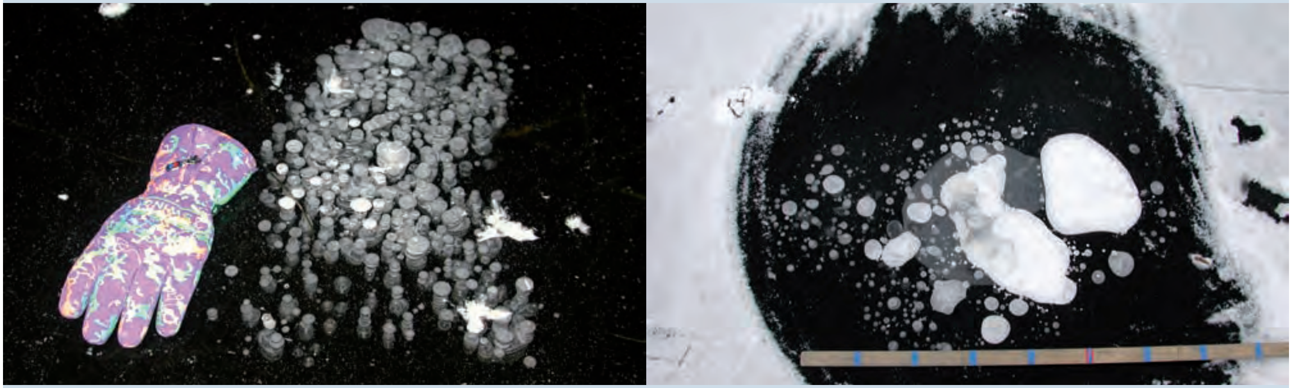


Figure 7.5: Methane bubbles trapped in lake ice form distinct patterns as a result of differing rates of methane bubbling. Methane emissions from the entire lake are estimated, taking into account the patchiness of bubbling, by surveying the distribution of bubble patterns in lake ice in early winter.
Photos: Katey Walter

Almost all permafrost in Europe, as well as permafrost along the southern coasts (below 70° N) of Greenland, will also be thawing by the end of the 21st century. The model predicts permafrost cooling in some regions, due to a combination of predicted increase in air temperatures with predicted decrease in snow depth and duration in these regions.

Impacts on the carbon cycle – feedback mechanisms

The largest global impact of changes in permafrost is due to its role in the global carbon cycle. Permafrost soils gradually accumulate organic carbon as they form because carbon which has been removed from the atmosphere through photosynthesis is stored in the form of organic matter, as soils freeze and decomposition slows or stops. The upper part of permafrost (1–25 m below the surface) in boreal and Arctic ecosystems is estimated to contain ~750–950 gigatonnes of organic carbon[38–40], a quantity that exceeds the 750 gigatonnes of organic carbon currently in the atmosphere. This figure does not include carbon contained in deeper permafrost, in hydrates within or under the permafrost, or other non-permafrost soil carbon pools. The amounts of carbon stored in some of these locations are still poorly defined, but an assessment of current understanding was recently provided through a workshop hosted by the Arctic Council's Arctic Monitoring and Assessment Programme[41]. Yedoma, an extremely carbon-rich type of permafrost found mostly in northern and central Siberia, contains roughly half of the organic carbon in the upper part of permafrost[38,42].

When permafrost thaws, decomposition of organic matter leads to production and emission of the greenhouse gases, carbon dioxide and methane, to the atmosphere. If thawing occurs in the presence of oxygen, decomposition produces carbon dioxide. For yedoma, which contains labile bioavailable organic material, this decomposition process occurs particularly rapidly[43,44]. When thawing occurs in the absence of oxygen, for example, when the permafrost thaws under a lake, decomposition of organic matter produces methane[45] (see box on thermokarst lakes). The warming potential (relative greenhouse effect) of methane is 23 times stronger than that of carbon dioxide, though methane does not persist in the atmosphere for as long as carbon dioxide. Thus, permafrost thawing acts as a positive feedback to global warming that is projected to intensify with further permafrost degradation in the future[34,46].

Impacts on ecosystems

Northern ecosystems depend on permafrost and ground ice conditions. Soil temperature, active-layer thickness, moisture content, presence of unfrozen water, and sur-

Effects of thawing of ice-rich permafrost on a forest in Alaska. *Photo: V. Romanovsky* face hydrology as they relate to permafrost all affect plant communities and productivity of ecosystems. The observed changes in permafrost temperatures and active-layer thickness can affect diversity and biomass of plant communities[50]. Thawing of ice-rich permafrost can result in the replacement of boreal forest with wetlands[51,52]. This reduces the habitat area for caribou and other terrestrial mammals and birds, while it increases the area favourable for aquatic birds and mammals. The thawing of permafrost with little ground-ice may result in replacement of the boreal forest ecosystems with steppe-like habitats. Long-term permafrost degradation will continuously increase subsurface water drainage, especially in sandy soils, which will increase dryness of soils and place significant stress on vegetation. Increased drainage will also shrink ponds in the degrading permafrost area, dramatically affecting aquatic ecosystems[47,53,54].

Impacts on infrastructure

Impacts of predicted global climatic changes on Arctic infrastructure are of increasing concern[39,55]. Warming and thawing of permafrost may pose a threat to human lives as well as to infrastructure. Construction activity and existing infrastructure usually increase the heat flow into the ground, due to heating of buildings and build-up of snow, and can result in warming of permafrost. This ongoing permafrost degradation, which can cause instability of building foundations, may be accelerated by increasing air temperatures. In addition, projected increases in air and soil temperatures, precipitation, and storm magnitude and frequency are very likely to increase the frequency of avalanches and landslides. In some areas, the probability of severe impacts on settlements, roads and railways from these events may increase due to warming and thawing of permafrost. Structures located on sites

Figure 7.6: Effects of thawing permafrost on infrastructure.
(a) Permafrost thawing caused differential settlement in the foundation of this apartment building in the Russian republic of Yakutia. The building partially collapsed only days after the first cracks appeared in the walls.
(b) A thermokarst depression in Fairbanks, Alaska. Ground ice melted, creating a void within the ground.
Photos: V. Romanovsky

prone to slope failure are more likely to be exposed to slide activity.

It is important to note that in permafrost regions the lifetime of structures, during which they should function according to design with normal maintenance costs, is typically 30 to 50 years. Total renovation, or demolition and replacement, of old structures should be expected and is part of responsible infrastructure planning. For this reason the effect of climate change on northern infrastructure is difficult to quantify. However, damage to structures is often blamed on climate changes while in reality it is due to human error, poor construction, or simply old age.

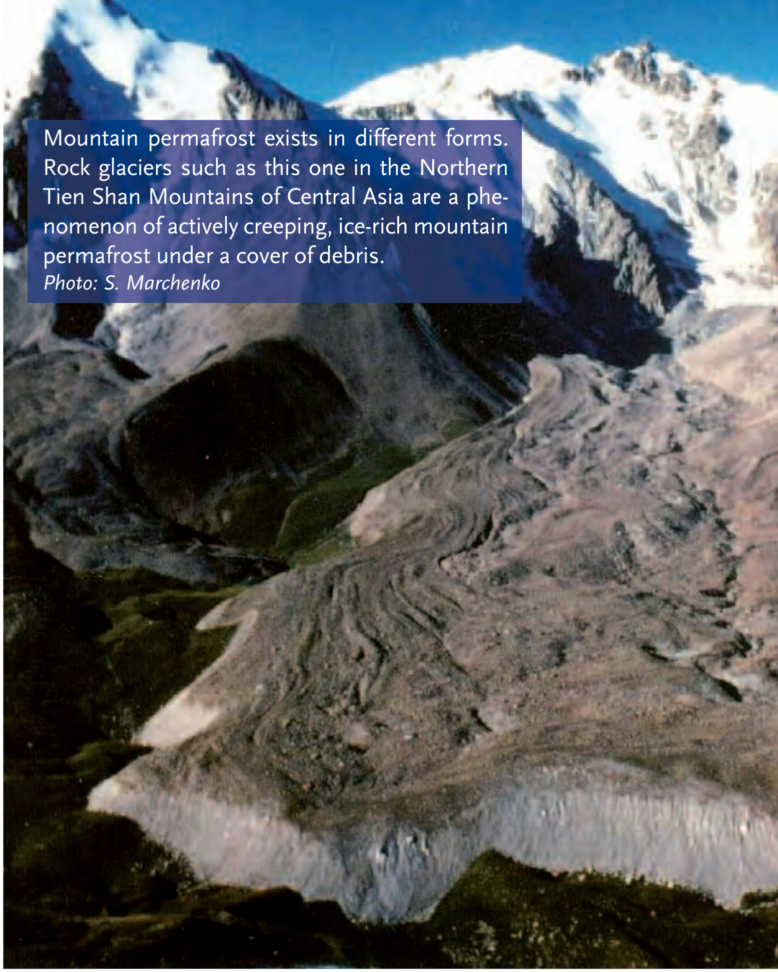
It is nevertheless necessary to prepare for and adapt to the effects of permafrost changes on infrastructure. In colder, continuous permafrost the predicted climate changes do not pose an immediate threat to infrastructure. Maintenance costs will probably increase, but it should be possible to gradually adjust Arctic infrastructure to a warmer climate. However, transportation infrastructure such as roads, railways and airstrips that are on ice-rich permafrost will generally require relocation or replacement using different construction methods. The predicted warming may have a serious effect on infrastructure in warmer, discontinuous permafrost zones, where permafrost is already close to thawing[56]. These areas, together with coastal areas where the thawing of ice-rich permafrost is combined with the problem of sea-level rise, present the greatest challenges in a changing climate (Figure 7.6). However, many engineering approaches have already been developed over the last century to prevent and to cope with effects of permafrost warming. Such approaches are common practice in North America and Scandinavia[57–59] (Figure 7.7). These techniques can be adapted to handle the permafrost changes predicted in the future (see box on building on permafrost in northern Canada).

Figure 7.7: Examples of good engineering practices which prevent permafrost thawing.
(a) A house built on concrete blocks to allow cold air under the house during the winter, north of Fairbanks, Alaska.
(b) The Trans-Alaskan Oil Pipeline is built on pile-refrigerators to prevent thawing of permafrost underneath.
Photos: (a) V. Romanovsky; (b) Roger Asbury/iStockphoto.com

Building on permafrost in northern Canada

Permafrost and its ground ice present challenges to infrastructure development in northern Canada. Development of infrastructure disturbs the ground surface and changes the heat flow in the ground, causing thawing of ice-rich permafrost which in turn de-stabilizes the ground[9,60]. Current engineering practices consider permafrost and aim to minimize the impacts of thaw. Climate change, however, presents an additional challenge as warmer conditions may enhance the impacts of infrastructure development on the heat flow in the ground. The design of existing structures may not account for additional permafrost thaw resulting from climate changes. It is hard to tell if recent warming has already had an impact on existing infrastructure in Canada. It is difficult to separate the effects of climate change from the effects of construction and operation of a structure, which tend to be of greater magnitude[61].

Climate change, however, is now recognized as a concern over the lifetime of major development projects in northern Canada and has been included in engineering designs since the late 1990s. A screening tool has been developed by a working group of scientists and engineers[62] to assess the level of analysis on climate change needed for a particular project. It is also required to consider climate change in the environmental assessment for major projects, especially long-term ones[63,64]. For example, climate change was recognized as a concern for the Ekati Diamond Mine which opened in 1998, and potential climate change impacts were considered in the design of the mine's waste storage[65]. The proposed Mackenzie Gas Pipeline has considered climate change in both its design and environmental assessment.



