MELTING ICE
REGIONAL DRAMAS
GLOBAL WAKE-UP CALL

Melting snow and ice

A call for action

A report commissioned by Nobel Peace Prize laureate Al Gore
and Norway's Minister of Foreign Affairs Jonas Gahr Støre

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Melting snow and ice: a call for action

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Petermann glacier, Greenland, 2009. Photo: Nick Cobbing

Table of contents

FOREWORD

Snow and ice are melting far above normal seasonal changes, and the changes are occurring at an accelerating pace. We see this happening in all snow- and ice-covered regions: Antarctica, the Arctic, Greenland, the "third pole" of the Himalayas, and other glaciated areas throughout the world.

The consequences for the regions affected are already considerable and more are expected. However, the melting is not only an issue for the areas where it occurs. Snow and ice are important components of the Earth's climate system. Melting will be felt in all regions of the world through increased global warming and rising sea levels. Moreover, the loss of summer ice cover on the Arctic Ocean is leading to greater absorption of heat from the Sun. This is thawing the permafrost surrounding the Arctic and threatening the release of very large quantities of additional carbon dioxide and methane to the atmosphere.

In April 2009, climate scientists and foreign ministers from states affected by melting snow and ice brought the attention of the globe to the plight of the cryosphere in their conference *Melting Ice: Regional Dramas, Global Wake-Up Call.* As co-chairs of the conference we charged a group of leading scientists to summarize what we know about how fast this melting is occurring, and how it will affect the Earth and its climate.

Those scientists have now completed their work: and as bad as things looked last spring, today's reality turns out to be even worse. Melting to a degree thought physically impossible, from the Himalayas to the Arctic and even in Antarctica, is occurring now. Arctic sea ice has been shown to be more endangered, Greenland runoff has risen to unprecedented rates, and glaciers continue to shrink and disappear. Such changes already have begun to seriously impact water supplies, the pace of sea level rise, and the global climate system itself.

Norway's Minister of Foreign Affairs Jonas Gahr Støre and Nobel Peace Prize laureate Al Gore, Melting Ice conference, Tromsø, 2009.
Photo: Yngve Olsen Sæbbe

We strongly urge that political action be taken to ensure a globally responsible policy to substantially reduce the emission of greenhouse gases. We are not helpless against this threat. Indeed there is much that we as nations and as peoples can do, whether we are living in the realms of snow and ice or are affected by its melting in other parts of the globe.

The first is by now apparent and widely recognized internationally: deep cuts in global greenhouse gas emissions. No other remedy we know can ensure that we avoid dangerous man-made climate change and that we preserve the polar and alpine environments as we know them today.

However, even if we manage to turn the rising curve of global greenhouse gas emissions in the coming years, the reduction will not occur quickly enough to preserve the polar and alpine environments as we know them today.

Increasing concentrations of black carbon at mid-latitudes could be responsible for a significant fraction of the rapid Arctic warming observed over the last decades. That leads us to **a second way to respond**: take action that will make a real impact in the near future, and most especially, address short-lived climate pollutants such as black carbon, methane and tropospheric ozone.

Our third point is a more somber one: despite all our efforts, we likely cannot prevent some changes in the Arctic and glacier environments. Adaptation is inevitable. Many peoples affected cannot cope with the challenges alone. Industrialized nations must assist by becoming part of the solution, not least because they bear the main responsibility for the man-made climate change we have seen so far.

Our fourth and final point is the need to base political action on scientific findings – and to ensure that science is steadily improved and updated. There are uncertainties with respect to how snow and ice will continue to respond to a changing climate, as well as with regard to how these changes will affect natural and social systems. Reducing these uncertainties through scientific research is critical for making sustainable mitigation and adaptation strategies.

However, let there be no doubt: we know enough to act now. We need early action on short-lived forcers like black carbon, and we need more effective assistance to those affected across the world by these unprecedented rates of melting. But first and foremost, we need a strong international commitment to reduce greenhouse gas emissions.

Al Gore and Jonas Gahr Støre,
Copenhagen, 14 December 2009.

Executive summary

Snow and ice are important components of the Earth´s climate system and are particularly vulnerable to global warming. Significant changes have been observed over the last decades and it appears that these changes are occurring at an accelerating pace.

- The mean monthly snow cover extent in the Northern Hemisphere is decreasing at a rate of about 1.5% per decade.
- The Arctic sea ice extent has decreased significantly; the summer minimum is decreasing by 11.2% per decade, much faster than projected by current models.
- The Arctic sea ice is thinning, with thin seasonal ice replacing thick older ice. Currently, thin first-year ice makes up more than 70% of the total cover, compared to about 50% in the 1980s.
- Glaciers around the world are shrinking at an accelerated rate, with the largest mass losses per unit area in the European Alps, Patagonia, and northwestern parts of America.
- The Greenland Ice Sheet is losing volume and the mass loss has increased significantly over the last decade. The area experiencing surface melt increased by 30% between 1979 and 2008, with a record-breaking surface melt area measured in 2007. Recent data from Greenland indicate that the loss of ice due to accelerated ice flow into the ocean equals the loss from surface melt.
- Significant mass loss is documented for parts of the Antarctic Ice Sheet, and there are now indications that the Antarctic continent is experiencing net loss of ice.
- From 1993 to the end of 2007 data indicate global sea level rise between 3 and 4 mm per year. This rate is faster than the 1.7 mm per year average rate over the 20th century. Melting of land ice is now becoming the dominant contributor to sea level rise.
- The permafrost around the globe has typically warmed between 0.5 and 2°C.
- Over the past 150 years, river and lake ice cover duration has been decreasing at a rate of about 1.4 days and 1.7 days per decade, respectively; recent decreases are occurring even more rapidly.

Melting of snow and ice severely impacts the global climate. As snow and ice diminish, the Earth's surface reflectivity is reduced and more solar radiation is absorbed, accelerating global warming. Key components of the snow and ice system that contribute to such feedback processes are expected to continue to change and thereby enhance further change towards a warmer climate.

- Snow extent is expected to continue to decrease significantly. Decreases in snow cover extent amplify global warming by changing the reflectivity of the land surface.
- Models predict a nearly ice-free Arctic Ocean in late summer within this century, some models indicating this could happen before mid-century. Large reductions in summer sea ice extent will accelerate global warming and impact global climate and weather processes.
- Over the next century, near-surface permafrost across the circumpolar Arctic is expected to degrade significantly, increasing the flux of carbon dioxide and methane into the atmosphere, feeding back to further climate change.
- Black carbon deposited on snow and ice darkens the surface, and since dark surfaces absorb more solar radiation, this accelerates snow melt and ice disintegration, leading to further warming.

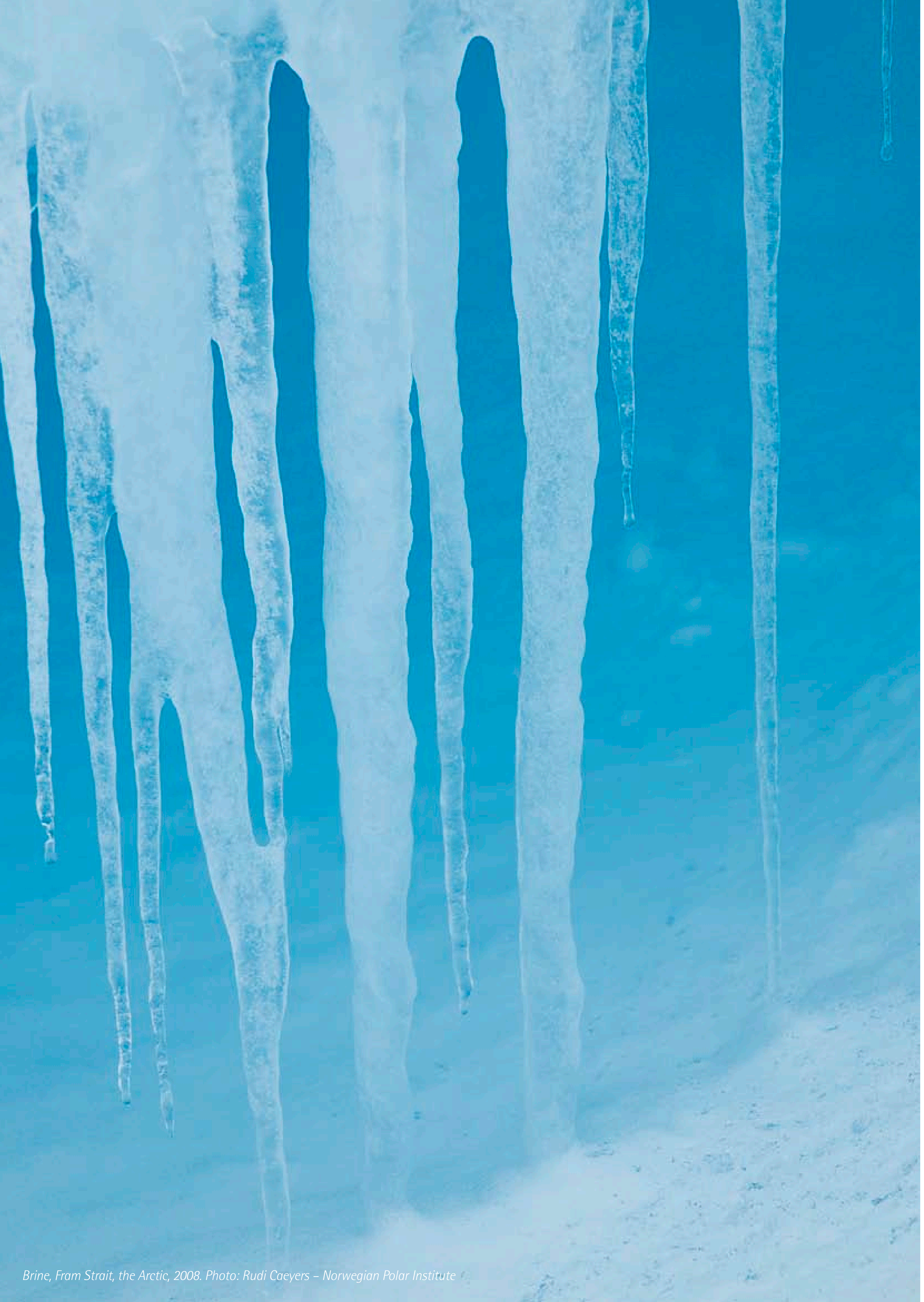
There are issues directly related to melting snow and ice that may significantly impact the well-being of millions of people, and threaten communities, cities, and nation states.

- Melting glaciers may strongly affect the seasonal availability of freshwater. There is a growing concern that melting glaciers may significantly affect millions of people living downstream of glacier areas, in particular in the Himalayas and the Andes region, where population densities are high and where many people and communities are economically vulnerable. Not enough data are available to make solid and quantitative assessments as to how serious and extensive this issue is, but the risk and potential consequences are so large that the lack of knowledge must not be used as an excuse for not taking action.
- Global climate models may under-predict future sea level rise, and current projections of future ice sheet related rises in sea level should be regarded as lower boundaries. Recent observations indicate increasing rates of ice sheet thinning and melting. Rapid disintegration of the Greenland and West Antarctic ice sheets would be a major concern as these two ice sheets contain enough water to raise sea level by 7 m and 5 m, respectively. Millions of people in low-lying coastal areas such as Bangladesh, the Netherlands, the Mekong Delta, and small island states will have to respond to rising sea levels during the 21st century and beyond.

Melting of snow and ice has other consequences that are regionally important.

- Snow and ice are defining components of the ecosystems in which they occur. Changes in snow and ice will significantly impact the ecosystem structure and biodiversity in these regions.
- Global warming can cause instabilities in snow and ice that create hazards to humans in the form of slope instability, rock and ice slides, and glacier lake outburst floods and mud flows.
- Less snow and ice reduce options and opportunities to use the environment in a traditional manner. The human sense of place is undermined as snow and ice disappear from a landscape that one calls home.

Chinstrap penguins on iceberg, Antarctica, 2001. Photo: Stefan Lundgren



Brine, Fram Strait, the Arctic, 2008. Photo: Rudi Caeyers – Norwegian Polar Institute

Melting snow and ice: a call for action

In this document we provide a brief overview of the response of snow and ice to a warming climate. Significant changes in sea ice cover, snow cover, lake and river ice cover, permafrost temperatures, glacier and ice sheet mass have been observed over the last decades. It appears that the changes are occurring at an accelerating pace. The global implications of these changes are potentially severe:

- Reduction of ice, snow and permafrost contributes to a continued and accelerated global warming through various feedback processes.
- The loss of mass from glaciers worldwide, and the Greenland and Antarctic ice sheets in particular, will lead to significant sea level rise within this century and beyond.

Although there are still uncertainties as to how much and how fast changes to snow and ice will occur in the years to come, it should be noted that all projections point towards a reduction of snow and ice. Also, very abrupt climate changes have occurred in the past and cannot be ruled out in the future.

The fourth Intergovernmental Panel on Climate Change (IPCC)* assessment report projects a global warming of 1.1–6.4°C with a 2.8–7.8°C warming in the Arctic by 2100, assuming the implementation of some greenhouse gas reduction measures[1]. Such a dramatic warming will bring new opportunities, but also serious challenges to the well-being of people and the stability of societies worldwide, such as:

- Hundreds of millions of people in low-lying coastal areas may lose their homes due to rising sea levels, and some nation states may even be at risk of extinction.
- Millions of people may be affected if freshwater availability decreases due to changes in snow and glacier reservoirs or flooding of groundwater reservoirs.
- Some people and communities around the world may have to cope with a more unstable and hazardous environment created by continuous changes in snow and ice conditions.
- Some cultures may suffer as less snow and ice limit options and opportunities to use the environment in a traditional manner.

The fourth IPCC assessment report concludes that it is very likely that most of the global warming during the last 50 years is due to human activity, and that continued greenhouse gas emissions at or above current rates would cause further warming.

We strongly urge that political action is taken to ensure a globally responsible policy to reduce greenhouse gases in the atmosphere. Further changes to snow and ice will have strong and serious impacts. Although uncertainties remain as to how these changes will unfold, we are certain that we do know enough to say that even the conservative estimates of change justify a strong call for action. We believe a globally responsible policy is urgently needed to reduce the current warming trend and enable the world's population to adapt to the consequences of changes in snow and ice.

Task Force, Copenhagen, 4 September 2009

* Terms in blue type are explained in the Glossary on page 82

The importance of snow and ice

Thin sea ice, Fram Strait, the Arctic, 2007. Photo: Rudi Caeyers – University of Tromsø

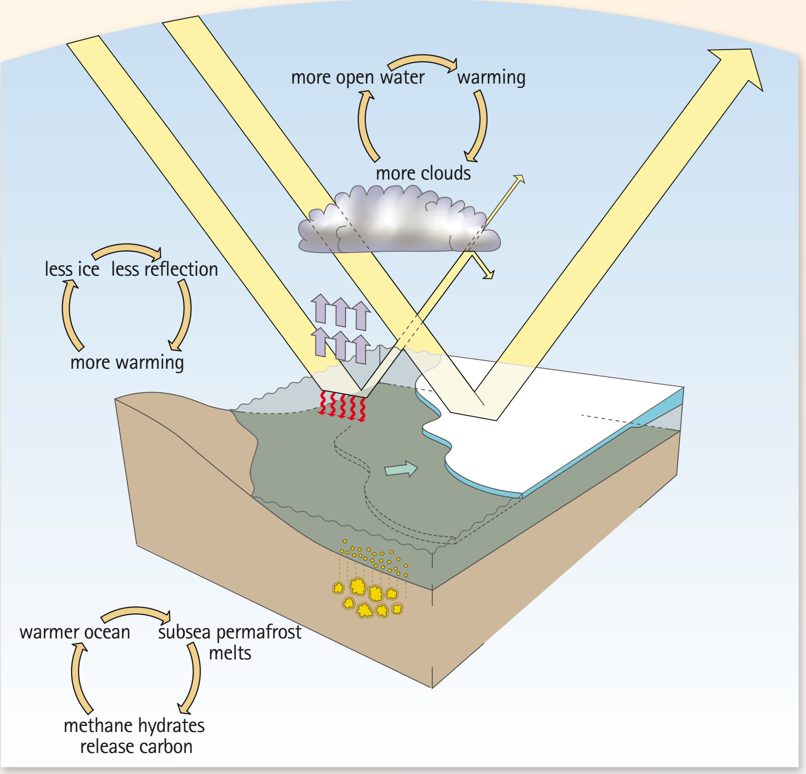
Snow and ice on land, in the sea, and in the ground are part of what is known as the cryosphere. Snow and ice are important components of the Earth´s climate system and are particularly vulnerable to global warming. Reduction of snow and ice contributes to an acceleration of global warming through feedback processes. Loss of snow and ice will impact the cultures and livelihoods of people around the world.

Changes in snow and ice affect the global distribution of heat

- Snow and ice reflect most solar radiation back to space, while open sea and bare ground absorb most of the solar radiation as heat. When snow and ice disappear, the areas normally covered will warm, contributing to further melting and warming through a self-reinforcing effect.
- Large amounts of methane and carbon dioxide (CO_2) are stored in the world's permafrost regions. When frozen ground thaws, these greenhouse gases are released into the atmosphere, another self-reinforcing effect that may amplify global warming.
- Melting of sea and land ice influence ocean temperature and salinity, which are important factors in the development and movements of the major ocean currents. Any changes to these may significantly alter the ocean current system and the global transport of heat.

Changes caused by melting snow and ice affect people´s homes and livelihoods worldwide

- Sea level rise is one of the most obvious consequences of melting ice on land. Even quite minor melting of ice masses will have major consequences for people and infrastructure in coastal communities, cities, and states.
- Melting of high mountain glaciers can have consequences for the availability of water for agriculture, domestic use, hydroelectric power stations, and industry. Melting of high mountain glaciers can also lead to hazardous conditions, particularly in the form of glacier lake outburst floods, which can significantly impact human populations and activities.
- The ecosystems and biodiversity in polar and mountain regions can change significantly as snow and ice cover diminishes. People depending on the natural resources of these regions will need to adapt to these changes.
- Access to resources may become easier as snow and ice disappear, but may also lead to challenges with respect to safety and pollution issues. In the Arctic Ocean, for example, sea ice is the main barrier to maritime transport and access to oil and gas resources.



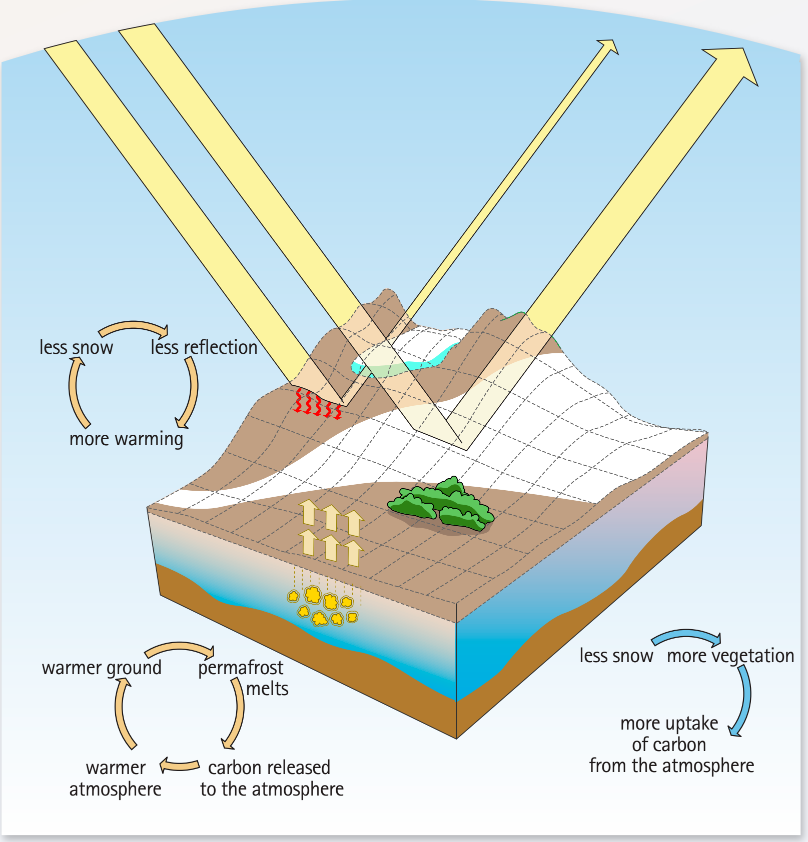


Illustration: Audun Igesund – Norwegian Polar Institute

SNOW AND ICE FEEDBACK PROCESSES

Processes which contribute to the amplification or decrease in the rate of a change are called feedback mechanisms. This illustration shows examples of climate feedback processes caused by changes related to the cryosphere. For example, snow-covered ice typically reflects around 80% of the sunlight it receives, whereas open water absorbs more than 90%. When snow and ice begin to melt darker land and water surfaces are revealed, and these darker surfaces absorb more of the sun's heat, causing more warming, which causes more melting, and so on. As the ocean warms, subsea permafrost thaws, releasing methane into the atmosphere. Methane is about 25 times more potent as a greenhouse gas than CO_2*. Declining snow cover accelerates local atmospheric heating by reducing the reflectivity of the surface, contributing to the further decrease of snow cover. As temperatures rise, near-surface permafrost thaws, increasing the flux of carbon into the atmosphere, feeding back to further climate change. Higher temperatures could, however, also lead to increased vegetation growth and thereby higher carbon uptake, offsetting some of the amplifying effects described above.*

Human induced climate forcers that enhance snow and ice melting

Barentsburg, Svalbard, 2009. Photo: Rudi Caeyers – University of Tromsø

Global and regional changes in temperature and precipitation significantly influence long-term changes in snow and ice. Such climate changes occur naturally over time, but are currently also substantially affected by human activities: emission of greenhouse gases and other climate forcing substances, such as black carbon, into the atmosphere.

Climate varies naturally over time. These variations are caused by natural processes external to the Earth, such as variations in sunlight intensity received on the surface of the Earth or internal forces such as changes in ice sheet extent and ocean circulation. Natural climate variations occur on time-scales ranging up to millions of years. Examples include 100,000 year glacial cycles with long cold periods, separated by shorter and warmer interglacial periods such as the one we are currently experiencing. Causes of such change include the positions of the continents, variations in the Earth's orbit, changes in the solar output and volcanic eruptions. There are many feedback mechanisms in the climate system that can either amplify or reduce the effects of climate change. For example, when snow and ice cover larger areas during a glacial period it increases the surface albedo, reflecting more of the Sun's energy back into space and thereby contributing to a further lowering of the atmospheric temperature, creating a feedback process. Numerous feedback processes are inherent to the Earth's climate system, contributing to its natural variability.

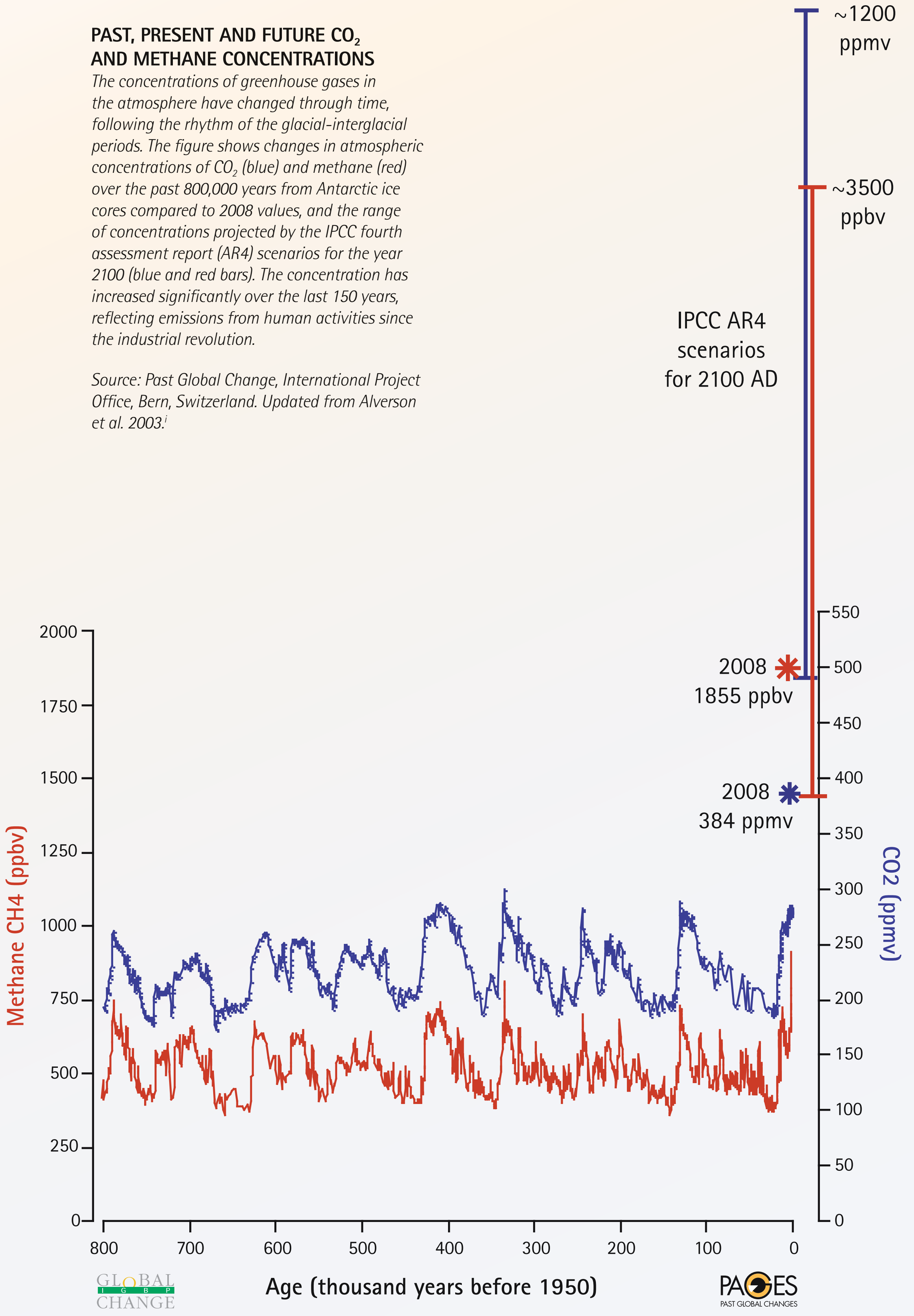
Greenhouse gases

- Greenhouse gases exist naturally in the atmosphere and because they trap some of the thermal radiation leaving the Earth, the average temperature is approximately 30°C warmer than it would be without these gases. Covering the past 800,000 years, ice core data show large natural variations in these gases. Studies also show a strong co-variation between the level of greenhouse gases in the atmosphere and the temperature during the pre-industrial period, which indicates a strong feedback in the system.
- Since the start of the industrial era, around 1750, human activities have increased concentrations of some naturally occurring greenhouse gases such as CO_2 and methane. Man-made compounds such as chlorofluorocarbons (CFCs) have added to the greenhouse effect.
- The fourth IPCC assessment report concluded that it is very likely (more than 90%) that most of the global warming during the last 50 years is due to the increase in human induced greenhouse gas concentrations. Continued greenhouse gas emissions at or above current rates will cause further warming and induce many changes in the global climate system during the 21st century. These changes are very likely to be larger than those observed during the 20th century. An increase in average global temperature of between 1.1 and 6.4°C is projected by 2100 (the exact warming depends on the level of emitted greenhouse gases). Such warming will contribute to further reductions in the world's snow and ice cover.[2]
- Estimates for how long a particular greenhouse gas lasts in the atmosphere differ among studies, but from a human perspective they are typically long. The lifetime of methane is on the order of a decade, but the lifetime of CO_2 extends over many human generations. The long lifetime of CO_2 in the atmosphere means that the high level of emissions occurring today will influence the climate far into the future. Reducing emissions is therefore urgent.