Mountain permafrost exists in different forms. Rock glaciers such as this one in the Northern Tien Shan Mountains of Central Asia are a phenomenon of actively creeping, ice-rich mountain permafrost under a cover of debris.
Photo: S. Marchenko

Trends and outlook for high altitude (mountain) permafrost

Europe

Significant amounts of mountain permafrost exist in Svalbard, Fennoscandia, the Urals, the Caucasus, the Pyrenees, the Alps, and Iceland. Data from a north-south line of boreholes, 100 m or more deep, extending from Svalbard to the Alps show a long-term regional warming of permafrost of 0.5–1.0 °C[66] during recent decades. In Scandinavia and Svalbard, monitoring over 5–7 years shows warming

down to 60 m depth and present warming rates at the permafrost surface of 0.04–0.07° C/year[67]. In Switzerland, a warming trend and increased active-layer depths were observed in 2003, but results varied strongly between borehole locations[68]. The warming signals from alpine boreholes are difficult to interpret due to the conflicting factors of topography and the heat released or absorbed during melting or evaporation[69]. However, observations of European mountain permafrost degradation are consistent with climate trends and with the major changes in permafrost and ground ice conditions observed globally. These changes are expected to continue in the near future.

Human activity and permafrost affect each other, especially in the densely populated Alps. The speed of most monitored alpine rock glaciers, a form of mountain permafrost in which frozen debris and/or ice underlie a layer of debris and which move downslope, has increased significantly during recent years. This acceleration is likely due to a reduction in viscosity of the underlying permafrost as a result of warming[70]. Warming of permafrost also affects infrastructure in alpine permafrost regions. An increase of instability problems has motivated the development of technical solutions to improve design lifetime, maintenance costs and safety[71]. Warming can reduce the stability of permafrost in steep areas and thus cause increased rock falls[72–75]. At least four large events involving rock volumes over 1 million m^3 took place in the Alps during the last decade. In 2002, the Kolka Glacier rock and ice slide killed 125 people in the Karmadon Valley of the Caucasus[76], illustrating the potentially catastrophic consequences of such events (see Figure 6B.8).

Central Asia

The Central Asian region is the largest area of widespread mountain permafrost in the world. Mountain permafrost in Central Asia occupies approximately 3.5 million square kilometers and makes up about 15 per cent of the total permafrost area in the Northern Hemisphere. The climatic variations during the 20th century and especially during the last two decades have impacted current permafrost temperatures. In the Tien Shan Mountains, Qinghai-Tibet Plateau, and western Mongolian sector of the Altai Mountains, observations over the last 30 years show that permafrost warmed by 0.3°C in undisturbed systems and by up to 0.6°C in areas affected by human activities (Figure 7.9). In the northern Tien Shan Mountains and the Mongolian Altai Mountains, the average active-layer thickness increased by 20–25 per cent in comparison with the early 1970s[77–79].

Mountain permafrost

At high elevations in mid-latitude mountains, permafrost is widespread where the mean annual air temperature is below –3°C. It often exists far below the altitudes to which glaciers extend, and even below the tree line in continental areas. Mountain permafrost exists in different forms – in steep bedrock, in rock glaciers, in debris deposited by glaciers or in vegetated soil, and contains variable amounts of ice. Since topography causes large variability in local climate, snow cover, and ground and surface properties through the processes of erosion, transport and deposition, mean annual ground temperatures in mountain regions can vary by 5–8 °C over distances as small as 100 m (Figure 7.8). For this reason, the distribution and characteristics of permafrost in mountain regions are very patchy.

Permafrost influences the evolution of mountain landscapes and affects human infrastructure and safety. Permafrost warming or thaw affects the potential for natural hazards such as rock falls, debris flows and secondary events triggered by them and also affects the topography itself in steep terrain. As in Arctic permafrost regions, construction in mountain permafrost regions requires special precautions and warming permafrost poses problems to infrastructure. Mountain permafrost also contains valuable information on climate change. The presence of permafrost, in an actively moving rock glacier for example, indicates a relatively cold climate, therefore inactive or fossil rock glaciers point to past colder climates. Measurements of permafrost temperature, as well as providing information on present-day permafrost stability, offer data on past climate changes.

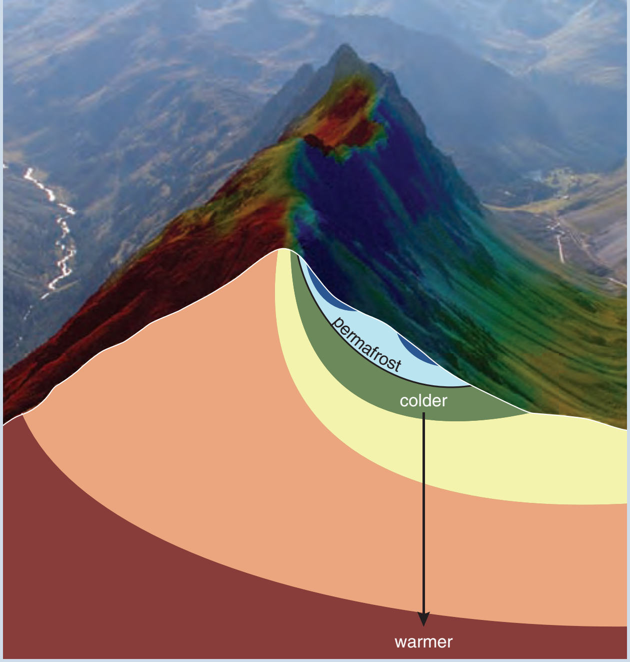


Figure 7.8: Temperatures in a mountain range containing permafrost (blue colours bordered by the black line), ranging from colder (blue) to warmer (red). Steep terrain and strong variability in surface temperatures are typical of mountain permafrost. The cross section in the foreground shows the complex distribution of subsurface temperatures characteristic of mountains, with the isotherms (lines linking points of equal temperature) nearly vertical in the ridge of the mountain. In the background, the colours on the mountain surface illustrate the strong variability in ground temperatures caused by differences in elevation, exposure to the sun, snow cover and ground properties. In the far background, one can only guess at this complex pattern of permafrost distribution because permafrost is invisible at the ground surface.

Source: S. Gruber, photo from Christine Rothenbühler

Mountain permafrost contains large quantities of stored fresh water in the form of ice. Mountain permafrost within debris deposited by glaciers, or in rock glaciers and other coarse blocky material has especially high ice content (up to 80 per cent of the total volume). The total volume of surface ice has been reported at about 462 km^3 while the estimate of ground ice volume is about 280 km^3 for one area of the Tien Shan Mountains[80,81]. Considering the continued glacier recession in Central Asia (see Chapter 6B), the melt waters from permafrost could become an increasingly important source of fresh water in this region in the near future.

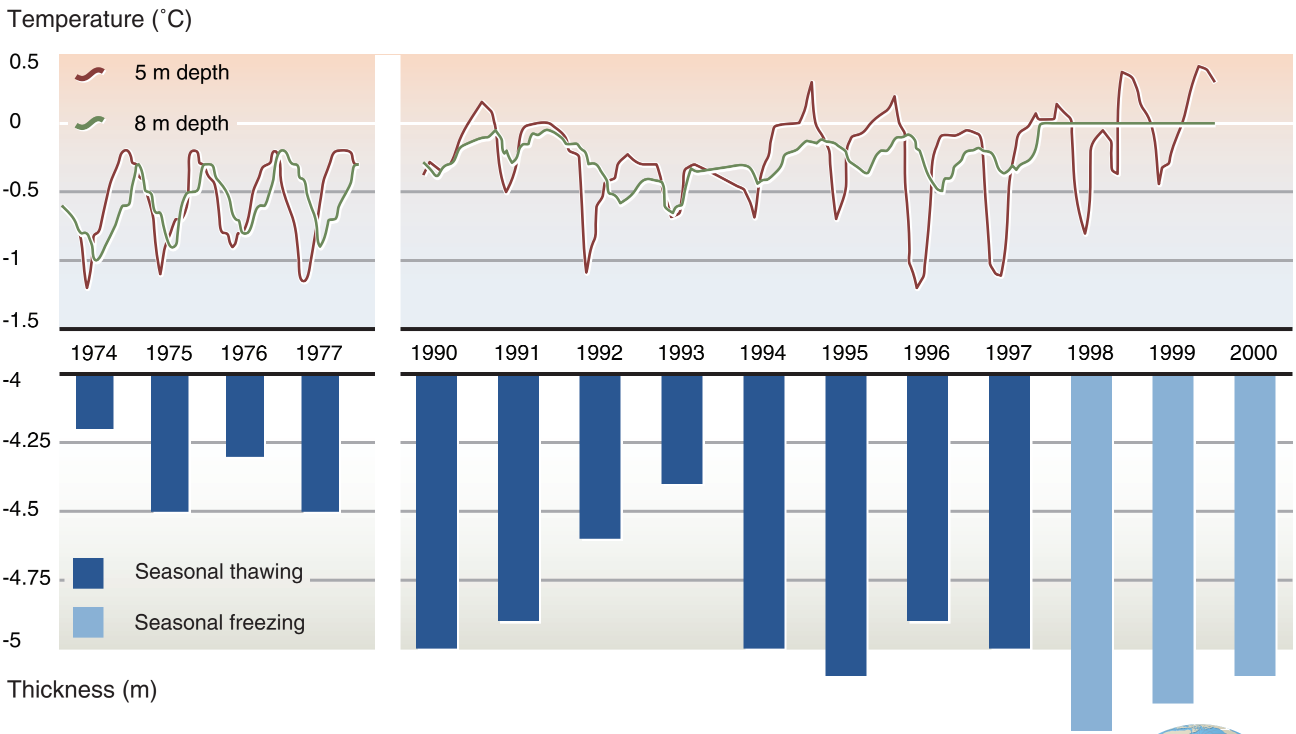


Figure 7.9: Permafrost temperatures and active-layer thickness during 1974–1977 and 1990–2004 measured in a borehole at the "Cosmostation" permafrost observatory, 3300 m above sea level, Northern Tien Shan Mountains in Central Asia**.**

Source: Based on Marchenko and others 2007[82]

China

Permafrost in China has degraded significantly during the past 40 years[79,83], with changes observed in both permafrost extent and temperature. The area of the southern Qinghai-Tibet highway with underlying permafrost decreased by 35.6 per cent between 1974 and 1996[84], while the permafrost area of the northern Qinghai-Tibet highway decreased by 12 per cent between 1975 and 2003[85]. In the Xing'anling Mountains in northeast China, many patches of permafrost have disappeared[86]. The permafrost area in China is projected to decrease by 30-50 per cent during the 21st century[79,87].

Morenas Coloradas rock glacier in Argentina. *Photo: D. Trombotto*

Changing permafrost conditions have already impacted and will continue to strongly impact many infrastructures in China. Design of the Qinghai-Tibet Railway has taken into account the 2.6° C increase in air temperature predicted for the 21st century by using various cooling techniques[88,89]. The impacts of climate changes on stability will also need to be considered in the design of the proposed China-Russia Oil Pipeline.