PAST, PRESENT AND FUTURE CO_2 AND METHANE CONCENTRATIONS

The concentrations of greenhouse gases in the atmosphere have changed through time, following the rhythm of the glacial-interglacial periods. The figure shows changes in atmospheric concentrations of CO_2 (blue) and methane (red) over the past 800,000 years from Antarctic ice cores compared to 2008 values, and the range of concentrations projected by the IPCC fourth assessment report (AR4) scenarios for the year 2100 (blue and red bars). The concentration has increased significantly over the last 150 years, reflecting emissions from human activities since the industrial revolution.

Source: Past Global Change, International Project Office, Bern, Switzerland. Updated from Alverson et al. 2003.[i]



Black carbon

- Black carbon has the potential to contribute to climate warming by absorbing sunlight in the atmosphere, by reducing the surface albedo when deposited on snow and ice, and by changing the properties of clouds. Because black carbon has a short atmospheric lifetime, reducing black carbon emissions may be effective in reducing anthropogenic climate change in the near-term.
- The atmospheric burden of black carbon in the Arctic shows a decreasing trend, likely due to reduced emissions in Eurasia. However, in the mid-latitudes of the Northern Hemisphere black carbon has increased as a result of increasing emissions in eastern Asia. Simulations of one climate model suggest that increasing concentrations of black carbon in the atmosphere at mid-latitudes could be responsible for a significant portion of the rapid Arctic warming over the last decades.[3]
- Black carbon deposited on snow and ice darkens the surface, and since dark surfaces absorb more solar radiation, this accelerates snow melt and ice disintegration, leading to further warming. The scarce data currently available suggest that deposition of black carbon on snow and ice has not played a major role in the recent warming of the Arctic. However, with changes in emission levels or transport routes, this concentration trend may change in the future. Black carbon has a strong seasonal pattern, but impacts on melt intensity are particularly important during spring melt. In places where melting is strong the accumulated deposition of black carbon throughout the entire season is of importance since it may collect on the surface during the melting.[4]
- A recent study based on chemical tracers indicated that biomass burning accounted for more than 90% of the black carbon deposited in Alaska, Canada, Greenland, and Russia in the spring of 2007. In the Arctic Ocean fossil fuel burning was the dominant source.[5]
- In some regions at lower latitudes the increasing atmospheric black carbon burden could contribute to accelerated melt of glaciers. For example, in western China some glaciers heavily contaminated by black carbon have 5% lower albedos due to these deposits.[6]
- Although curbing black carbon is desirable to help reduce the ongoing global warming, it is important to keep in mind that any meaningful effort to mitigate global climate warming requires reductions in CO_2 emissions. Action on black carbon must be seen as an additional measure, and not as an alternative.

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Greenland Ice Sheet, Kangerlussuaq, 2009. Photo: Rudi Caeyers

Snow

Ruoššavárri, Karasjok, Norway, 1996. Photo: Arvid Sveen

Snow cover extent in the Northern Hemisphere is declining. Major reductions in snow cover are projected for mid-latitudes by the end of this century. Although snow cover is expected to increase in some areas, there will be an overall decrease in snow cover that will exacerbate global warming by changing the reflectivity of the land surface.

Trends

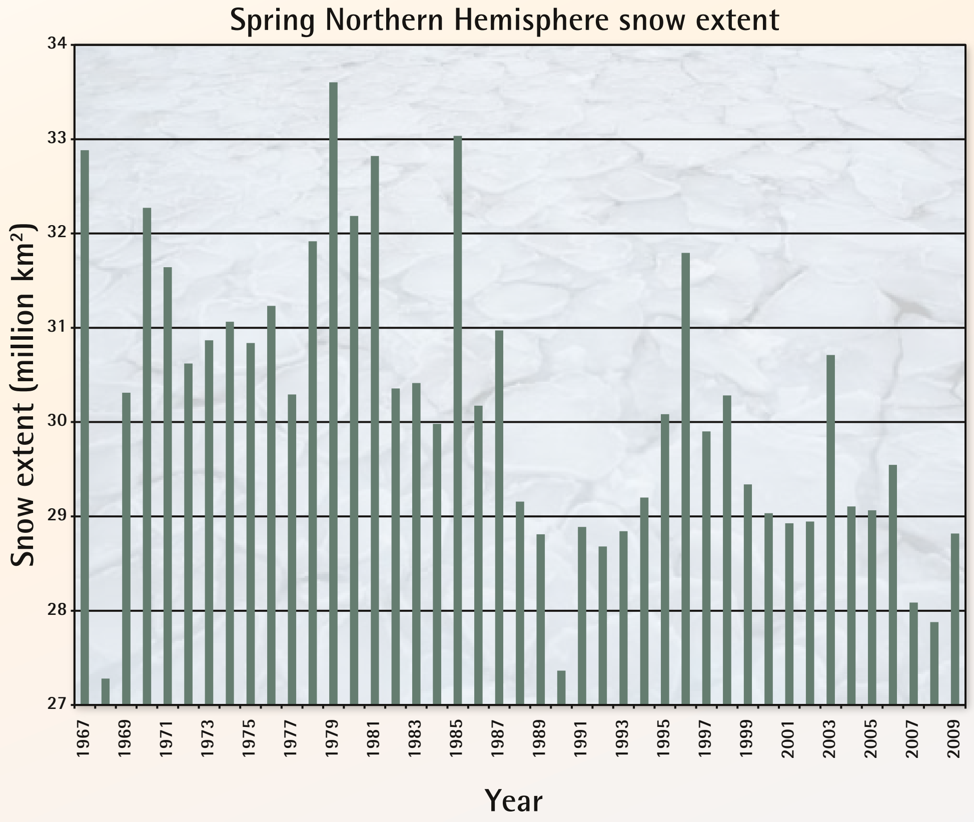
The area covered by snow is decreasing

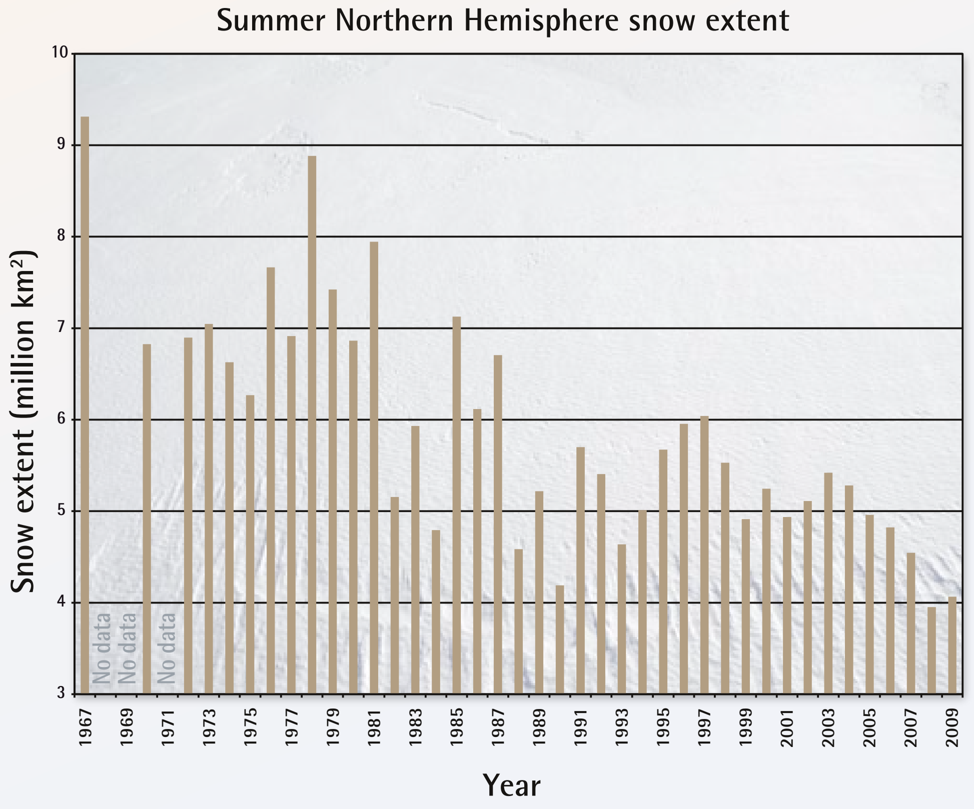
- Satellite monitoring indicates that mean monthly snow extent in the Northern Hemisphere is decreasing by about 1.5% per decade. This decreasing trend is occurring throughout the year, particularly during spring and summer, with exceptions only during mid-winter.[7]
- Annual Northern Hemisphere snow cover extent averaged 24.2 million km^2 for the 2008/09 winter. This is 1.2 million km^2 less than the 37-year average, making 2008/09 the winter with the third lowest snow cover extent on record.[8]
- Apart from the Antarctic there is very little snow-covered land in the Southern Hemisphere and data from these areas are scarce. However, some formerly snow- and ice-covered islands in the Southern Ocean are now increasingly snow-free during the summer, and snow cover in mountainous areas, in Australia, for example, has shown significant declines.[9,10]
- The decrease in snow cover has been caused by higher temperatures, and these have resulted in earlier melt at low to mid-elevations. At some higher elevation locations, increases in precipitation have resulted in increased snowpack. So far, higher temperatures have not affected these higher elevations, although in some locations there is now evidence of an earlier melt.[11]
- Some places show inconsistencies with the general findings, likely because of local climate trends, local topography, vegetation, atmospheric circulation patterns, data record lengths, or data quality issues.

Outlook

Global snow cover is expected to continue to decline

- Further decreases in snow cover are expected, although model simulations vary significantly. Some models project decreases of 60–80% in monthly maximum snow water equivalent over most of the mid-latitudes by the end of this century. The largest decreases are projected for Europe, the west coast of North America, Scandinavia, and the Pacific coast of Russia.[12,13]
- At high northern latitudes, while snow cover is projected to decrease in the south of the region, snow cover is expected to increase at the highest latitudes.[12]
- In locations where snow accumulates at temperatures close to its melting point, small increases in temperature will have large effects on snow cover.
- In arid climates increasing deposition of dust on snow has resulted in earlier and more rapid spring snow melt. Under global warming, increased drought is projected for several regions in the world that are sources of dust that is eventually deposited in snow-covered areas. In a warmer climate forest fires may also become more prevalent, projected to lead to greater deposition of black carbon on snow. With enhanced dust and black carbon deposition, earlier snow melt and increased glacier melt are likely scenarios in many of the world's mountain ranges and snow-covered areas.[14,15]

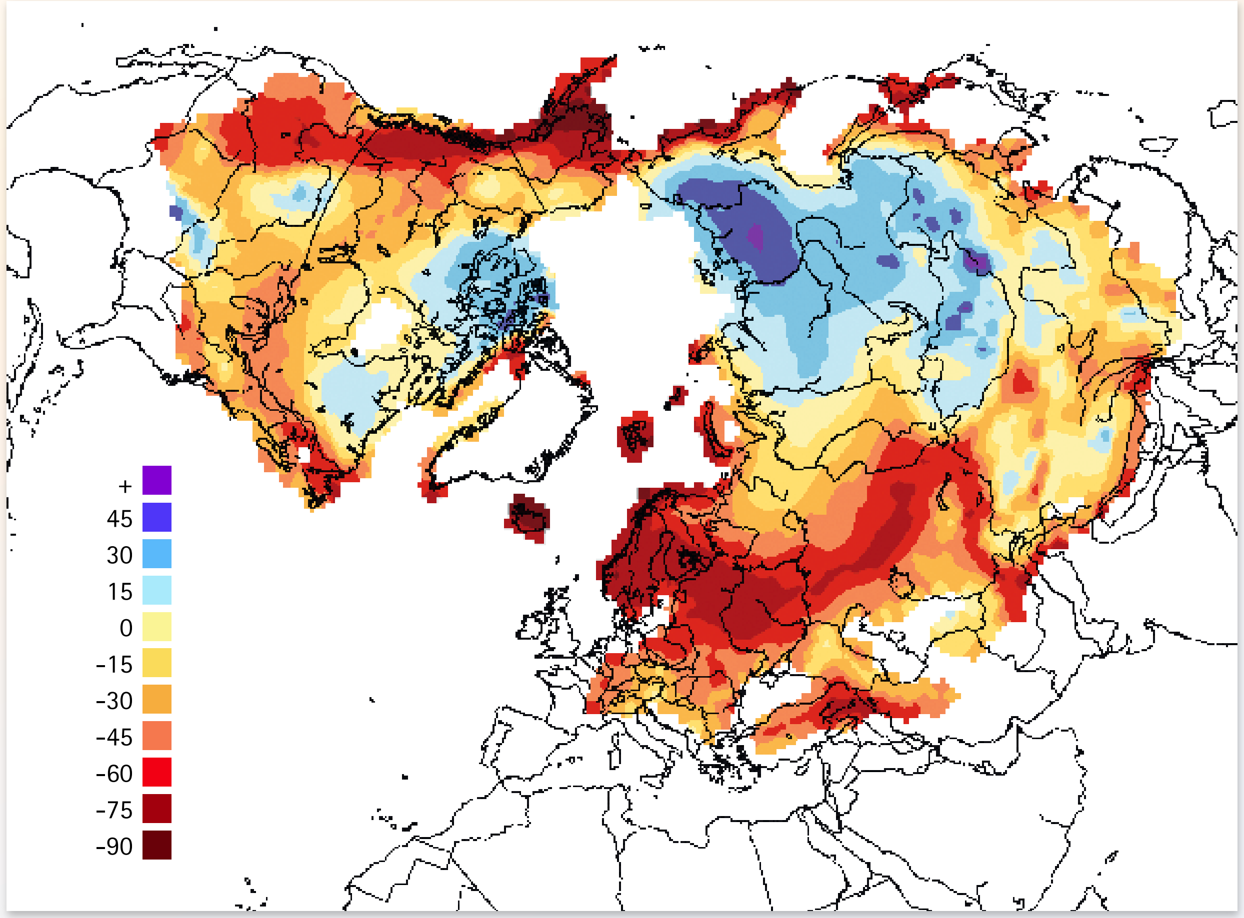




NORTHERN HEMISPHERE SNOW COVER DECREASE

The mean monthly snow cover extent in the Northern Hemisphere is decreasing by about 1.5% per decade. The figure shows the spring and summer snow cover extent over the Northern Hemisphere lands (including Greenland) between 1967 and 2009. While no obvious trends appear in the fall and winter seasons, the strong decreasing trends for spring and summer stand out. Snow cover extent is calculated from US National Ocean and Atmosphere Administration snow maps.

Source: David A Robinson, Global Snow Lab, Rutgers University, New Brunswick, New Jersey, USA.



PROJECTED SNOW COVER CHANGE

Further decreases in snow cover are expected in the centuries to come. The figure shows projected change (%) in mean annual maximum monthly snow water equivalent between the 1970–1999 period and 2070–2099v period from one specific model (CCSM3, using the SRES A2 emission scenario). CCSM3 is the only model that has provided realistic simulations of the observed rapid reduction of Arctic sea ice extent over the late 20th century. Changes in snow water equivalent over mountain regions are captured better in CCSM3 than in other models. CCSM3 projects more extensive decreases in snow water equivalent maximums over temperate mountain regions (for example, the western cordillera of North America, Scandinavia, and western Russia).

Source: Ross Brown, Environment Canada, Montréal. Based on analysis of CMIP3 model output presented in Brown & Mote 2008.[ii]

Key implications

- Decreases in snow cover extent will act as a feedback that amplifies global warming by changing the reflectivity of the land surface. Snow-free land can absorb four to five times more solar energy compared to snow-covered land.[7]
- Changes in snow will affect land- and seascapes: snow insulates permafrost and vegetation, interacts with sea ice, adds to the mass balance of glaciers and ice sheets, and affects hydrology.
- Decreasing snow cover can have consequences for water resources, as snow in mountain regions contributes to water supplies for almost one-sixth of the world's population. More knowledge is needed to assess the relative importance of snow (compared to total precipitation) for supplying water to people in these regions.[16]

Snow leopard, 2005. Photo: Bernard Landgraf

- Snow cover changes may have numerous consequences for people and communities, inducing environmental hazards such as snow avalanches and affecting transport and infrastructure development and maintenance. In some countries, snow melt is crucial to hydropower production. Where snow cover is vital to tourism – mountain regions dependent on the ski industry, for example – the economy will be negatively impacted.[9]
- Snow plays a fundamental role in the lifeways of indigenous peoples, particularly in the Arctic, who may have to make significant adaptations to cope with changes in snow cover.[17]
- Snow is an important ecological factor. Projected changes in snow cover will affect the structure and function of ecosystems, as well as crops and animal husbandry.

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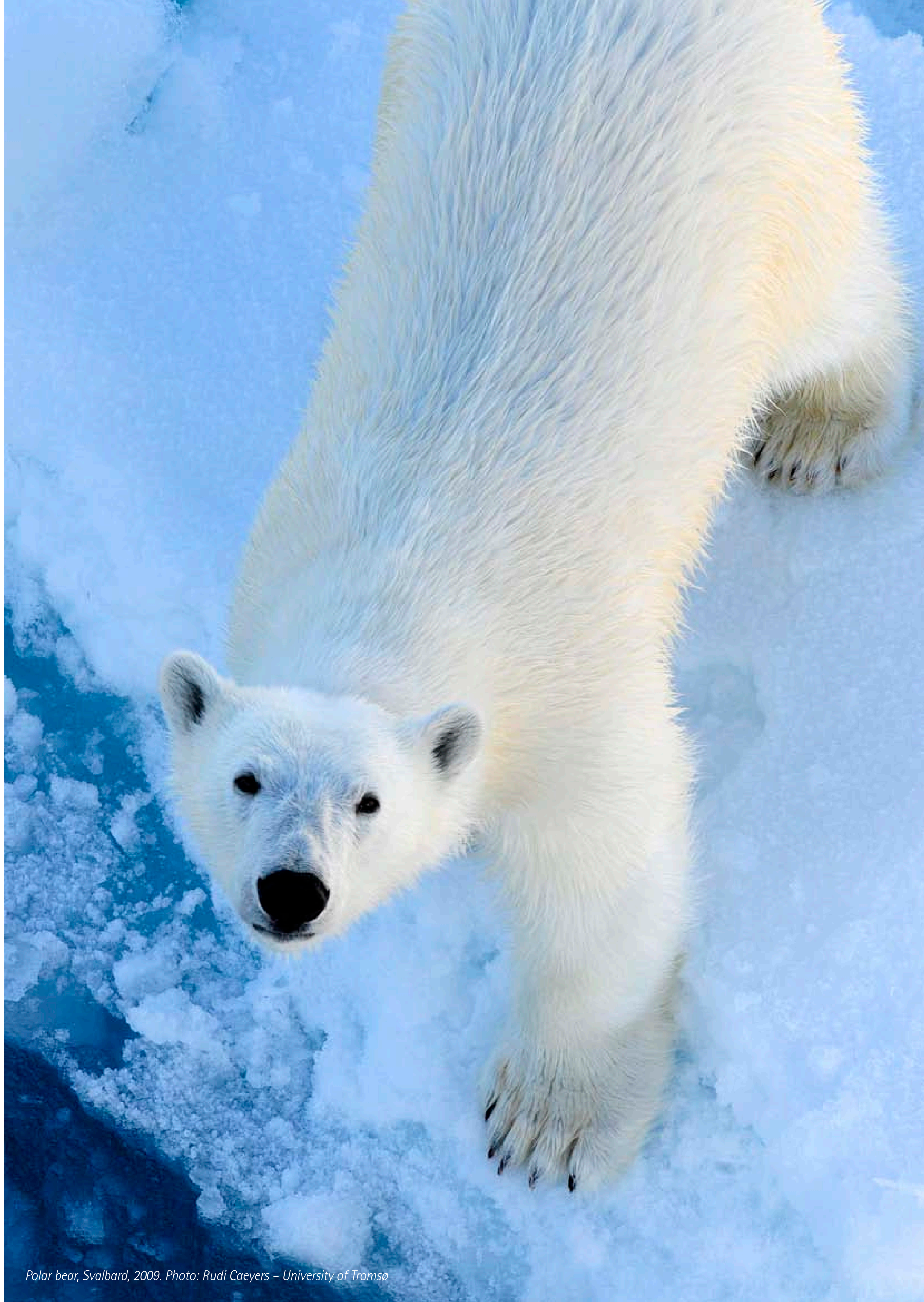


Polar bear, Svalbard, 2009. Photo: Rudi Caeyers – University of Tromsø

Sea ice

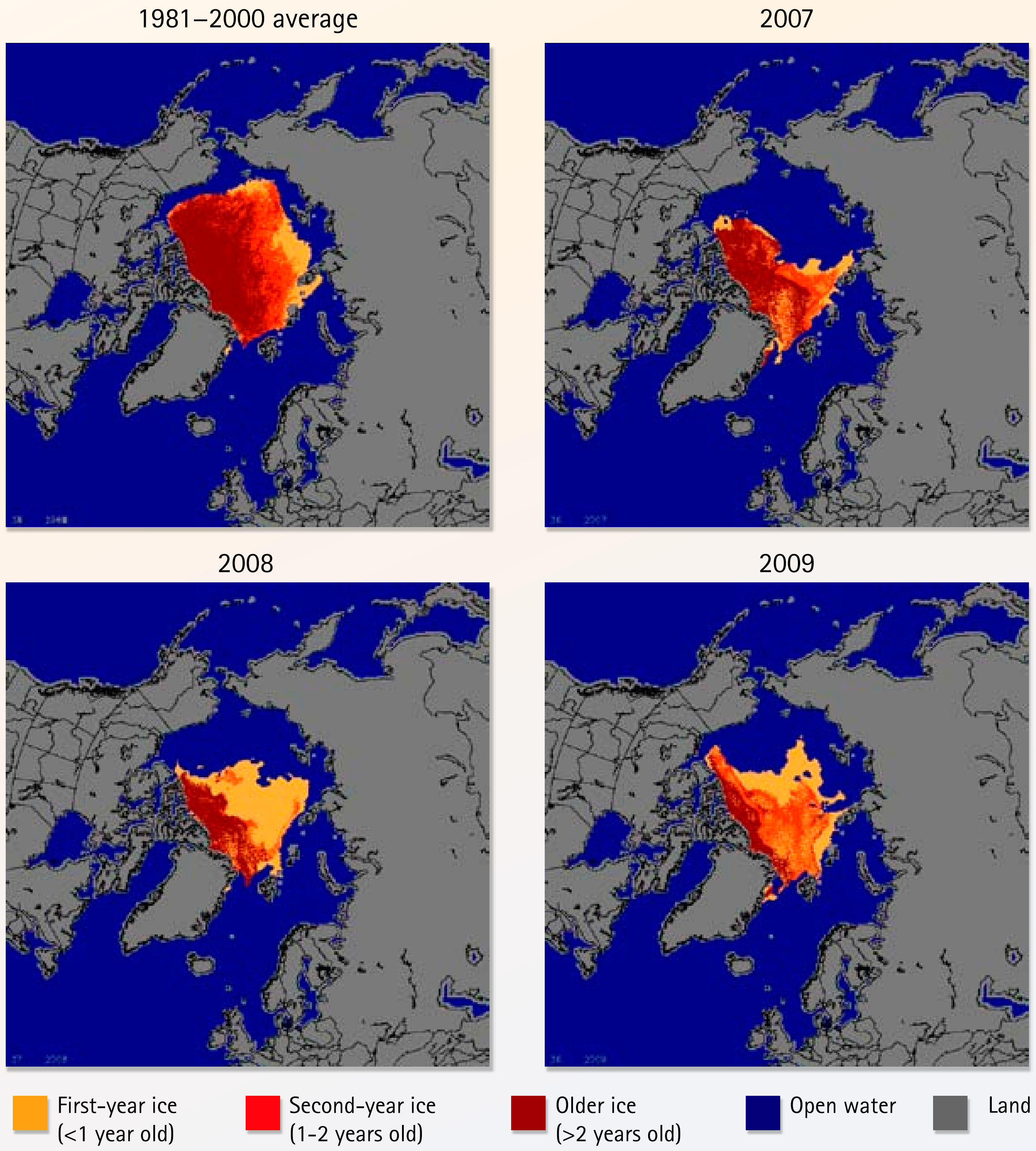
Fogbow, Svalbard, 2009. Photo: Rudi Caeyers – University of Tromsø

Rapid sea ice loss is one of the most prominent indicators of global climate change. Sea ice extent in the Arctic has shrunk by almost 40% since 1979, with the lowest amounts of ice observed in the last three summers: 2007, 2008, and 2009. There is less multi-year sea ice and in some regions sea ice is thinning. An Arctic summer almost without sea ice may be expected before mid-century. Winter sea ice extent in the Antarctic is also expected to become smaller. Sea ice cover is diminishing significantly faster than climate model predictions. Decreasing sea ice cover speeds up sea ice decline through feedback mechanisms.

Trends

Over the past few decades the area covered by sea ice in the Arctic has decreased, the ice has thinned, and less ice survives the summer melt.

- Since reliable satellite observations began in 1979, there have been significant negative trends in annual Arctic sea ice extent. The maximum sea ice extent, measured in March each year, has decreased by 2.8% per decade and the minimum, in September, has decreased by 11.2%.[18]
- In September 2007, ice extent reached a record minimum of only 4.2 million km^2, compared to 7.8 million km^2 in 1980, representing a sea ice loss equal to a third of the United States or an area slightly larger than India in size. September 2008 saw the second lowest sea ice extent in the Arctic since September 1979, and the 2009 minimum was the third lowest on record. The three last minimum years reinforce the long-term downward trend in Arctic sea ice extent.[18]
- Sea ice extent is declining at an accelerating rate, especially in the summer. Data from 2007, 2008, and 2009 show that sea ice cover in the Northern Hemisphere is shrinking significantly faster than projected by climate models.
- Arctic sea ice is thinning: thin seasonal ice has replaced thick older ice as the dominant type for the first time on record. Between 2004 and 2008, the total area covered by the thicker, older, multi-year ice shrank by more than 40% (1.54 million km^2). First-year ice made up more than 70% of the total cover in the 2008/09 winter, compared to 40–50% in the 1980s. Currently less than 10% of the Arctic sea ice is older than two years. As first-year ice is generally much thinner than multi-year ice, this implies that the volume of Arctic sea ice has greatly diminished.[18, 19, 20]
- Low sea ice extent and large regions of thin first-year ice were observed in September 2008. This potentially represented the lowest volume of Arctic sea ice since 1979. However, few direct ice thickness measurements are available to support estimates of the ice volume loss.[18]
- Seasonal sea ice zones (including the Barents, Baltic, Bering, and Okhotsk seas) do not show the same rapid sea ice loss as in the central Arctic Ocean in recent years.
- Satellite observations show an increasing trend in the extent of Antarctic sea ice of around 1% per decade over the last 30 years. Whether this change is significant is uncertain because ice extents vary considerably from year to year and from sector to sector. While an increase in sea ice coverage has been observed in the Ross Sea (around 4.5% per decade), there are large reductions in the Bellingshausen Sea (around 5.3% per decade). Trends in Antarctic sea ice thickness are unknown due to a lack of systematic observations. The different responses of sea ice in Antarctica to climate change compared to the Arctic are largely consistent with the known oceanic and atmospheric dynamics acting on contrasting topography, land and sea distribution and regional environmental factors.[21, 22]