South America

Most mountain permafrost in South America is found at high elevations in the Andes. The total area of South American permafrost is estimated at 100 000 km^2. Permafrost in the Andes varies significantly in temperature, ice content, and distribution (whether it is continuous or discontinuous). Andean permafrost also varies in its vulnerability to future changes in climate[90]. Continuous permafrost is found at various elevations, in regions where mean annual air temperatures are –2 to –4 °C and mean annual precipitation is 500–900 mm[91]. Continuous permafrost can also exist in areas with air temperatures between –1 °C and –2 °C but much lower amounts of precipitation (300 mm per year), as in the case of the Argentine Puna region. In the central Andes, permafrost appears in groups of rock glaciers. The lower limit of Andean permafrost, which on the Cordón del Plata mountain range occurs at an elevation of 3700–3800 m, is marked by the absence of rock glaciers.

Features indicating permafrost degradation can be seen in some rock glaciers[92]. Ground subsidence in the central Andes is related to warming during the Holocene, six to eight thousand years ago (see timeline on inside back cover). However, there are some signs that permafrost degradation has recently restarted. Since degradation of permafrost in rock glaciers directly affects the discharge volume of Andean rivers[93], permafrost warming could temporarily enhance the regional supply of fresh water. On the other hand, degrading permafrost leads to slope instability, increasing risks of hazards such as rock falls and mud flows, which will affect Andean passes and mountain roads.

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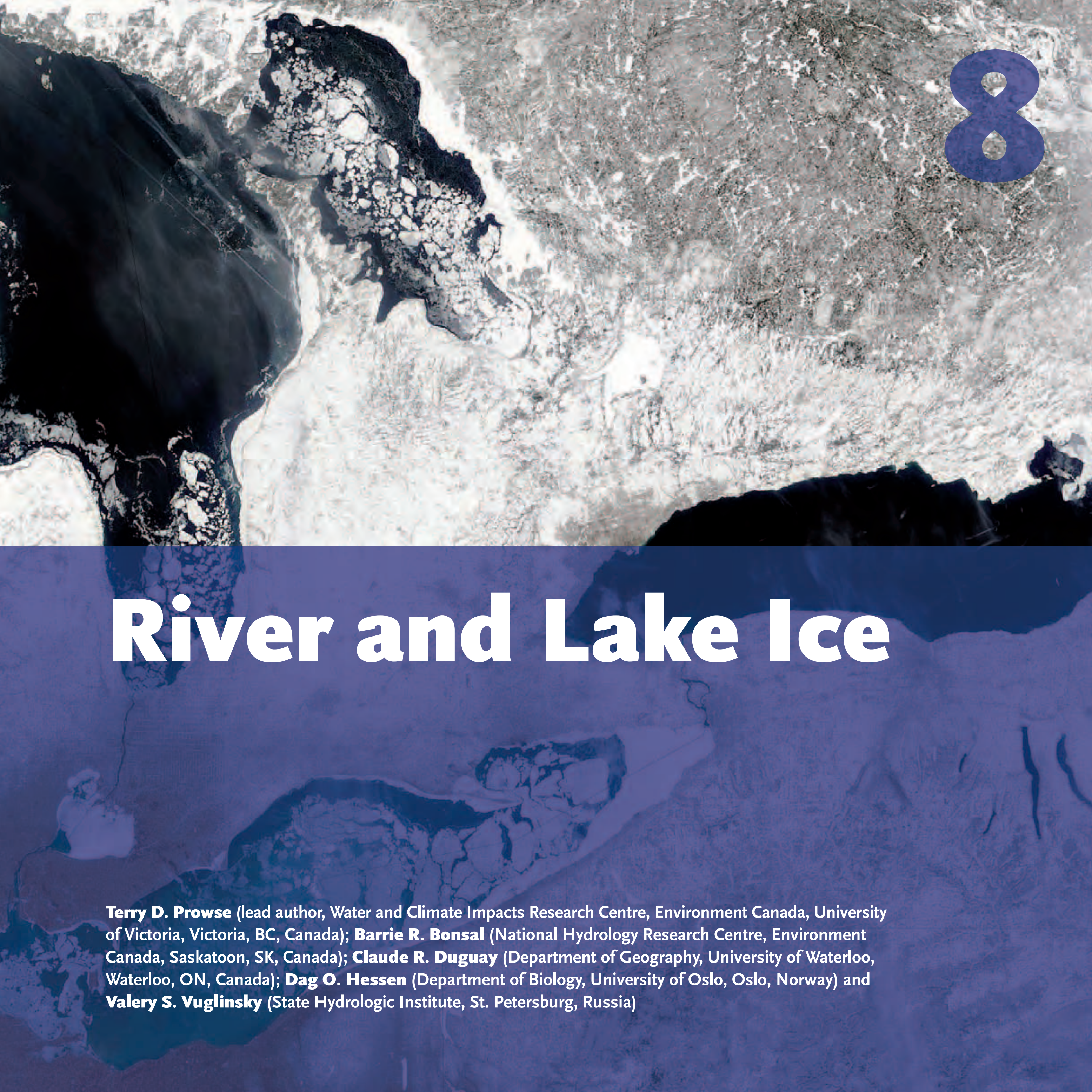

8

River and Lake Ice

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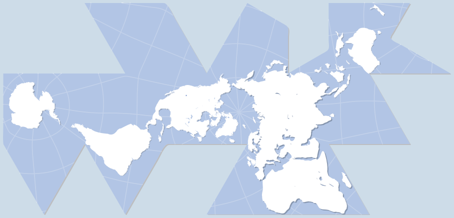
River and Lake Ice

Summary

Floating freshwater ice is a key component of cold-regions river and lake systems. Ice creates and controls unique aquatic habitats and related biological productivity and diversity. It also poses major challenges (for example, flood threats) and opportunities (for example, transportation) for communities. Changes in freshwater-ice cover have largely mirrored trends in air temperature, with large regions of the Northern Hemisphere experiencing reductions in ice-cover duration characterized by earlier spring break ups and, to a lesser degree, later autumn freeze ups, particularly over the last 50 years. Although more dramatic changes in the timing and duration of the ice season are projected for the future, our understanding of how climate has affected or will alter the more important freshwater-ice processes (such as ice-cover composition, thickness and break-up dynamic,) remains poor. Improving our knowledge of these climate-ice relationships is the key to being able to properly adapt to, or even mitigate, future environmental change.



River and lake ice: floating ice formed in rivers and lakes.
Distribution: high latitude and mountain regions mainly in the Northern Hemisphere.

Introduction to river and lake ice

Freshwater ice is a major component of the terrestrial cryosphere. It affects an extensive portion of the global hydrologic system, including the rivers and lakes found throughout high-latitude and alpine areas, mainly in the Northern Hemisphere. Seasonal ice cover can develop as far south as 33°N in North America and 26°N in Eurasia producing effects on 7 of the world's 15 largest rivers[1], and 11 of the 15 largest lakes.

River and lake ice are important modifiers of numerous biological, chemical and hydrologic processes[1–3], key sources of winter transportation and, in the case of rivers, capable of causing extensive and costly damage to human infrastructure[4]. Because the various forms and processes of freshwater ice are directly controlled by atmospheric conditions (temperature and precipitation), their spatial and temporal trends can be used as indicators of climate variability and change. Given the broad ecological and economic significance of river and lake ice, scientific concern has been expressed regarding how future changes in climate might affect ice-covered hydrologic and aquatic systems[5–7].

Trends and outlook

Limited by the availability of detailed observations, most historical evaluations of changes in freshwater ice have focused on relatively simple characteristics, such as the timing of autumn freeze up and spring break up, and maximum ice-cover thickness. Based on 27 long-term (about 150-year) records from around the Northern Hemisphere, Magnuson and others[8] (Figure 8.1) discovered that freeze up has been delayed by approximately six days per hundred years and break up advanced by a

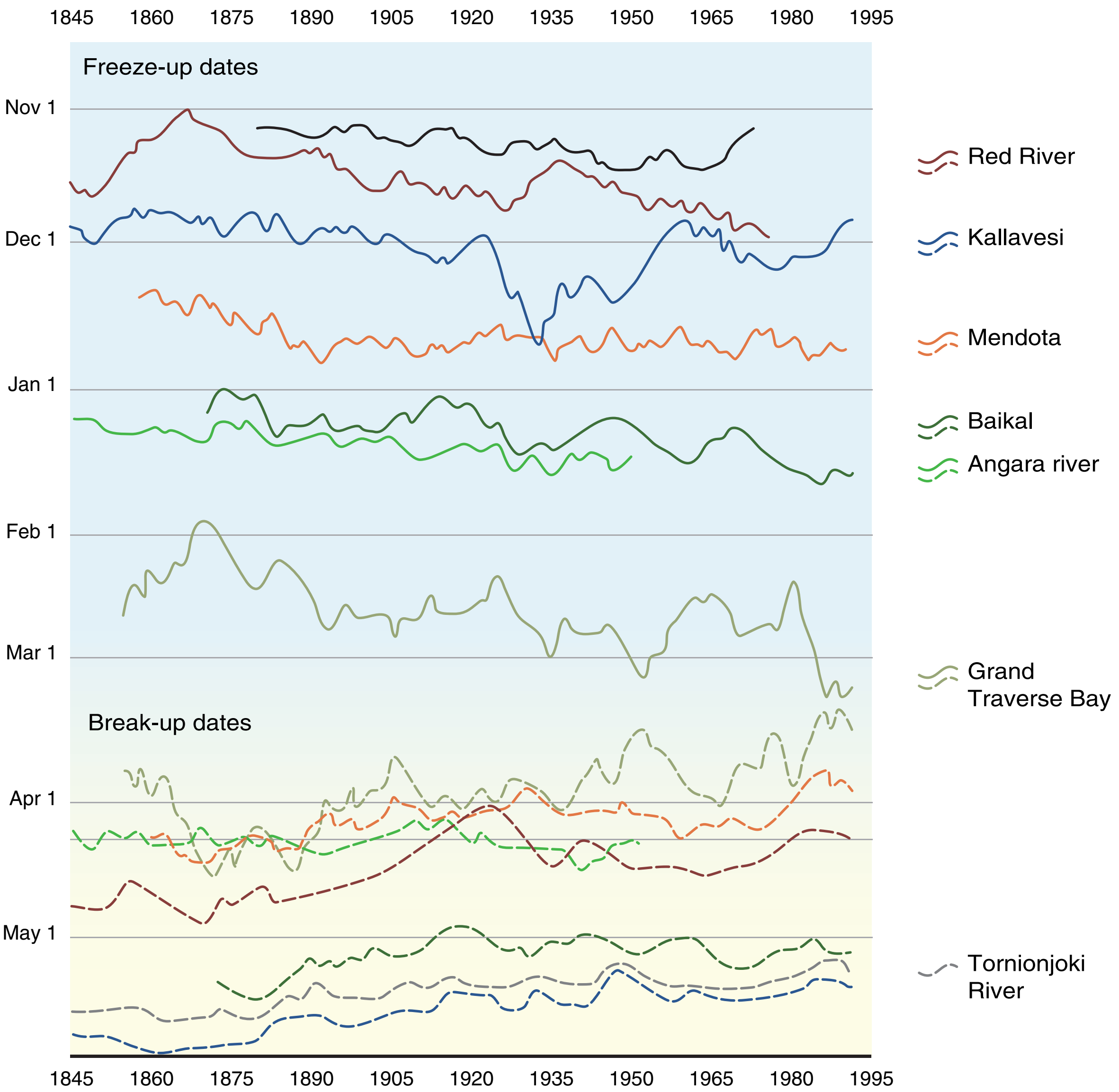


Figure 8.1: Time series of freeze-up and break-up dates from selected Northern Hemisphere lakes and rivers (1846–1995). Data were smoothed with a 10-year moving average.