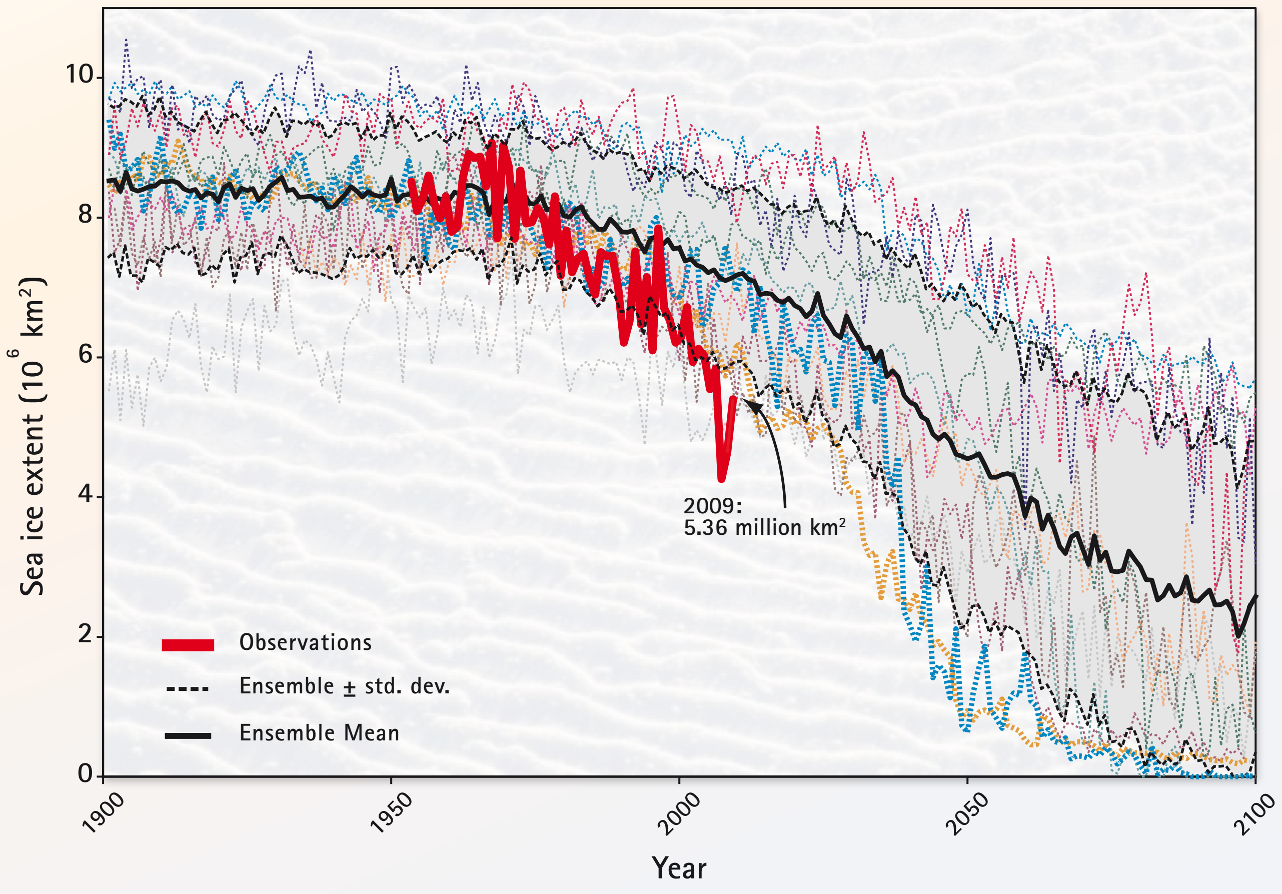
THINNING ARCTIC SEA ICE
In the Arctic, thin seasonal ice is replacing thick older ice as the dominant type for the first time on record. Thin ice is more vulnerable to summer melt. These images compare ice age, a proxy for ice thickness, in 2007, 2008, 2009, and the 1981–2000 average. 2009 saw an increase in second-year ice over 2008. At the end of summer 2009, 32% of the ice cover was second-year ice. Three-year and older ice were 19 percent of the total ice cover, the lowest in the satellite record.

Source: National Snow and Ice Data Center, courtesy C Fowler and J Maslanik, University of Colorado at Boulder, USA.

Outlook

A nearly sea ice-free Arctic summer may be expected before mid-century, and relatively large decreases in Antarctic winter sea ice extent are expected by the end of the century.

- Most models predict nearly sea ice-free summers in the Arctic Ocean within this century, some within 30 years. However, the precision levels of model simulations of future sea ice reductions are still not adequate: the rapid decline since 2005 has not been projected accurately by models. Summers almost without sea ice may occur in the Arctic Ocean well before mid-century.[23, 24]
- The losses of multi-year sea ice during the last decade partially resulted from changes in atmospheric circulation, which work against Arctic sea ice returning to conditions of the 1980s and 1990s. The future may witness abrupt decreases of Arctic sea ice rather than a yearly gradual loss. The reduction in 2007 is an example of such an abrupt decrease. Recent increases of the sea ice drift velocities in the Arctic Ocean are mostly related to decreases in sea ice concentration and ice thickness.[19, 20, 24, 25]



ARCTIC OCEAN SEA ICE LOSS

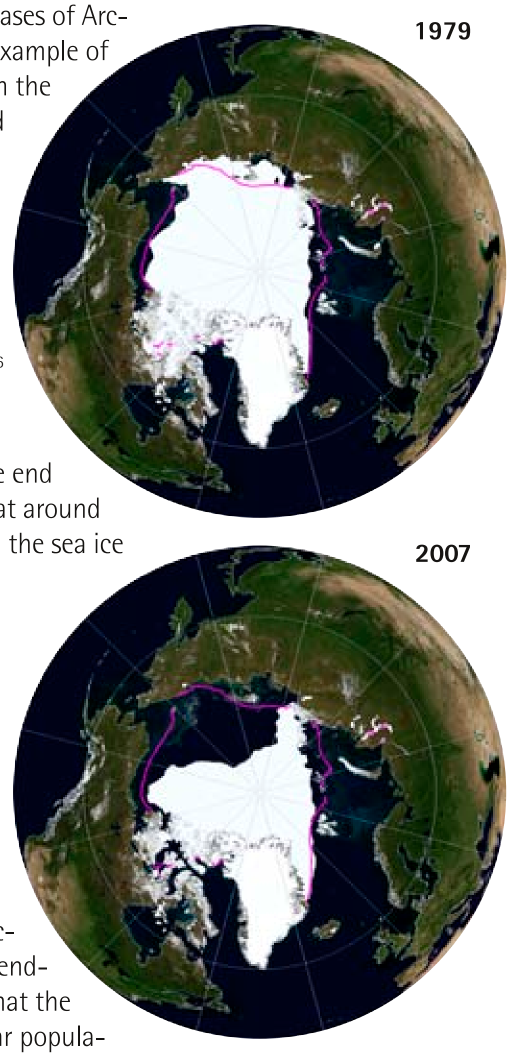
The figure shows the Northern Hemisphere sea ice extent in September as projected by 15 models used by the 2007 IPCC assessments (dotted lines). The mean of the models is shown in black, while observations from the satellite era are shown in red. The figure shows that the ice is melting at 11.2% per decade, a significantly faster rate than projected by any of the IPCC models. At the end of the summer of 2009, more ice remained in the Arctic this year than during the previous record-setting low years of 2007 and 2008. However, sea ice has not recovered to previous levels, and the shrinking of summertime ice is about 30 years ahead of the climate model projections. More recent model runs show that a nearly ice-free summer can be expected before mid-century.

Source: National Snow and Ice Data Center, University of Colorado at Boulder, USA. Updated from Stroeve et al. 2007.[iii]

- A net loss of heat in the Arctic winter promotes a southward extension of sea ice into the seas on the margins of the Arctic Ocean, such as the Barents and Bering seas. While the central Arctic Ocean appears to be on a fast track for major summertime sea ice loss before mid-century, the projected sea ice loss in the marginal seas during winter and spring appears to be occurring at a slower rate, with a 40% areal loss by 2050.[26]
- There is strong consensus among the models for an Antarctic-wide decrease in sea ice in the 21st century. Models suggest that the annual average total sea ice area will decrease by 2.6 million km^2, or 33%, by the end of the century. The decrease in sea ice volume in Antarctica is projected at around 30%. Most of the simulated ice retreat occurs in winter and spring when the sea ice extent is largest.[27]

Key implications

- Snow-covered ice typically reflects around 80% of the sunlight it receives, whereas open water reflects about 10%. As a consequence, large reductions in summer sea ice extent by mid-century will accelerate global warming through the ice-albedo feedback and will impact global climate and weather processes.
- Sea ice changes have major impacts on marine ecosystems, through processes and feedbacks in the physical and biological environments. Ice dependent species are at particular risk. For example, a recent study estimates that the projected changes in sea ice conditions may reduce the world's polar bear population by two-thirds by the mid-21st century.[28, 29, 30, 31]
- The uptake of CO_2 by Arctic surface waters is expected to increase with sea ice loss. However, the effect of sea ice retreat on the acidification of the ocean is still not well understood.[32]
- Increasing ice-free areas in coastal Arctic seas will provide longer seasons of navigation and better access to marine natural resources (oil, gas, minerals), although there will be regional variability. As the ice retreats, access to new areas will also impact fisheries. Even though summer sea ice conditions may accommodate trans-Arctic shipping before mid-century, prospects are uncertain and depend on a wide variety of factors.
- Diminishing Arctic sea ice is already impacting indigenous people and cultures. Sea ice is an important part of the hunting grounds and travel routes of many Arctic peoples, and as ice retreats they are forced to change subsistence strategies and address safety concerns.



ARCTIC OCEAN SEA ICE EXTENT IN SEPTEMBER

The magenta line shows the median ice extent for September from 1979 to 2000.

Source: National Snow and Ice Data Center, University of Colorado at Boulder, USA.

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Glaciers and ice caps

Smeerenburgfjorden, Svalbard, 2009. Photo: Rudi Caeyers – University of Tromsø

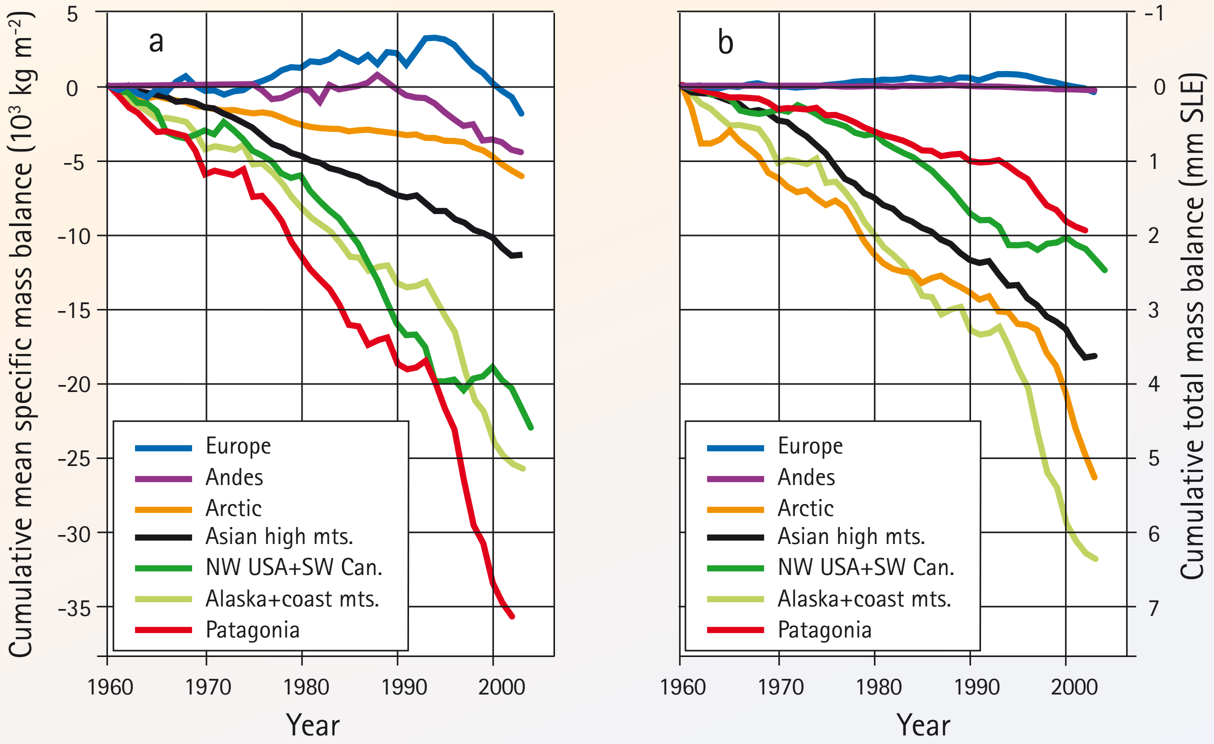
Glaciers around the globe have been shrinking since the end of the Little Ice Age, with increasing rates of ice loss since the early 1980s. The ongoing trend of worldwide and rapid glacier shrinkage may lead to the complete deglaciation of large parts of many mountain regions by the end of the 21st century.