Source: Based on Magnuson and others 2000[8] similar rate, resulting in an almost two-week per century reduction in the ice-covered season. Numerous other regional and continental studies have been conducted using the more spatially-detailed sets of observations available for the latter half of the 20th-century. Results reveal strong contrasts in freeze-up and break-up timing between decades and between regions[9–13] (see box on spring temperatures and ice break up) largely paralleling trends in major atmospheric patterns that have produced regional climatic warming or cooling[14,15].

Overall, the data for river ice indicate that long-term increases of 2–3°C in autumn and spring air temperatures have produced an approximate 10 to 15 day delay

Spring temperatures and ice break up

Although ice-cover duration on rivers and lakes of the Northern Hemisphere has significantly decreased in response to increasingly warmer climate conditions during the 20th century, the response has been shown to vary regionally and to be strongly related to the variability and regime shifts in large-scale atmospheric and oceanic oscillations.

In Canada, recent evidence indicates a shortening of the freshwater-ice season over much of the country with the reduction being mainly attributable to earlier break ups. These trends match those in surface air temperature during the last 50 years (Figure 8.2). For example, similar spatial and temporal patterns have been found between trends (1966 to 1995) in autumn and spring 0°C isotherms[14] (lines on a map showing location of 0°C air temperatures) and lake freeze-up and break-up dates, with generally significant trends toward earlier springs and earlier break-up dates over most of western Canada and little change in the onset of cooler temperatures and in freeze-up dates over the majority of the country in autumn[9].

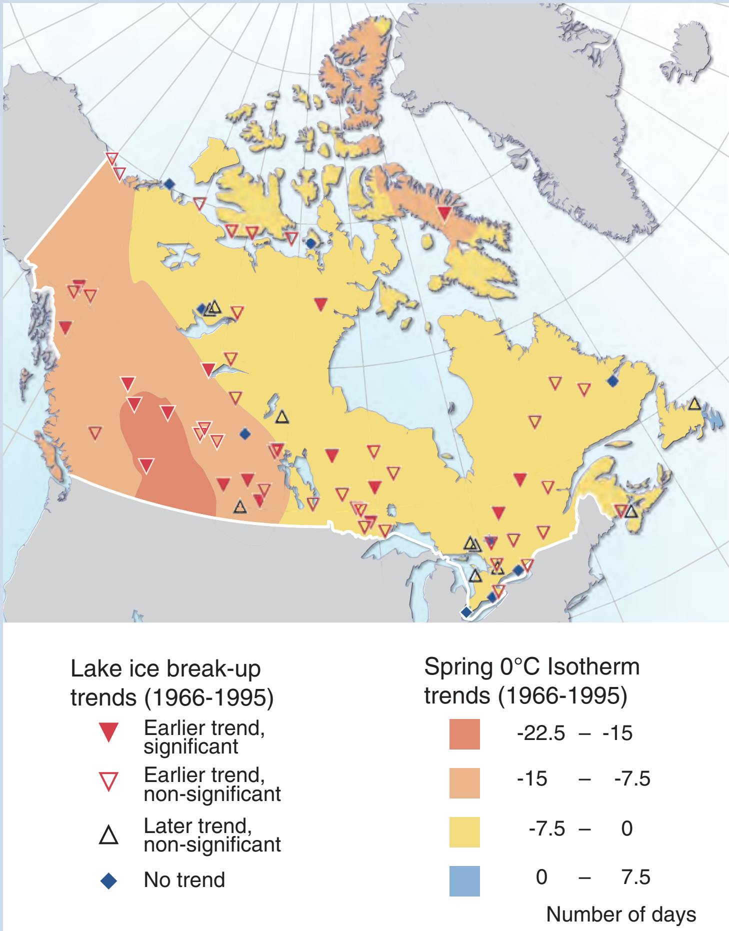


Figure 8.2: Trends in spring temperatures and in ice break-up dates in Canada.

Source: Based on Duguay and others 2006[9] in freeze up and a similar advance in break up[16]. These mirror the longer term response rates found by Magnuson and others[8] but caution is required in relying on such simple temperature-based relationships because they can change over time[6,17].

Large-scale, comprehensive records of river and lake-ice thickness are relatively rare. One data set compiled for Canada over the last 50 years[18] does not reveal any obvious trends over the latter part of the 20th century[19], although smaller-scale regional trends in Northern Europe and Asia have shown a tendency to thinner ice over the same period[20].

Due to the complex relationship between climate and freshwater ice conditions[6,21], future projections of river and lake ice have largely relied on the temperature-based relationships described above. Projections generally indicate further delays in freeze up and further advances in break up, with the amount of change depending on the degree of warming that is forecast[10,22]. For accurate prediction of many ice characteristics, such as composition, thickness, strength and even duration, however, the complicating effects of snow cover need to be considered[2,23–26].

River flows, break up and flooding

River-ice break up on cold-region rivers is often the most dramatic hydrologic event of the year and capable of producing flood-level conditions exceeding those possible under higher flows during the open-water period[1] (Figure 8.3). In temperate climates, river ice can go through a series of freeze-up/break-up cycles, whereas in colder climates break up is typically a spring event. In either case, break up starts when the driving forces – primarily the flood wave from snowmelt, sometimes augmented by rainfall – exceed the resisting forces operating to keep the ice cover intact (ice thickness and strength). The mildest break ups occur when both forces are reduced to a minimum and the ice cover simply melts away, similar to the way lake ice melts. By contrast, the largest floods are produced when the two opposing forces are greatest – a large flood wave colliding with a strong, intact ice cover[4].

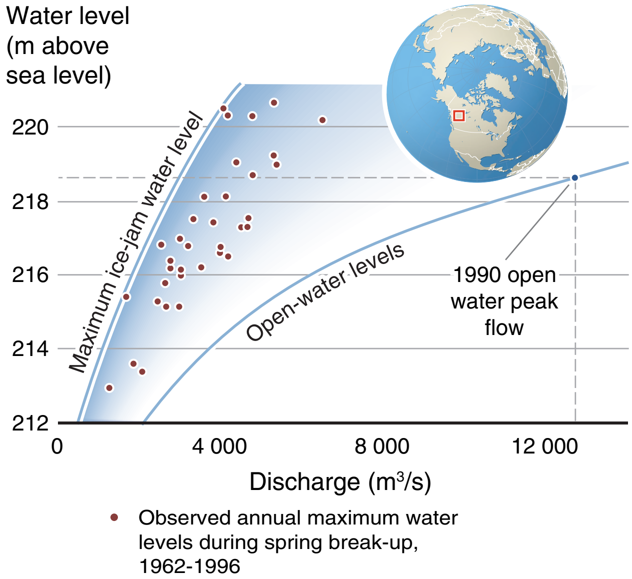


Figure 8.3: Example of enhanced water levels produced from river ice, Liard River (Canada). The lower curve shows the correspondence between river flow and water levels under open-water conditions. The much greater maximum water levels possible under ice-jam conditions are illustrated by the upper curve. The transition in break-up severity from dynamic to thermal break-up effects (see text) is depicted by the gradually shaded area between the two curves. Dots are observed annual maximum water levels during the spring break up. The 1990 dashed line shows the maximum recorded flow for the Liard River – but note that the water level corresponding to this peak flow is lower than for many break-up events with much lower flows. Effects of climate on snowmelt runoff and ice characteristics will lead to regional changes in break-up severity and associated frequency and magnitude of ice-induced flooding.

Source: Based on Prowse and others 2002a[27]

River temperature gradients and floods

Generally the most severe spring floods in Northern Hemisphere cold-region north-flowing rivers are the result of a strong temperature gradient between the headwaters in the south and the downstream river reaches in the north. In these cases, the spring flood wave produced by snowmelt must "push" downstream into colder conditions, and hence towards a relatively intact ice cover that has experienced little melting. Changes in this north to south temperature gradient would alter the severity of break up and the associated flooding.

In the future, cold season (October to May) temperatures are projected to warm more at higher latitudes as compared to lower latitudes (Figure 8.4). The largest north to south differences are evident in East Greenland, Scandinavia and northwest Russia (region d) and Chukotka, Alaska and the western Canadian Arctic (region b), and become particularly magnified in the 2080s. This warming pattern would lead to a reduced temperature gradient along the course of some major Arctic rivers. If such reductions prevail during particular parts of the cold season, they are likely to have major implications for hydrologic events such as the spring snowmelt period and ice break up. High-latitude temperature increases are likely to lead to less severe ice break ups and flooding as the spring flood wave pushes northward.

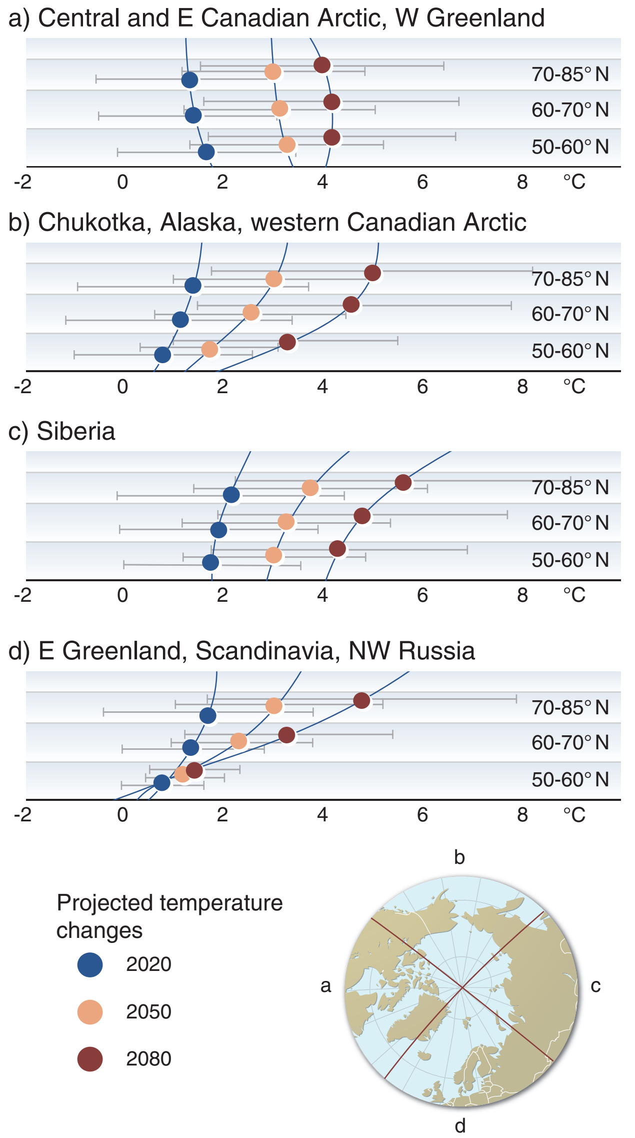


Figure 8.4: Average projected changes in cold-season mean temperatures over Arctic land regions. The changes are broken into three latitudinal bands for each region, as shown on the small map (which has an outer rim of 50° N). Error bars represent standard deviation from the mean. Where greater warming is projected at higher latitudes than at lower latitudes, temperature gradients will be reduced along large north-flowing rivers and this will likely reduce break-up severity. The reverse is true for regions where warming is most pronounced in the southern latitudes.

Source: Based on Prowse and others 2006[29]

As noted earlier, historical trends indicate that the timing of break up has advanced with warming but few attempts have been made to consider changes in the severity of break up[11,28]. Concern has been raised, however, about how large-scale patterns of warming might affect thermal gradients along large northward-flowing rivers – changes in these gradients can be expected to affect the incidence and magnitude of ice-induced flooding[29] (see box on river temperature gradients and floods). A related concern involves the increased potential for mid-winter break ups, which are more unpredictable than spring events but can be just as severe[27,30].

Impacts on human economies and well-being

The greatest impacts of freshwater ice on humans are associated with the dramatic ice and flooding that accompany dynamic freeze-up and break-up events. For many cold regions, it is ice-induced flood events that regularly outweigh costs associated with open-water floods[31]. The economic costs of river ice jams in North America average almost US$250 million per year[32,33] (converted to 2006 values), although this could be a conservative value considering that the cost of a single 2001 break-up season in Eastern Russia in 2001 exceeded US$100 million[34]. They also pose significant risk to human life, particularly because they are less predictable and occur more rapidly than open-water events.

Many northern settlements were established at the confluence of rivers or where rivers enter lakes and these sites are known to be highly susceptible to ice-jam formation[4] (Figure 8.5). Damage by ice action and flood waters to such settlements by infrequent but severe ice jams can be costly. Freeze up, break up and changes in ice thickness and production also cause regular problems for in-channel operations such as hydropower generation, bridges and pipelines, and transportation[32]. All such freeze-up, break-up and ice-thickness related impacts will vary under changing climates.

Figure 8.5: Ice-jam flooding, Ounasjoki River, Finland.
Photo: Esko Kuusisto

Figure 8.6: Loss of ice coverage reducing ice transportation access to northern communities, Liard River, Canada.
Photo: T.D. Prowse

Even the general loss of ice cover through shrinkage of the ice season has been identified as a major economic concern for some northern regions where winter river-ice and lake-ice road networks currently provide essential and relatively inexpensive access to communities and industrial developments[35,36]. Loss of ice-based transportation (Figure 8.6) and ice-related effects on aquatic systems that influence fish and small mammal productivity will be especially important for small indigenous communities, particularly in the Arctic[7,36]. Many indigenous people depend on frozen lakes and rivers for access to traditional hunting, fishing (Figure 8.7), reindeer herding or trapping areas, and for some isolated communities winter travel on frozen rivers is the principle access to larger centres.

Impacts on biological productivity

Freshwater-ice covers control most major interactions between the atmosphere and the underlying aquatic systems (for example solar radiation, thermal regimes and oxygen levels), and hence biological productivity. Reductions in lake-ice covers under future climates will produce changes in temperature and light levels, water circulation patterns and aquatic UV radiation exposure, all of which are important to biological productivity and diversity[37,38]. Of particular concern are variations and change in light and nutrient availability, water circulation patterns, and layering of warm and cold water during the ice-off period. In general, the life cycles of most aquatic organisms are linked with ice cover and temperature, and future changes in these will result in unpredictable responses (see box on alpine lakes).

Figure 8.7: Lake ice fishing, Nunavut, Canada.
Photo: Shari Gearheard

Alpine lakes, snow cover and fish production

Climate warming means that lowland lakes typically are experiencing longer ice-free periods, promoting greater biological productivity. However, despite this warming trend, biological productivity may be reduced, at least temporarily, in alpine areas with increased winter precipitation.

During years with high winter precipitation in alpine areas of western Norway, in spite of higher temperatures, fish growth and recruitment were lower than in low-snowfall years (Figure 8.8). Annual fish growth rates were negatively correlated with spring snow depth – the greater the snow depth, the less the fish grew[23]. During the years 1992 to 1995, a period with mean spring snow depth of 275 cm, fish growth was reduced by 50% compared to years with much less spring snow accumulation (1991 and 1996). A further increase in winter snowfall in these regions, as projected by climatic scenarios, would be expected to result in further reductions in biological production.

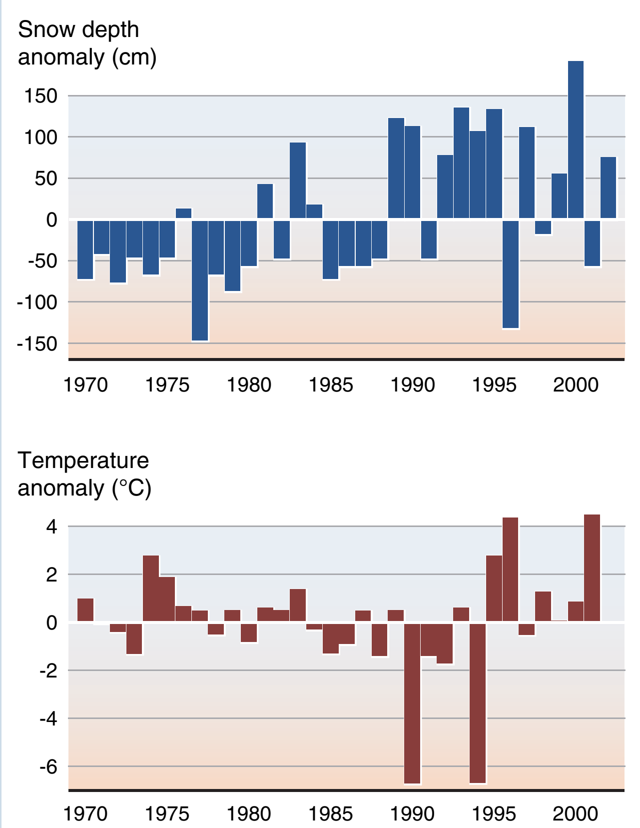


Figure 8.8: Strong interannual changes in snow depth and ice cover may occur in some mountain areas due to increased winter precipitation (as snow). Photos show an alpine lake at the Hardangervidda plateau, western Norway, in early July, for years of high and low winter precipitation. High snowfall years are associated with a strong North Atlantic Oscillation. The charts show that snow cover is not related to temperature.

Source: Based on Borgström and Museth 2005[39]
Photos: R. Borgström

The ice scour and flooding produced by river ice are known to be major reasons for the high biological productivity and diversity found in northern rivers, particularly along their margins and in deltas where break-up events are also the key suppliers of water and nutrients[40,41]. Decreases in the frequency and/or severity of break-up flooding that may arise under future climates could threaten the ecosystem health of such river systems[29,42] (see box on maintaining delta pond ecosystems).

Maintaining delta pond ecosystems

The physical development and ecosystem health of river deltas in cold regions are strongly controlled by ice processes and thus are highly susceptible to the effects of climate change. As an example, the photograph shows a typical lake/pond and river network in the Peace-Athabasca Delta (Canada), one of the largest freshwater deltas in the world. The water budget and sediment-nutrient supply for the multitude of lakes and ponds that dot the riparian zones of such deltas depend strongly on the supply of floodwaters produced by river-ice jams during the spring. These spring floods usually exceed those from open-water flow events, as illustrated in Figure 8.9(a). Studies of future climate conditions for the Peace-Athabasca Delta indicate that a combination of thinner river ice and reduced spring runoff, due to smaller winter snowpack, will lead to decreased ice-jam flooding[42]. This, combined with greater summer evaporation from warmer temperatures, will cause a decline in delta-pond water levels[43].

An adaptation strategy that has been successfully used to counteract the effects of climatic drying of delta ponds involves the use of flow enhancement through water releases from reservoirs. This increases the probability of ice-jam formation and related flooding of the delta ponds (Figure 8.9(b)).

Peace-Athabasca Delta.
Photo: Dörte Köster

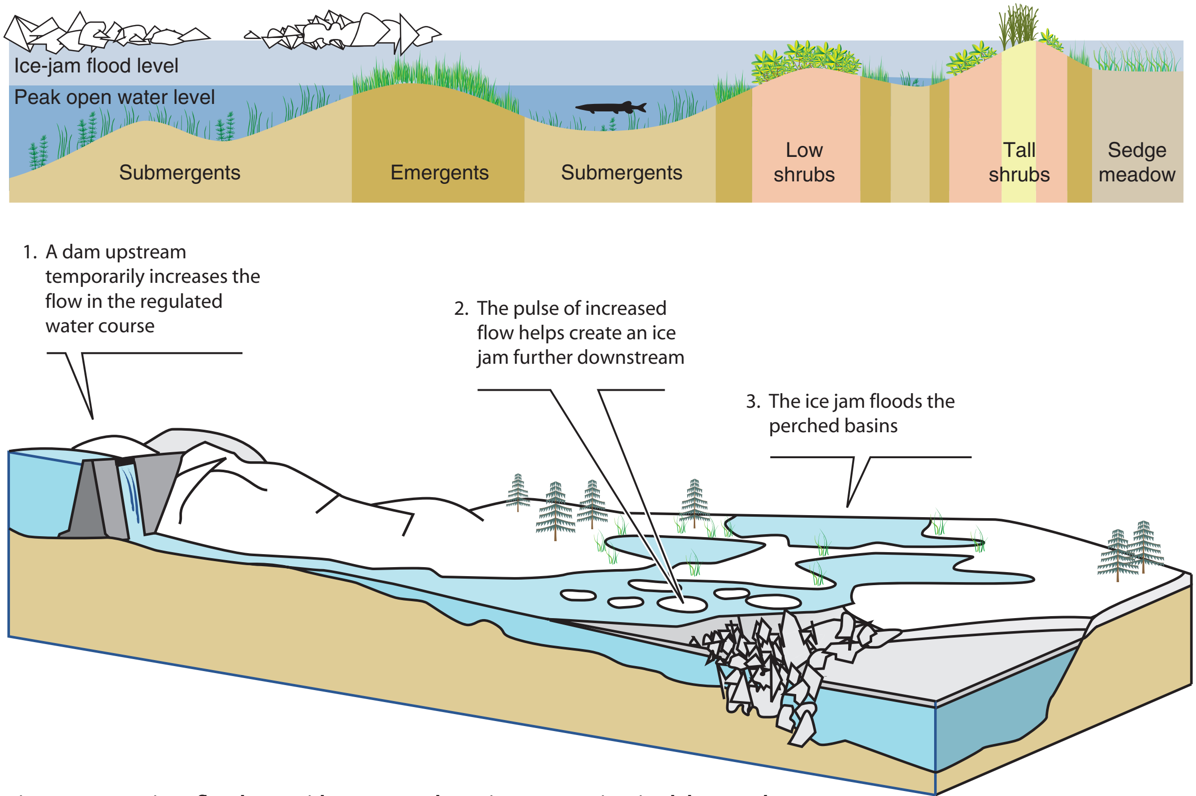


Figure 8.9: Ice-jam floods provide water and nutrients to maintain delta ponds.
(a) Higher flooding levels in spring break up reach the perched basins.
(b) An adaptation strategy: water released from the reservoir on the left increases the probability of ice jams and flooding of the ponds.