Trends

Measurements indicate that the world's glaciers and ice caps are losing mass and retreating

- Mass balance measurements are the primary quantitative measure for assessing the response of glaciers to the climate. Six decades of annual mass balance data indicate a pronounced loss of ice underway at the start of the record, followed by moderate mass loss until the end of the 1970s, and subsequent acceleration. It should be noted that mass balance measurements prior to 1976 are only available for the Northern Hemisphere and are strongly biased towards Europe. Over the last decades the greatest mass losses per unit area have been observed in the European Alps, Patagonia, Alaska, northwestern USA, and southwestern Canada. Alaska and the Arctic are the most important regions with respect to total mass loss from glaciers, and thereby to sea level rise.[33, 34]
- Length change measurements show a general global glacier recession from their maximum positions during the Little Ice Age. Within this general retreat trend there have been intermittent periods of readvancing glaciers, for example, in coastal Scandinavia and New Zealand's Southern Alps in the 1990s, which mainly were due to increased winter precipitation. The glaciers in these areas have recently been reduced, both in volume and length. Information from glacier length change studies supplements the findings of mass balance studies, supporting the findings of a global and centennial negative trend.[35]
- The Himalayas is among the regions with the least available data. Although glacier retreat is widespread here, records of glacier fluctuations are extremely sparse and do not allow a sound quantitative comparison of change rates with other regions.
- Iceberg calving is a significant source of mass loss from many large ice caps, accounting for 20–40% of the total mass loss in several cases (for example, from the Canadian, Russian, and Svalbard ice caps, and also from large tidewater glaciers in Alaska and Patagonia). Changes in the dynamics of calving tidewater glaciers and ice cap outlets can be abrupt and can produce large changes in the rate of mass loss by calving.[36, 37, 38]
- Floating ice shelves also calve. In some areas, the extent of ice shelves is decreasing substantially. In 2008 alone, ice shelf disintegration reduced the area of ice shelves in Arctic Canada by 23%. Major disintegration events have also taken place on the ice shelves around the Antarctic Peninsula (see chapter on Antarctic Ice Sheet).[39]

The Qori Kalis glacier is the largest outlet glacier from the Quelccaya ice cap in the Andes of Peru. Dramatic mass loss from the glacier has created a glacial lake. Top: 1978. Bottom: 2004. Photos: Lonnie Thompson



GLACIER MASS LOSS

Mass balance measurements are the primary quantitative measure for the climate-glacier relation. The figure shows cumulative mass balance change based on available data from six decades of annual mass balance data. Over the last decades the strongest mass losses per unit area have been observed in the European Alps, Patagonia, Alaska, northwestern USA, and southwestern Canada (a). However, cumulative total mass loss has been largest in Alaska and the Arctic, and these areas are therefore most important as contributors to sea level rise (b). It should be noted that the data in some regions, such as the Himalayas, are based on short time series from few glaciers.

Source: Kaser et al. 2006.[iv] Reproduced by permission of the American Geophysical Union.

- Looking at changes to individual glaciers reveals high variability and sometimes even changes that contradict those of neighboring glaciers. Reasons for this lie in the different topographical settings of the glaciers as well as in non-climate drivers such as calving, surge instabilities, and heavy debris covers. Prime examples are Pio XI in Chile, Perito Moreno in Argentina, and Hubbard and Muir glaciers in Alaska, with impressive fluctuations linked to variable rates of iceberg calving.[38, 40]

Outlook

Under the present climate as well as under future climate scenarios, the ongoing trend of worldwide and rapid glacier shrinkage will continue

- Deglaciation of large parts of many mountain regions is expected in the coming decades. Glaciers that extend to the lowest elevations may in some regions be particularly susceptible to warming and disintegration. However, more data are needed for a robust modeling of regional glacier cover scenarios.[33, 41, 42]

In 2002, glacier retreat contributed to a large landslide beside the moraine-dammed Safuna Lake, Cordillera Blanca, Peru. The landslide created a wave over 100 m high, splashing over the moraine and partly eroding it. Photo: John M Reynolds

- Recent estimates show that glaciers and ice caps are not in balance with the present climate and that adjustment will cause a mass loss of 18 cm of sea level equivalent even if the climate does not continue to warm. Given current warming trends, a mass loss of about 38 cm sea level equivalent is expected by 2100.[43]

Implications

Melting of glaciers and ice caps contributes significantly to sea level rise.

- Changes in glaciers may strongly affect the seasonal availability of freshwater. Significant runoff increases are being reported in some regions in Canada, Europe, central Asia, and the Andes. With further warming, as glaciers retreat and finally disappear, runoff is expected to decrease. Glacier basins with decreasing runoff have been observed in some regions of southern Canada, at low elevations in the European Alps, and in the central Andes of Chile, which is probably a combined effect of reduced seasonal snow cover and glacier area losses.[44]
- Changes in glaciers may lead to hazardous conditions, particularly in the form of avalanches and floods. This could have dramatic impacts on human populations and activities located in glaciated mountain regions. Glacier lake outburst floods are the hazard with the highest potential for disaster and damage. Large icebergs calved from floating ice shelves or glacier tongues may also present a hazard to shipping and offshore oil and gas exploration.
- Glacier melt input to rivers can affect the ecosystem in a number of ways. Habitats may be altered by changes to stream temperatures, sediment concentrations, water chemistry and nutrient availability. Fish and other organisms may be harmed as pollutants, once accumulated and stored in glaciers, are released into the environment.[45]

Key scientific contributors

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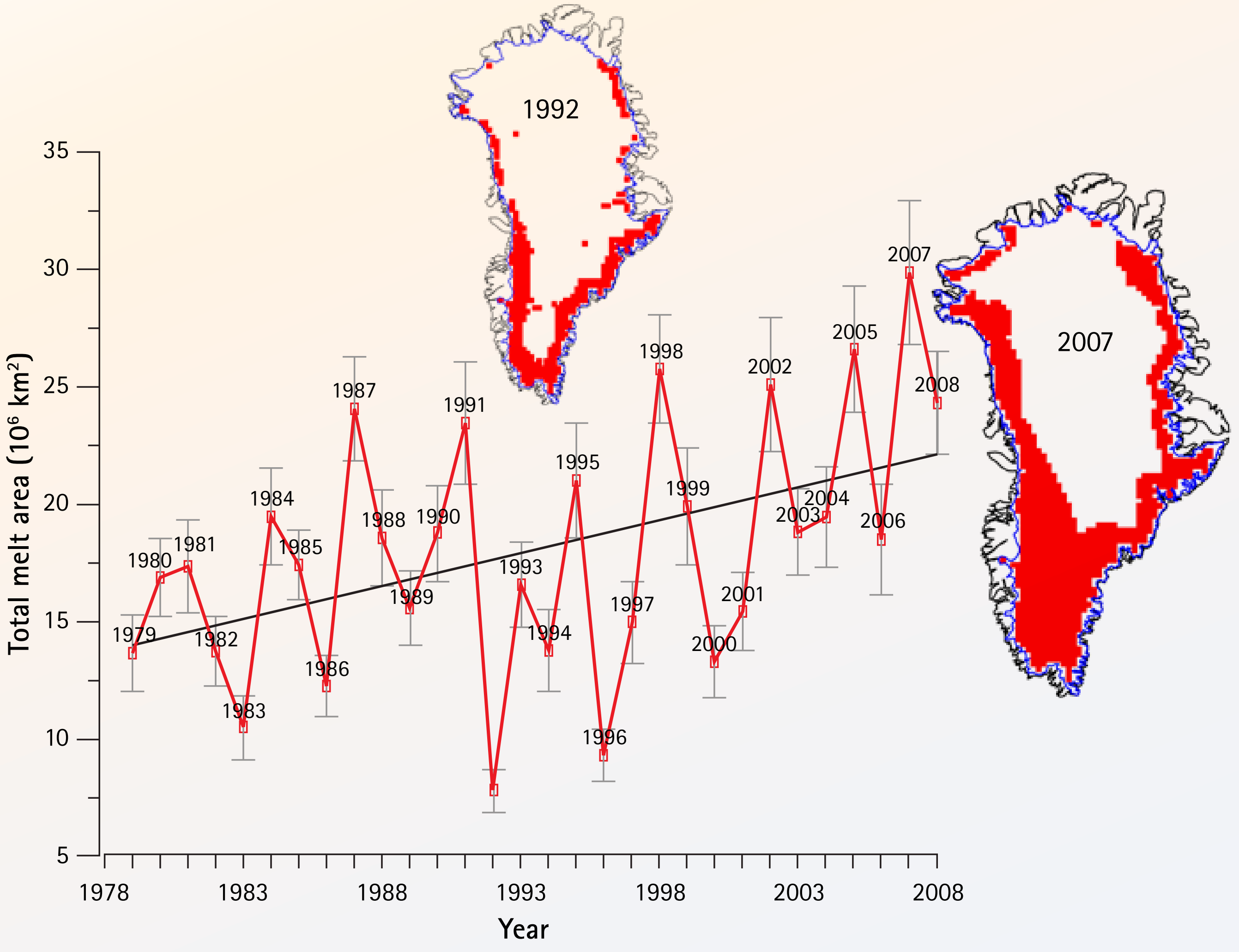
Greenland Ice Sheet

Ummannaq, Greenland, 2009. Photo: Rudi Caeyers

The Greenland Ice Sheet is losing volume and mass, and at an increasingly higher rate over the last decade. The interior, high altitude areas are thickening due to increased snow accumulation, but this is more than counterbalanced by the ice loss due to melt and ice discharge. Since 1979, the area experiencing surface melting has increased significantly, with 2007 breaking the record for surface melt area, runoff, and mass loss. In the coming decades and centuries, the Greenland Ice Sheet will be highly susceptible to the predicted strong warming of this part of the Arctic.



GREENLAND ICE SHEET MELT

The figure shows the area of the Greenland Ice Sheet melting during 1979–2008, derived from satellite remote sensing. Between 33 and 55% of the total mass loss from the Greenland Ice Sheet is caused by surface melt and runoff. The ice sheet melt area increased by 30% between 1979 and 2008, with the most extreme melt in 2007 (for comparison, the year of minimum icemelt, 1992, is also shown). In 2007, the area experiencing melt extent was modeled and observed by satellite data to be around 50% of the total ice sheet area.

Source: Steffen et al. 2008.[v]

Trends

The Greenland Ice Sheet has experienced an increase in surface melt extent, mass loss, freshwater runoff, and thinning along its periphery over the last few decades

- Satellite and aircraft data indicate that ice mass loss from Greenland has been increasing since at least the early 1990s, and that the rate of loss has increased significantly in the 21st century. The interior, high altitude areas of the ice sheet have thickened as a result of greater snowfall. The area above 2000 m has gained an average of 4–6 cm annually since 2000, adding 30–90 Gt of mass to the ice sheet each year. This is, however, more than counterbalanced by the amount of mass lost by melt and ice discharge into the ocean.[46, 47]
- Surface melt and runoff accounts for 33–55% of the total mass loss from the Greenland Ice Sheet. The ice sheet melt area increased by 30% between 1979 and 2008, with the most extreme melt in 2007. In that year, the area experiencing melt was around 50% of the total ice sheet area. The melt period started earlier and lasted for a longer period than normal, especially in southern Greenland.[46, 48, 49]
- Glacier acceleration in Greenland, documented south of 66°N between 1996 and 2000, expanded to 70°N in 2005. Annual mass loss through ice discharge has increased 30% during the recent decade, from 330 Gt in 1995 to 430 Gt in 2005. This loss exceeds the loss caused by melt processes during the few recent warm years.[46, 50]
- Overall mass balance estimates, taking into account accumulation, melting and ice discharge, indicate that the Greenland Ice Sheet is losing volume, and at an increasing rate. Whereas the annual net loss in 1995–2000 was 50 Gt, in 2003–2006 160 Gt was lost per year (with an uncertainty of the estimates on the order of 50 Gt).[46, 49, 51]

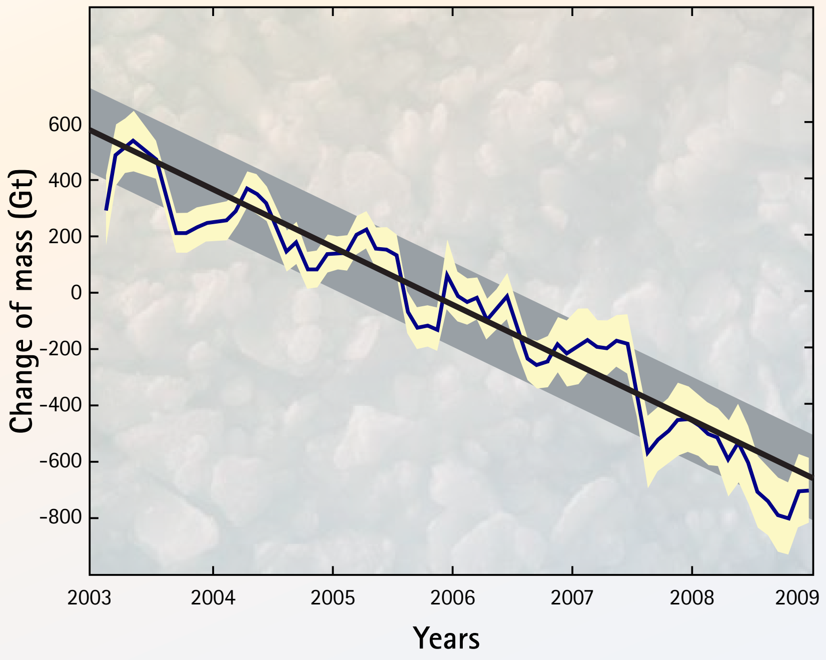
Outlook

Current projections show that the Greenland Ice Sheet will continue to lose mass and contribute to sea level rise

- Projections of the future response of the Greenland Ice Sheet to climate warming show that the surface melt area and the loss of mass will increase. The current annual average mass loss of 160 Gt would cause a 5 cm sea level rise by the year 2100, but projections that take into account increasing rates of ice discharge and melt suggest a 14 cm sea level rise by the year 2100.[46, 52]
- Greenland's southern ice dome is under threat from both increased summer melt near the coasts and increased ice discharge from glaciers that extend their influence far inland. Climate models predict an Arctic warming of 3–8°C by the year 2100. Thus it is quite possible that the ice dome in southern Greenland will reach a temperature threshold that could lead to an irreversible retreat within the next century.

Key implications

- The Greenland Ice Sheet strongly influences sea level. The Greenland Ice Sheet may have been responsible for nearly 20% of global sea level rise in the past 13 years. Further changes in the Greenland Ice Sheet due to global climate changes are consequently of great significance. Model estimates range from a sea level rise of 1 to 14 cm by 2100. Sea level rise is covered in a separate chapter in this report.



GREENLAND NET ICE LOSS

The figure shows the loss of ice mass from the Greenland Ice Sheet between 2003 and 2008 based on observations from the GRACE satellite. The interior, high altitude areas are thickening due to increased snow accumulation, but this is more than counterbalanced by ice lost to melt and ice discharge, both of which have increased significantly over the decades. Overall, the Greenland Ice Sheet is losing mass at an accelerating pace. Note that the observations from the GRACE satellite give a loss of mass of 200 Gt per year for the period 2003–2009, slightly larger than the current average value of 160 Gt per year.