Source: Based on Prowse and others 2002b[44]

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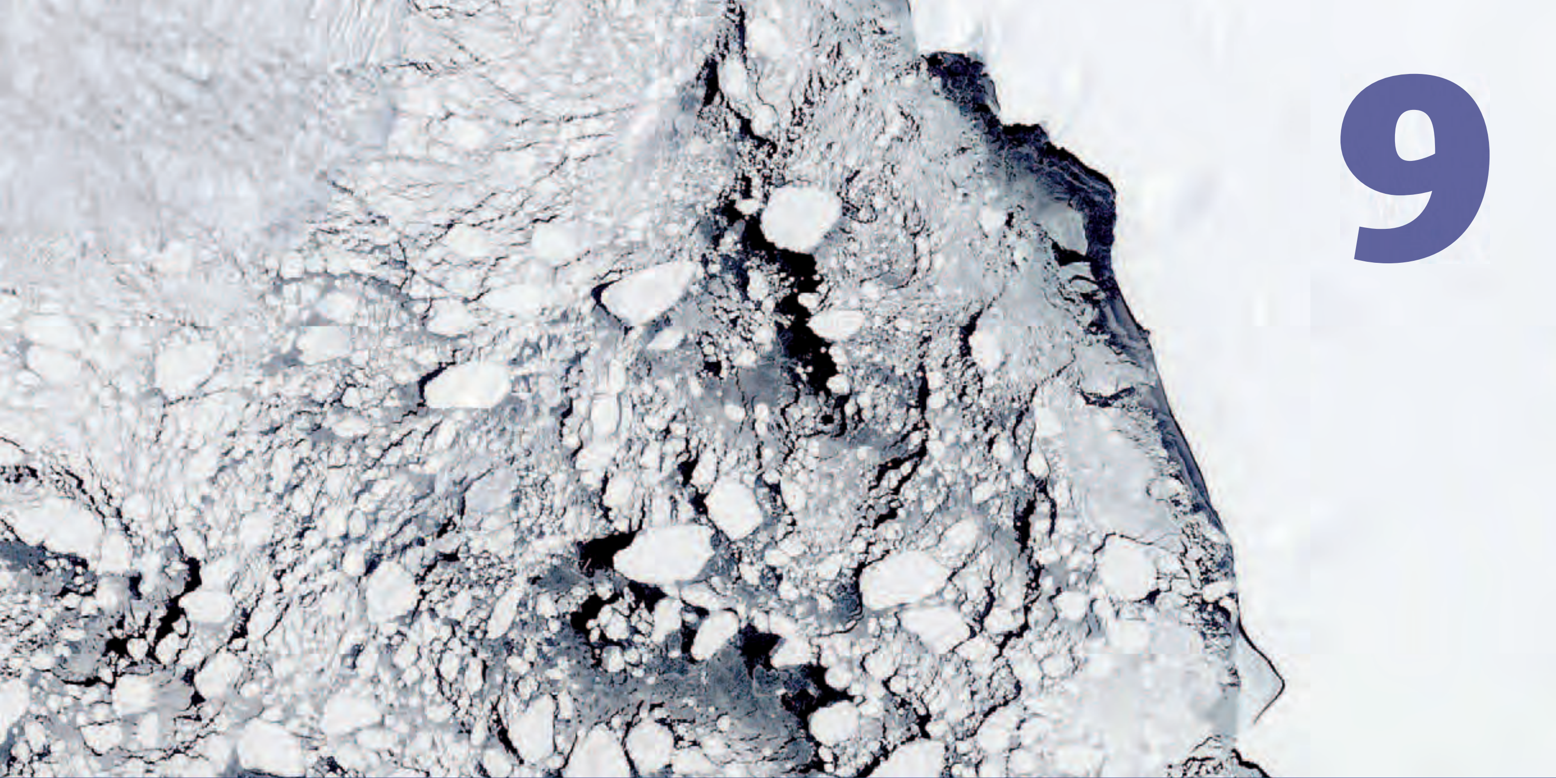

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Policy and Perspectives

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Policy and Perspectives


Photo: Christopher Uglow/UNEP/Still Pictures

Wrap up of key messages

The underlying theme in the preceding chapters is that changes are now observed in ice and snow and bigger changes are projected. The greenhouse gases from past and current emissions remain in the Earth's atmosphere for decades to centuries. Most of the extra heat on Earth caused by emissions of anthropogenic greenhouse gases is stored in the oceans. These two factors will lead to further changes in ice and snow no matter how quickly the world acts to reduce emissions. There is a danger of this time gap between policy implementation and real results leading to thinking that the situation is beyond control – but the projections for future change also make it clear that policies implemented now will have a real impact in slowing global warming in the decades and centuries to come.

Some of the impacts from changes in ice and snow are immediately visible, often showing up as increased frequencies of events that are within the range of natural variation. For example, winter roads might be open on average fewer days in the Arctic; feeding conditions might be poor for caribou and reindeer more frequently than in the past; amount and timing of runoff from snowmelt in the Andes, Alps or Himalayas might result in local water shortages in more years. Over time these short-term events lead to longer-term consequences including changes in biodiversity, ecosystems and regional economies.

In several chapters the theme of gradual and abrupt changes is discussed. Projections for future change are built on climate models, incorporating to the extent possible the complexity of interactions and feedbacks among atmosphere, oceans and land. The results are projections of incremental change – a bit warmer each decade, on average a bit more ice melting from the Greenland ice sheet each year. This type of change is somewhat predictable, as long as one takes into account the natural year-to-year variability in climate conditions. In discussing changes in ice and snow in the preceding chapters, authors reference the possibility of another type of change – abrupt, 'catastrophic' and unpredictable change that results in a jump in the line on the graph, a shift from one state to another. We know from ice cores in Greenland that abrupt climate change may happen naturally. These 'tipping points' can be related to the cryosphere itself. For example the break up of a section of an ice shelf in Antarctica may remove the plug at the end of glaciers draining the ice sheet, leading to a sudden increase in the rate of movement of land ice to the sea, directly translated into sea-level rise. Some of these abrupt changes are related to ecosystems, biodiversity

Sea-ice research in the Fram Strait between Greenland and Svalbard. *Photo: Sebastian Gerland, Norwegian Polar Institute*

and human well-being. When there is no more summer sea ice in the Arctic, some ice-adapted animal populations and species could be driven rapidly to extinction, from the ice algae and crustaceans that are key components of polar marine food webs to polar bears whose life cycles are built around the existence of year-round sea ice. There are potential cascading effects from these abrupt changes, including on the people whose livelihoods and cultures are tied to the affected resources.

The chapters in this book are built around components of the cryosphere, and the impacts are considered one by one. But in the real world, these impacts interact with one another, often in unexpected ways, in some cases resulting in greater impacts, in some cases partially compensating for one another. This is further complicated by negative and positive feedbacks altering the rates of change. This theme of complexity is introduced in the discussion of feedbacks and interactions in Chapter 3 and picked up in the subsequent chapters in discussions of impacts. The chapter on sea-level rise (Chapter 6C) discusses the complexity of interactions associated with assessing and responding to the impacts from sea-level rise.

Another message from the preceding chapters is the need for a concerted effort to improve research and long-term monitoring to address the gaps in our knowledge about what is happening with ice and snow. Some of the biggest questions, of most significance for the long-term future of human societies on Earth, are related to the fate of the ice sheets and the consequences to sea-level rise. But there are many other questions that need to be answered about how the changes in ice and snow affect climate and oceans, biodiversity, and human well-being. It is clear from these chapters that there is optimism that the research and monitoring campaigns initiated through International Polar Year 2007–2008 will address these questions and reduce uncertainty about the outlook for ice and snow.

Policy responses and options

How will these changes in ice and snow affect human well-being? What policy issues will arise from these impacts? How are policymakers likely to frame these issues for public consideration and to evaluate the benefits and costs of the policy responses and options they identify? In order to answer these questions, we address a selection of key policy issues arising at the global, regional and local or community levels.

Global policy issues

From understanding to addressing climate change

Throughout the 1980s, a growing body of scientific documentation on the potential threat anthropogenic climate change could pose to ecosystems and human societies led the World Meteorological Organization (WMO) and the United Nations Environment Programme (UNEP) to establish the Intergovernmental Panel on Climate Change (IPCC) in 1988. The IPCCs mandate is to assemble the best understanding and knowledge on climate change, its potential impacts and options for adaptation and mitigation (see box on the IPCC process).

The first IPCC assessment report in 1990 triggered the negotiation of the United Nations Framework Convention on Climate Change (UNFCCC). Thereafter, the momentum towards addressing climate change has further increased leading to the adoption of the Kyoto Protocol in 1997 which set targets to reduce greenhouse gases emissions and mitigate climate change.

Complementary to mitigation, adaptation measures are needed to respond to the impacts of past and on-going greenhouse gas emissions. Adaptation policy and measures, being region-specific, require increased resolution in scientific knowledge and call for regional climate impacts assessment. In 2000, the Arctic Council, the organization for governmental cooperation among the eight Arctic states, decided to conduct a full impact assessment for the Arctic region. Completed in 2004, the Arctic Climate Impact Assessment (ACIA) was submitted to the ministerial conference of the Arctic Council. The ACIA is the only regional impact assessment conducted for ice and snow covered areas.

Under the Norwegian Chairmanship (2006–2009), the Council is working on follow up on the ACIA's recom-

The Intergovernmental Panel on Climate Change

The mandate of the IPCC is to "assess the scientific, technical and socio-economic information relevant for the understanding of climate change, its potential impacts and options for adaptation and mitigation." The IPCC does not carry out research, nor does it monitor climate-related data or other relevant parameters. Rather, it bases its assessment mainly on peer-reviewed scientific and technical literature that has already been published. The comprehensive assessment process involves the input of hundreds of scientists in compiling, analysing and synthesizing existing scientific publications to draw conclusions about the status of our scientific understanding of climate change.

One of the factors that have made IPCC successful is that it strives to be policy relevant but not policy prescriptive. IPCC reports benefit from a process founded on scientific integrity, objectivity, openness and transparency. Confidence in the results is enhanced through a rigorous review process and an adoption and approval process that is open to all member governments.

mendations by producing status reports on the impacts of vanishing sea ice, possible meltdown of the Greenland ice sheet, and on changes in permafrost. A study on adaptation challenges will also be carried out with the aim of enhancing the adaptive capacity of Arctic residents.

Options to mitigate climate change

One of the main conclusions of the fourth IPCC assessment report is that it is very likely (more than 90 per cent) that most of the global warming during the last 50 years is due to the observed increase in human-made greenhouse gas concentrations, and that continued greenhouse gas emissions at or above current rates would cause further warming and induce many changes in the global climate system during the 21st century that would very likely be larger than those observed during the 20th century[1].

Today, the CO_2 level in the atmosphere has increased by 40 per cent over pre-industrial levels. Under a business-as-usual scenario for emissions from human activities, a doubling will occur in 50–80 years, depending on the rate of increase in emissions and how much nature will absorb, which would most probably lead to a global temperature increase of 3 °C.

A global temperature increase of more than 2–3 °C will constitute dangerous climate change with unacceptably high risk of:

- Significant negative impacts on global food production and water supply;
- Large-scale changes in ecosystems and biodiversity that will negatively affect ecosystem services;
- Melting of parts of the Greenland and Antarctic ice sheets with subsequent devastating sea-level rise;
- Irreversible abrupt climate changes, such as large-scale changes in ocean currents.

To avoid such temperature increases, greenhouse gases must be stabilized at a level below a doubling of pre-industrial levels. Achieving this means that no later than 15 to 25 years from now emissions will have to stop increasing and start decreasing significantly – to about 10–50 per cent of currents levels by 2050[2]. In the longer term, emissions must be cut by as much as 70–80 per cent in order to stabilize the Earth's climate system.

Recent comprehensive assessments and reports[2,3,4] indicate that such emission cuts can be achieved over the next few decades without significant welfare losses. The cost is estimated to be less than 2 per cent of the gross domestic product (GDP), well below the rate of growth in the economy. Many of the needed technologies exist, and the potential for improving them and developing new technologies is high. It is the sum of many small and medium contributions to reductions in emissions through the use of several different kinds of technologies for energy efficiency, renewable energy, and carbon capture and storage (CCS) that is likely to constitute the solution in the end.

At the political level, there is a wide variety of policies, measures and instruments that could be applied to stimulate the use of alternative existing technologies, improve them and develop new technologies. According to the IPCC[2], "A positive 'price of carbon' would create incentives for producers and consumers to significantly invest in lower carbon products, technologies and processes." A carbon price of US$20–50 per tonne of CO_2 equivalent could largely decarbonise power generation and make many mitigation options in the end-use sectors attractive[2–4]. A uniform carbon price must be globally accepted to ensure equal conditions for competition in a globalized economy. In addition, incentives related to direct governmental funding and regulations are required. For example, the development of new technologies will depend on large-scale governmental funding of research and development.

Regional policy issues

It is natural to turn first to the polar regions in thinking about regional policy issues. But the impacts of changes in ice and snow are not limited to the high latitudes. In mountainous areas where glaciers are prominent features of the landscape and the annual snow pack is an essential source of fresh water, changes in ice and snow will produce substantial impacts on human well-being. In this discussion of regional policy issues, we look at selected issues in three regions: the Arctic, the Antarctic, and the Himalayas.

Arctic: jurisdiction, oil, and minerals

In the Far North, the key policy issues centre on the prospects that retreating sea ice will open up the Northeast and Northwest Passages for commercial shipping and increase access to commercially significant deposits of oil and gas located in shallow waters of the Arctic littorals. If current forecasts regarding the navigability of Arctic waters (such as ice-free navigation along the Northern Sea Route for up to 120 days per year during this century) hold, incentives to ship a variety of goods – especially between Europe and the Far East – will grow rapidly in the coming decades. The combination of large recoverable reserves of oil and gas (25 per cent or more of the Earth's untapped reserves according to the US Geological Survey) and the relative security of the Arctic in geopolitical terms can be expected to make the extraction of hydrocarbons in this area irresistibly attractive.

These developments will give rise to two sets of policy issues that cannot be avoided even in the short run. The first set concerns jurisdiction. Already, Canada and Russia are taking steps to assert extended Exclusive Eco-

Arctic sea ice.
Photo: Andrea Taurisano, Norwegian Polar Institute

nomic Zones and enhanced control over continental shelves in the Arctic Basin. These jurisdictional issues will require resolution under the terms of Parts V (Exclusive Economic Zone) and VI (Outer Continental Shelf) of the UN Convention on the Law of the Sea (UNCLOS), even though the United States has never formally ratified UNCLOS. Article 234 on "ice-covered areas" may provide a point of departure for some initiatives relating to these matters. One option that may prove attractive is an agreement on jurisdiction in the Arctic Basin settling competing claims among the five littoral states, granting primacy in the region to these states, and making some provision for navigation in Arctic waters on the part of others.

The second set of issues concerns rules governing shipping and oil and gas development. The creation of regulatory regimes will be the first order of business. Some existing agreements, such as the International Convention for the Prevention of Pollution from Ships (MARPOL), already apply to the Arctic Basin. Designation of the Arctic as a Special Area under MARPOL was proposed by the Arctic Council's working group on the Protection of the Arctic Marine Environment several years ago, but the proposal did not receive the necessary consensus from the eight Arctic nations.

Other potential mechanisms include the development of a regional regime intended to articulate and codify standards for environmental protection in the Arctic under UNEP's Regional Seas Programme. The US and probably Russia are likely to oppose such a move. To the extent that oil and gas development occurs in areas under coastal state jurisdiction, national regimes governing such activities will apply. Even so, the fact that the Arctic Basin is a single system with its own biophysical dynamics will almost certainly stimulate efforts on the part of some coastal states to develop a regional regime to minimize adverse impacts of oil and gas development on Arctic ecosystems.

Antarctic: tourism expansion

Antarctic annual sea-ice extent is projected to decrease by 25 per cent by 2100 (Chapter 5), and this will bring easier access to the Antarctic continent by ship. This is likely to affect not only research, which is a main activity in a continent designated as a "natural reserve devoted to peace and science", but also commercial activities, such as tourism.

Tourism activities are expanding tremendously with the number of shipborne tourists increasing by 430 per cent in 14 years and land-based tourists by 757 per cent in 10 years (Figure 9.1). The majority of the seaborne voyages are to the Antarctic Peninsula region where the open sea condition in the summer season makes those voyages feasible and safer. Parallel to the growth in tourism is a substantial increase in tour-

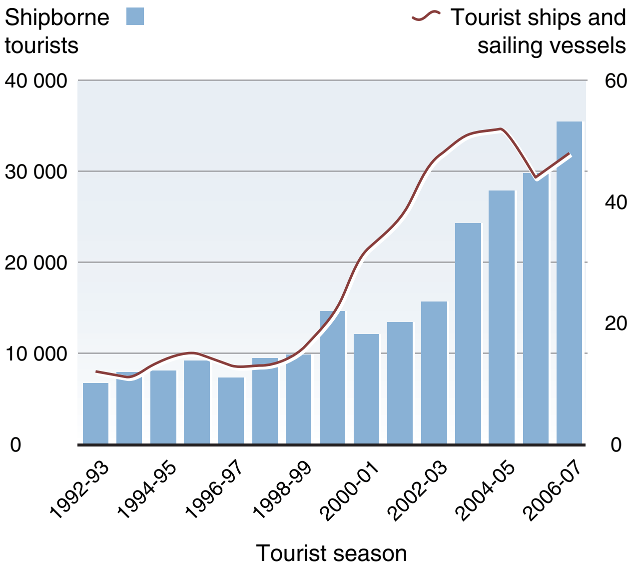

Figure 9.1: Growth of tourism in Antarctica.

Source: IAATO 2007[6]

ism vessels, some with large passenger capacities and without ice-strengthened hulls, such as the *Golden Princess* which has a capacity of 3700 persons, exceeding the estimated peak in personnel based in all Antarctic stations[5].

The projected retreat of sea ice is likely to lead to an expansion of tourism activities, as more sites will become accessible by sea and the season will lengthen. This, in turn, is likely to increase the risk tourism presents to the marine environment, as well as to terrestrial ecosystems, as over 80 per cent of the tourists land during their journeys. This will also present new challenges in maintaining the unique characteristics Antarctica presents for scientific monitoring and research on processes of global and regional importance. The growth in tourism has the potential to affect national research programmes through increased demand for services such as weather forecasting and search and rescue services.

In order to address these challenges, a comprehensive regime on tourism should be developed, complementary to the Madrid Protocol on Environmental Protection to the Antarctic Treaty, which provides a regulatory framework for human activities in Antarctica.

Himalayas Hindu Kush region: water supply and flood risk

Hundreds of millions of people are vulnerable to impacts from climate change in the mountain ranges and lowlands surrounding the Tibetan Plateau, far into Central Asia, Pakistan, India, Bangladesh and China. As discussed in Chapter 6B, projected changes in snowfall and in glacier melt are expected to lead to major impacts including increased flood risk and water shortages in many parts of this huge and densely-populated region.

River in Nepal.
Photo: Christian Lambrechts

These changes are exacerbated by unsustainable natural resource management practices which lead, for example, to substantial deforestation and overgrazing in most watersheds[7,8].

Addressing these issues will require strategies and policies related to land-use and water management, for example:

- Watershed management and protection: In most of the countries only 1-5 per cent of the watersheds are protected, leaving little in the way of natural buffers against flash flooding.
- Poverty alleviation and financial mechanisms to support development of more sustainable grazing and wood-cutting practices. In particular, improved household consumption patterns of firewood would increase the resilience of watersheds to greater seasonal fluxes of water flows.
- Development of alternative settlement opportunities for impoverished people who often settle in the available flatlands and low-lying urban areas exposed to floods.
- Assistance with transition to new economic bases for livestock-based villages in dry mountain areas where less snowfall and reduced snow seasons may lead to loss of traditional grazing lands.

Drying fish in a Greenland community.
Photo: Stine Rybråten/CICERO

Local policy issues in the Arctic

The impacts of changes in ice and snow are already major concerns in small communities scattered throughout the circumpolar North. Among the most significant of these are damage to infrastructure (such as buildings, municipal water and sewage system, roads, pipelines and airfields) arising from coastal storm surges and the deepening of the active layer of the permafrost; threats to safety (such as disintegration of sea ice used by hunters as a staging area) caused by unfamiliar weather conditions; health and nutritional concerns (related to availability of country food) associated with changes in the abundance and migratory patterns of subsistence resources, and a variety of social effects arising from the growth of commercial shipping and oil and gas development. The significance of these effects will vary from one community to another, and responses will differ – sometimes dramatically – from one part of the Arctic to another. What is clear is that most individual communities lack the capacity to cope effectively with these stresses, either because they do not have the resource base needed to reconstruct physical infrastructure or to relocate or because they do not have the authority to make binding decisions about key issues (such as the social impacts of commercial shipping). Actual responses are likely to reflect differences in the political and legal systems of the individual Arctic states. In the US, the State of Alaska will be a source of support for individual communities facing the impacts of changes in ice and snow. In Greenland, the government of Denmark is a likely source. Other affected communities, for example in the Russian North, may not receive sufficient support from outside of their regions.

While the impacts considered in the preceding paragraph are generally negative, changes in ice and snow may also have positive consequences at the local level. Oil and gas development can become a source of jobs; there is some prospect that changes in sea ice will permit the development of commercial fisheries in areas located farther north than existing fisheries, and conditions for agriculture may improve under a moderate warming. Jobs in the energy industry are often transient, and the sustainability of commercial fisheries in the Arctic may be low. So long as expectations are moderate and communities are careful to avoid undue dependence on these sectors, however, changes in ice and snow can become a source of benefits as well as threats to human well-being.

Perspectives on changing ice and snow

The essays below are from people living with and planning for the consequences of changing ice and snow in the Arctic, Pacific Islands and Nepal.

All things are connected...

A perspective from an indigenous world view

Patricia Cochran, Chair,
Inuit Circumpolar Council

In indigenous cultures, no one part of an ecosystem is considered more important than another part and all parts have synergistic roles to play. Indigenous communities say that "all things are connected" – the land to the air and water, the earth to the sky, the plants to the animals, the people to the spirit.

The Arctic may be seen as geographically isolated from the rest of the world, yet the Inuit hunter who falls through the thinning sea ice is connected to melting glaciers in the Andes and the Himalayas, and to the flooding of low-lying and small island states. What happens in foreign capitals and in temperate and tropical countries affects us dramatically here in the North. Many of the economic and environmental challenges facing Inuit result from activities well to the south of our homelands, and what is happening in the far North will affect what is happening in the South. If the Greenland ice sheet melts (as it seems to be doing now), not only do world water levels rise, but scientists speculate that dumping such massive quantities of cold water into the Atlantic may very well affect the Conveyer Belt. This circularly moving body of cold and warm waters regulates climate in much of the Northern Hemisphere. We are all connected on this planet and the Arctic plays an important role.

Living with snow and ice changes

An Indigenous Elder perspective

Caleb Pungowiyi,
Kotzebue, Alaska

"Since the late 1970s, communities along the coast of the northern Bering and Chukchi Seas have noticed substantial changes in the ocean and the animals that live there. We are seeing clear trends in many environmental factors and, we can expect major, perhaps irreversible, impacts if those trends continue.

The patterns of wind, temperature, ice and currents in the Bering and Chukchi Seas have changed. The winds are stronger and there are fewer calm days. In spring, the winds change the distribution of the sea ice and, combined with warm temperatures, speed up the melting of ice and snow and force many marine mammals to move away, often too far to be hunted. Near some villages, the wind may force the pack ice on the shore, making it impossible for hunters to move their boats from and back to the shore. High winds also make it difficult to travel in boats, reducing the number of days that hunters can go out. These reasons have reduced access to animals during the spring hunting period.