Source: Updated from Wouters et al. 2008.[vi]

- Changes in the ice sheet may have major impacts on people and society in Greenland. New prospects for large-scale mineral and energy resource production are influenced by changes in accessibility and transportation. Changes in drainage patterns and amount of meltwater from the Greenland Ice Sheet are important for hydropower development.

Key scientific contributors

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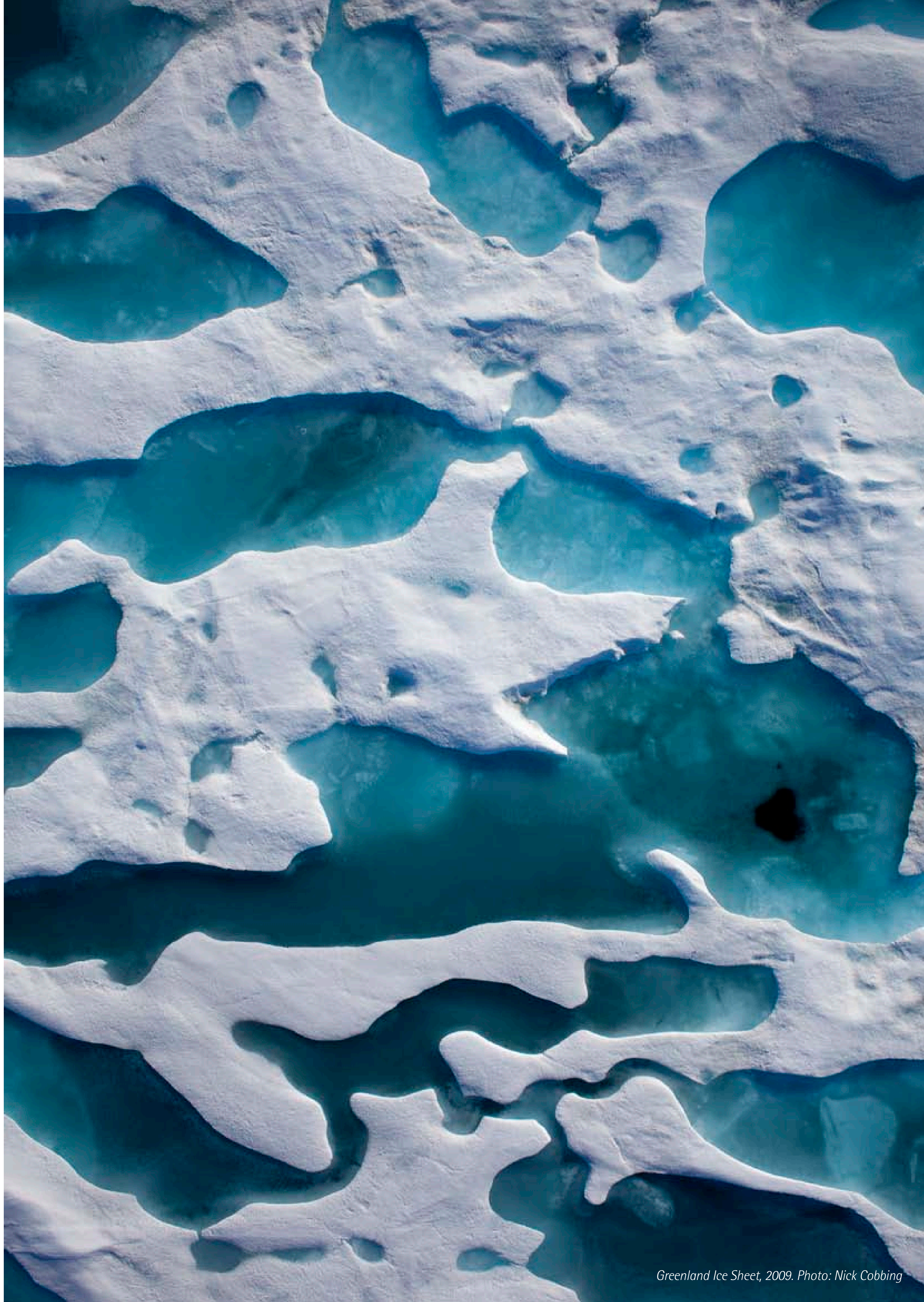


Greenland Ice Sheet, 2009. Photo: Nick Cobbing

Antarctic Ice Sheet

Orca, Antarctica, 1989. Photo: Stefan Lundgren

Chinstrap penguins on iceberg, Antarctica, 2002. Photo: Stefan Lundgren

There are indications that the Antarctic continent is now experiencing a net loss of ice. Significant mass loss is occuring in parts of West Antarctica, the Antarctic Peninsula, and limited parts of East Antarctica, while the ice sheet on the rest of the continent is relatively stable or thickening slightly. Future predictions of Antarctic Ice Sheet mass changes are difficult, but large areas of the West Antarctic Ice Sheet seem likely to continue to lose mass, significantly influencing future sea level.

Trends

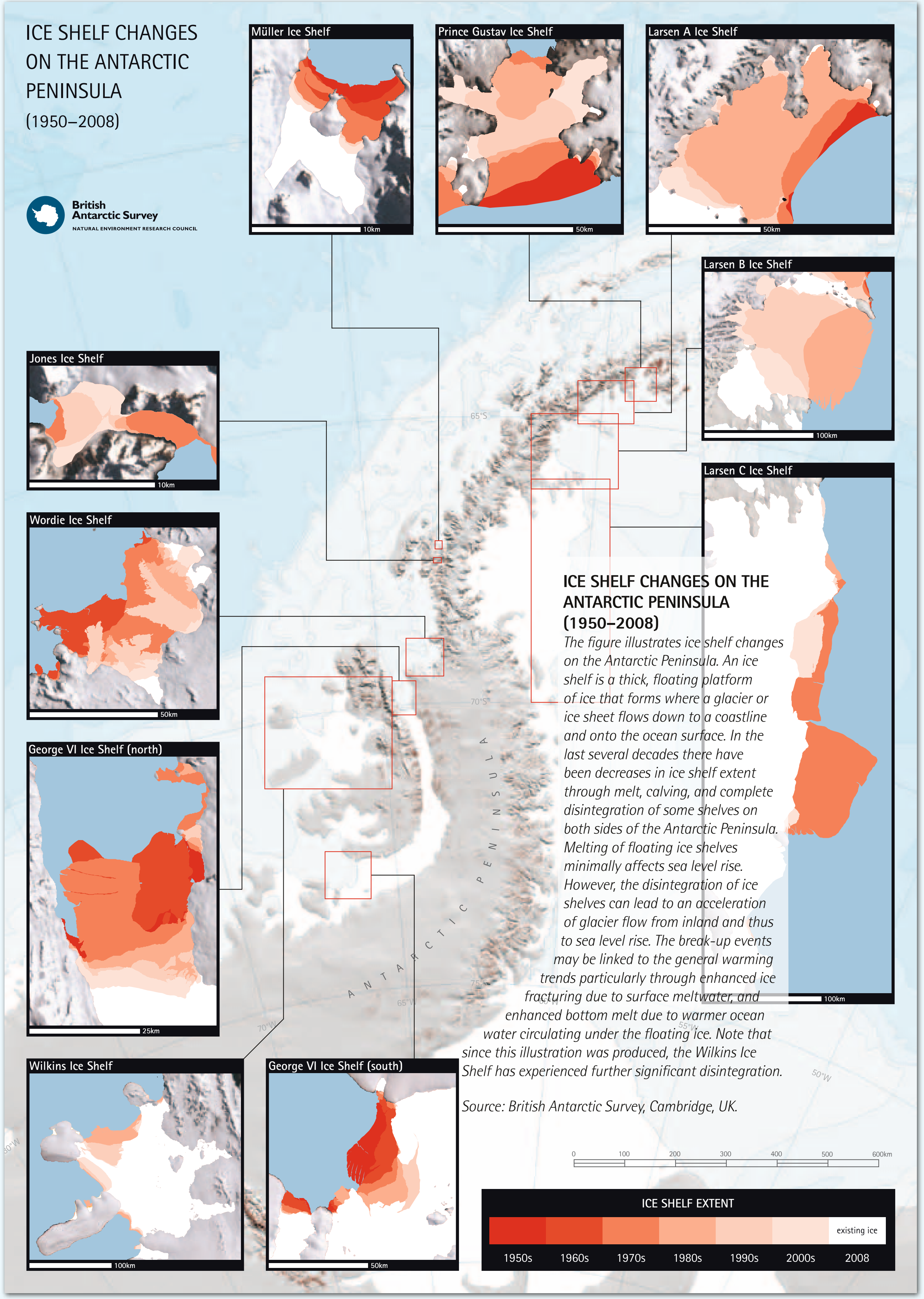
There are now indications that the Antarctic continent is experiencing a net loss of ice

- Estimates show that annual mass loss in Antarctica has increased, from 75–231 Gt in 1996 to 104–288 Gt in 2006, comparable to losses to the Greenland Ice Sheet. The estimates are uncertain because direct measurements for vast areas of the continent are lacking.[53]
- The largest loss of ice mass has been from the West Antarctic Ice Sheet, where ice mass loss has increased steadily since the 1990s. The losses are occurring in a region that is particularly susceptible to the erosive forces of the ocean. The Amundsen Sea sector is the most rapidly changing region. It has been estimated that the ice sheet loss along the Bellingshausen and Amundsen seas increased by 59% between 1996 and 2006. Calculations of the current rate of mass loss from the Amundsen Sea Embayment range from 50 to 137 Gt per year.[53, 54, 55, 56]
- Ice shelves on both sides of the northern Antarctic Peninsula have disintegrated rapidly in recent decades, exemplified by the collapse of the Larsen B Ice Shelf in 2002 and the break-up of parts of the Wilkins Ice Shelf in 2008. The disintegration of the ice shelves has led to an acceleration of glacier flow from inland. Calculations show that glaciers that fed the former Larsen B Ice Shelf have increased their velocity by factors of two to eight following the collapse, significantly adding to the mass loss.[55, 57, 58]
- The rates of change on the East Antarctic Ice Sheet, which contains around 90% of the ice volume of the total Antarctic Ice Sheet, are much smaller than both the West Antarctic Ice Sheet and the Antarctic Peninsula. This indicates that this ice mass is changing more slowly. Studies have shown thickening at modest rates in the interior of the ice sheet and a mixture of modest thickening and pronounced thinning among the fringing ice shelves. Although no consistent pattern of change has been observed over East Antarctica, it is important to note that even small rates of changes in East Antarctica would have major impacts due to the large volume of ice held in this region.[56]

Outlook

Long-term changes in the Antarctic Ice Sheet are uncertain, but severe regional losses are possible

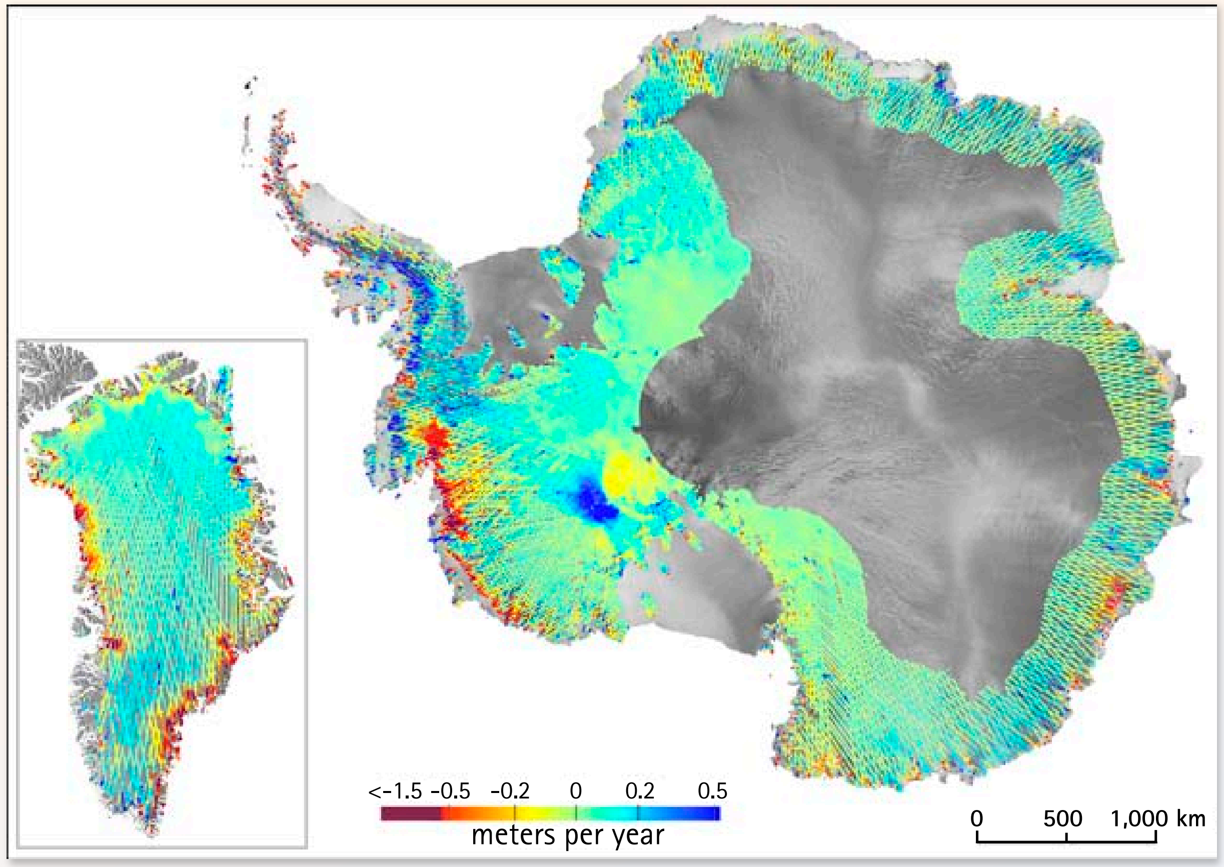
- The oceans are the cause of the most pronounced ongoing changes in the Antarctic Ice Sheet. There is little predictability of ocean circulation change, and it is therefore difficult to project the long-term changes in the ice sheet. In the near future, however, it is likely those areas that are experiencing the most pronounced changes today will experience further change.
- There is concern that the ice in the Amundsen Sea Embayment could be entering a phase of collapse that could lead to deglaciation of parts of the West Antarctic Ice



ICE SHELF CHANGES ON THE ANTARCTIC PENINSULA (1950–2008)

The figure illustrates ice shelf changes on the Antarctic Peninsula. An ice shelf is a thick, floating platform of ice that forms where a glacier or ice sheet flows down to a coastline and onto the ocean surface. In the last several decades there have been decreases in ice shelf extent through melt, calving, and complete disintegration of some shelves on both sides of the Antarctic Peninsula. Melting of floating ice shelves minimally affects sea level rise. However, the disintegration of ice shelves can lead to an acceleration of glacier flow from inland and thus to sea level rise. The break-up events may be linked to the general warming trends particularly through enhanced ice fracturing due to surface meltwater, and enhanced bottom melt due to warmer ocean water circulating under the floating ice. Note that since this illustration was produced, the Wilkins Ice Shelf has experienced further significant disintegration.