From mid-July to September, there is more wind from the south, making the season wetter. With less sea ice, fall storms are eroding much more of the coastline, threatening houses and even entire communities. Wave action has changed some sandy beaches into rocky ones as the sand washes away.

The formation of sea ice in fall has been late in many recent years. In such years, the ice is thinner than usual, which contributes to early break-up in spring. Another aspect of late freeze-up is the way in which sea ice forms. Under normal fall conditions, the cold water and the permafrost under the water help create ice crystals on the sea floor. When large enough, these crystals float to the surface, carrying sediments. The sediments contain nutrients that will be released in spring stimulating algae growth and the entire food chain.

Precipitation patterns have also changed, with a shift in snowfall from fall to late winter or early spring. The lack of snow makes it difficult for polar bears and ringed seals to make dens for giving birth, or in the case of male polar bears, to seek protection from the weather. The lack of ringed seal dens may affect the numbers and condition of polar bears, which prey on ringed seals and often seek out the dens. Hungry polar bears may be more likely to approach villages and encounter people.

Other marine mammals have been affected by the changes in sea ice, wind and temperature. The physical condition of walrus was generally poor in 1996-98 due to reduced sea ice which forced the walrus to swim farther between feeding areas in relatively shallow water and resting areas on the distant ice, compounded by a lower productivity of the sea bed. In the spring of 1999, however, the walrus recovered following a cold winter with good ice formation in the Bering Sea.

As we think about the future, we wonder what alternatives are available to Native villages in the Arctic. If marine mammal populations are no longer accessible to our communities, what can replace them? Today, there are stores with food and other resources that can be harvested. A gradual change might give us time to adjust, but a sudden shift might catch us unprepared and cause great hardship. We need to think about the overall effects on marine mammals and other resources. Some may adjust, but others will not. Our ancestors taught us that the Arctic environment is not constant, and that some years are harder than others. But they taught us that hard years are followed by times of greater abundance and celebration. As we have found with other aspects of our culture's ancestral wisdom, modern changes, not of our doing, make us wonder when the good years will return.

Vanishing beneath the waves

A Pacific island perspective

Taito Nakalevu,
Apia, Samoa

The sea has been part of Pacific islanders' life since the beginning of time. It has influenced the way they build, plan and carry out daily activities. It has also been an agent of chaos and change. Pacific islanders are now used to seeing islets vanish beneath the waves after cyclones or other extreme events. The greater worry at present for most Pacific nations is whether extreme events will increase in the future.

Pacific Island countries are some of the most vulnerable communities in the world and are already experiencing the effects of climate change. The Intergovernmental Panel on Climate Change, which represents the consensus of 2,000 scientists, talks about a rise in sea level up to a metre or possibly higher, depending on the melting of the Antarctic and Greenland ice sheets over the next 50 to 100 years. This is worrying particularly for low-lying atoll islands like Tuvalu, Kiribati and other Pacific islands. Many of the islands are not more than a few metres above water, so a sea-level increase of as little as half a metre would completely inundate some of those island States and threaten their populations.

The problem with sea-level rise is that it would exacerbate storm surge, erosion and other coastal hazards, threatening vital infrastructure, settlements, and facilities that support the livelihood of island communities. Prior to 1985, the Cook Islands had been considered to be outside the main cyclone belt and could expect a major twister every 20 years or so. But all that has changed. In 2005, in one month alone, five cyclones swept the Cook Island waters, three of which were classified at Category 5 intensity. In 2004, Niue had been hit by Cyclone Heta, with the ocean rising above the 30 metre cliffs, leaving two people dead and 20 per cent of the population homeless.

Early in the morning of April 16 this year, six families from the settlements of Tekavatoetoe on Funafuti in Tuvalu were evacuated from their homes after severe flooding from unusually high swells. Radio Tuvalu says the families were moved to the Tuvalu Red Cross with the assistance of the Disaster Management, the Police and the Red Cross. One of the woman rescued from her home told Radio Tuvalu that the first huge wave came around 4 o'clock on Monday morning. It swept most of their belongings out into the sea.

Many international environmental activists argue that Tuvaluans and others in a similar predicament should be treated like refugees and given immigration rights and other refugee benefits. This tiny nation was among the first on the globe to sound the alarm, trekking from forum to forum to try to get the world to listen. New Zealand did agree to take 75 Tuvaluans a year as part of its Pacific Access Category, an agreement made in 2001. But Tuvalu is not alone in the Pacific with its worries. Other states, such as Kiribati, are also confronted with rising sea level problems.

Some theorize that sea level rise and storm surges would simply "rearrange", but not obliterate, an atoll island like Tuvalu. Rearrangement would be bad enough for people in Pacific nations because any new land tenure issue would compound the already complex land tenure systems currently plaguing many Pacific nations. In fact, it could lead to a new security issue for the islands as some people may benefit while others lose out completely.

Himalayan meltdown

A Himalayan perspective

Kunda Dixit,
Kathmandu, Nepal

Ang Phurba lives in Khumjung near the base of Mt Everest in Nepal. The 65-year-old Sherpa has seen mountaineering expeditions come and go, but he has also seen other changes. In his own lifetime, the snowline on the northern flank of the 7000 m Thamserku is higher. "The ice used to come down to there in this season," he says pointing to eye-level, "now it's up there."

On nearby Ama Dablam, the signs of glacial retreat are dramatic. Seracs at the mouth of a short glacier on its west face are now 1000 m higher than the remnants of a terminal moraine. Right across the Nepal Himalaya, glaciers are receding dramatically. Moraine ponds in the Annapurnas, Everest and other mountains that climbing expeditions had taken pictures of in the 1950s have now become lakes up to 3 km long. In the Rolwaling Valley northeast of Kathmandu, the Tso Rolpa glacier has a lake that is about to burst its moraine dam. Nepal and Bhutan have more than 50 new glacial lakes that could unleash catastrophic outburst floods downstream.

Dorje Sherpa lost his daughter and grandchild during a flashflood triggered by a glacial lake on Ama Dablam that burst in 1993. He does not link the tragedy to global warming. He says: "The gods must have been angry, why else would it have happened?"
Photo: Naresh Newar

The lake-side town of Pokhara in central Nepal is one of the most spectacularly scenic places on earth. It is located at 600 m and less than 30 kilometres away rises the dramatic fishtail-shaped double peak of Machapuchre at 7000 m. The past two winters, the people of Pokhara have seen an apocalyptic sight: the black summit pyramid of Machapuchre completely devoid of snow.

Most Nepalis realise that something crazy is going on with the weather. Kathmandu saw its first snow in 63 years this spring. A localized hailstorm in central Nepal in April was so severe it pulverised a whole village. But most of us don't link all this to global climate variability. And even if we did, there is a feeling that it is beyond our control.

The Himalaya and the Tibetan Plateau are the water towers for Asia's biggest rivers. The source of the Yangtse, Mekong, and Irrawady are in eastern Tibet. The Brahmaputra, Ganges and Indus all begin within 30 km of each other near the tri-junction of the borders between Nepal, China and India.

What happens to the snows that feed these rivers due to global warming will determine the future of the billion people who live downstream. Think of that the next time you stop at a petrol station.

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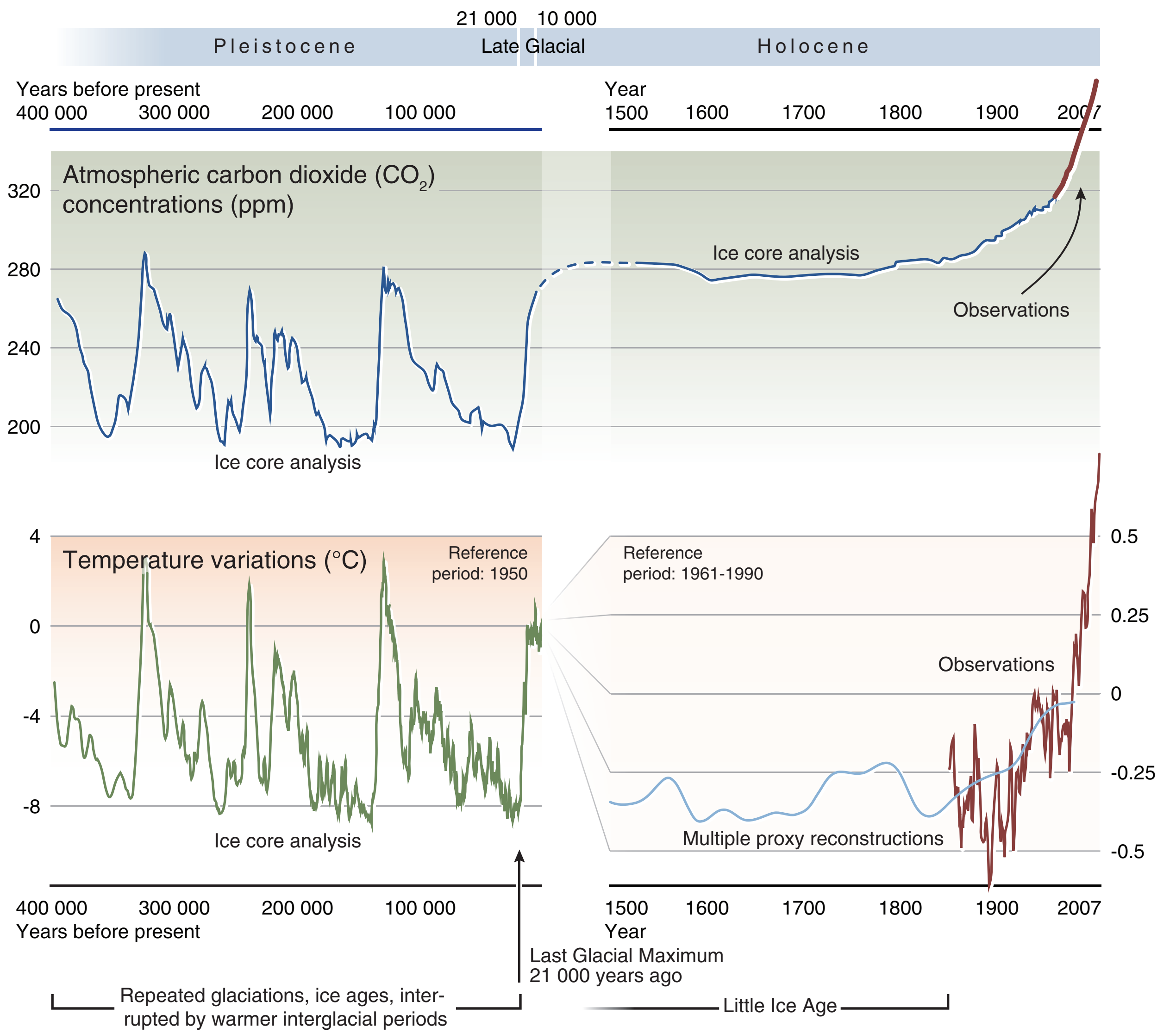

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This book is about ice and snow in polar and mountain regions of the world. It covers all parts of the cryosphere (the world of ice): snow, land ice, sea ice, river and lake ice, and frozen ground. It presents information on the trends in ice and snow, the outlook for this century and beyond, and the consequences to ecosystems and human well-being of changes in ice and snow.

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