Source: British Antarctic Survey, Cambridge, UK.



ANTARCTIC ICE SHEET THICKNESS CHANGE

The figure shows the patterns of surface height change over the Antarctic Ice Sheet between 2003 and 2007 (based on ICESat measurements). Significant mass loss (indicated in dark red) can be seen for parts of West Antarctica, the Antarctic Peninsula, and limited parts of East Antarctica, while the ice sheet on the rest of the continent is relatively stable (pale green) or thickening slightly (blue). There are no measurements for the areas shown in gray. Thickness changes in the Greenland Ice Sheet are illustrated for comparison.

Source: Pritchard et al. 2009.[vii]

Sheet. A collapse of the ice in the Amundsen Sea Embayment has the potential to raise global sea levels by more than 1.5 m. A collapse of the entire West Antarctic Ice Sheet would cause a potential sea level rise of around 5 m. The central parts of the West Antarctic Ice Sheet overlie bedrock that is located below sea level; these areas are the most vulnerable for undergoing rapid change, and disappearance of this ice corresponds to about 3 m of sea level rise. Given plausible future increases in ocean–ice interaction, the central West Antarctic Ice Sheet could collapse within several hundred to one thousand years.[56, 59, 60, 61]

- The Antarctic Peninsula is one of many sub-polar glacier systems showing especially rapid loss of ice. Increased warming will lead to a continued southerly progression of ice shelf disintegrations along both coasts of the peninsula.[56]

A view of the Antarctic Ice Sheet, 1996. Photo: Michael Hambrey, www.glaciers-online.net

- Due to the great volume of ice held in this region, future changes in East Antarctica are crucial for the total ice mass balance of Antarctica and thus for Antarctica's impact on global sea level. Today, the uncertainty related to future changes is very large.

Key implications

- Ice mass loss from the Antarctic Ice Sheet will contribute to global sea level rise, and the potential contribution can be of major importance. Future changes to the ice masses are therefore of obvious concern. Sea level rise is covered in a separate chapter in this report.

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Chinstrap penguins on iceberg, Antarctica, 2005. Photo: Stefan Lundgren

Ice and sea level change

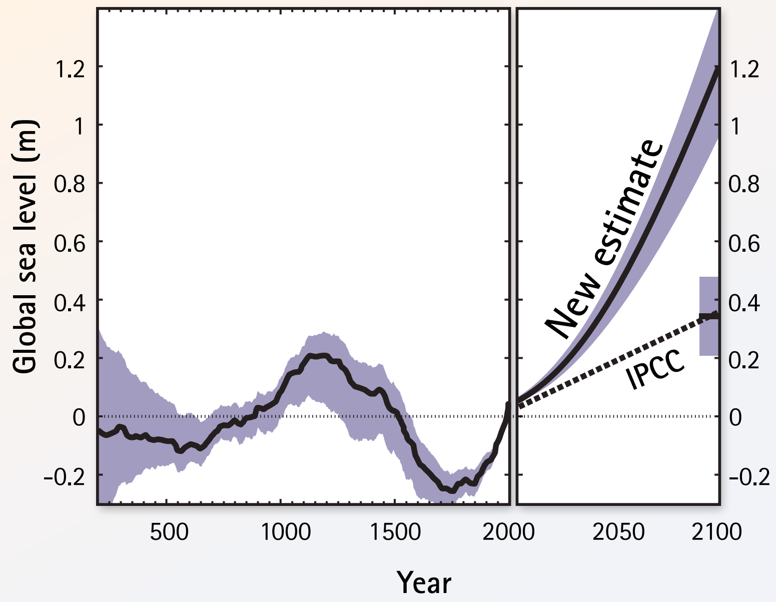
An eroding village south of Dhaka, Bangladesh, July 2005. Photo: Gary Braasch

Global sea level is rising and will continue to rise through the 21st century. Ocean thermal expansion and glacier melt have been the dominant contributors to sea level rise until quite recently. Within the last decade icemelt from glaciers combined with melt from ice sheets has become more important than thermal expansion. The ice sheets of Greenland and Antarctica have the greatest potential to increase the sea level in the future.

Trends

Glaciers and ice sheets play an increasingly important role in the ongoing global sea level rise

- From 1993 to the end of 2007, data indicated global average sea level rise at 3–4 mm per year. This rate is faster than the 1.7 mm per year average rate of rise during the 20th century. The sea level changes are not evenly distributed and regions such as the east coast of North America, the east coast of China, and the Pacific Ocean near Japan are particularly susceptible to higher sea level rises than the global average.[62, 63, 64]
- Ocean thermal expansion and glacier melting have been the dominant contributors to 20th century sea level rise. Recent studies estimate that icemelt now has become the most dominant factor, one study indicating as much as 75–85% of the recent sea level rise coming from glaciers, ice caps, and ice sheets. This represents a significant change in the relative contributions to sea level rise as compared with the 1993–2003 period.[65, 66]
- Studies of sea level rise from melting ice indicate that the Greenland Ice Sheet contributes about 25%, Antarctica contributes about 25%, and the remaining 50% comes from melting glaciers in the mid-latitudes and polar regions.



GLOBAL SEA LEVEL RISE

Data indicate global average sea level rise at 3–4 mm per year from 1993 to the end of 2007. This rate is faster than the 1.7 mm per year average rate of rise during the 20th century, and significantly higher than projected by the 2007 IPCC report, as shown in the figure (the IPCC range shown in the figure as a dashed line is based on the A1B scenario). Global climate models are likely under-predicting future sea level rise. While changes during this century may remain relatively low, continued warming over time can lead to a more rapid reduction of the Greenland and West Antarctic ice sheets, significantly influencing sea level. This would be of major concern as these two ice sheets contain enough water to raise sea level by 7 m and 5 m, respectively.

Source: Modified from Grinsted et al. 2009.[viii]

Top: large house in Rodanthe, Cape Hatteras, North Carolina, USA, July 1999.
Bottom: same house after five years of beach erosion and storms, September 2004. Photos: Gary Braasch

IMPACTS OF SEA LEVEL RISE

The figure shows how a sea level rise of 1 m would impact the low-lying Ganges-Brahmaputra delta area (Bangladesh) and the state of Florida (USA). Susceptible areas are shown in red. Sea level rise of the magnitude predicted for the relative near future would impact heavily populated low-lying coastal areas, such the Ganges-Brahmaputra delta and Florida, but also, for example, the Rhine (the Netherlands) and the Mekong (Vietnam) deltas.

Source: Jeremy L Weiss & Jonathan T Overpeck, Department of Geosciences, University of Arizona, Tucson, USA.

Outlook

During the 21st century, sea level will continue to rise due to warming

- Using a number of models, the 2007 IPCC report projected that average sea level will rise 18–59 cm from the period 1980–2000 to the period 2090–2100. However, although the IPCC made an allowance for additional ice sheet contribution of 10–20 cm, the dynamics of the large ice sheets were not included in these models, and larger changes are therefore possible.[67, 68]

- Some of the more recent projections of sea level rise give values between 0.5 and 1.5 m in the year 2100. These values result both from models based on observed sea level rise combined with climate projections, and ice flow models based on observed ice discharge and melt combined with climate projections.[69, 70]
- The contribution of melting glaciers and ice caps to 21st century sea level rise will be of the same order as that from thermal expansion. On longer time scales, the ice sheets of Greenland and Antarctica have the greatest potential to contribute to meter-scale changes in sea level.

Tidal flooding has become an increasing problem for the people of the Pacific island state of Tuvalu. Saltwater intrusion is adversely affecting food production and drinking water. Funafuti, Tuvalu, February 2005. Photo: Gary Braasch

Key implications

- The impacts of sea level rise will be felt through both an increase in mean sea level as well as more frequent extreme sea level events, such as storm surges. Impacts include increased severity and frequency of flooding of low-lying areas, beach erosion, and damage to infrastructure, agriculture, and the environment, including wetlands, inter-tidal zones, and mangroves, with significant impacts on biodiversity and ecosystem function. Hundreds of millions of people live in low-lying coastal areas, including deltas such as Ganges-Brahmaputra (Bangladesh), the Rhine (the Netherlands), and the Mekong (Vietnam).[71]
- Sea level rise severely threatens the existence of a number of small island states. They are in danger of becoming completely submerged or facing increased coastal flooding. Several of these states, such as the Maldives in the Indian Ocean, the Bahamas in the Caribbean, and Tuvalu in the Pacific, are topographically flat and at or near sea level. Others are volcanic with only narrow coastal strips. Sea level rise coupled with storm surges from stronger and longer lasting tropical storms will have a great impact on the socioeconomics of small islands and small island states. Adaptations will be challenging in many island settings, and in some places may not be feasible at all.[72]
- Changes in ocean circulation due to ocean temperature rise and freshening of sea water may affect regional sea level, particularly in the northeastern US, eastern China, and Japan, where sea level is projected to rise more than the global average. This would place large coastal cities, such as Shanghai (China) and New York City (USA) at greater risk of permanent inundation and coastal flooding.[62, 63]
- Rise in sea level causes submergence and increased flooding of coastal land and saltwater intrusion into surface waters. Longer-term effects in coastal areas include increased erosion, ecosystem changes, and saltwater intrusion into groundwater.

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Permafrost

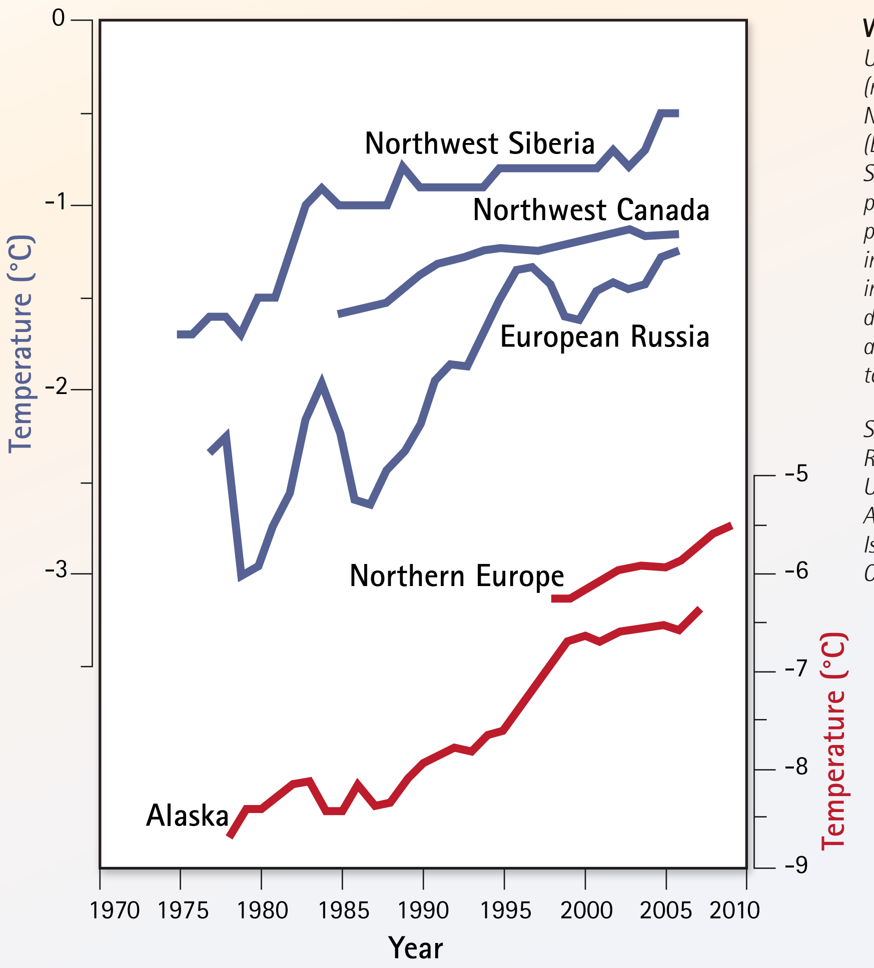
Dramatic erosion caused by permafrost melt, Yamal Peninsula, Russia, 2009. Photo: Kajsa Sjölander

Permafrost temperatures have risen during the last 20–30 years in almost all areas of the Northern Hemisphere. Higher air temperature and changes in snow conditions are projected to initiate widespread permafrost thawing in the subarctic and mountain regions in both hemispheres. This could release large amounts of greenhouse gases into the atmosphere.

Trends

During the last several decades permafrost temperatures have increased in Alaska, northwestern Canada, Siberia, and northern Europe

- Ground temperatures are being measured in approximately 600 existing and newly drilled boreholes in both hemispheres. Most observations show a substantial warming over the last 20 to 30 years. The magnitude of warming varies with location but has typically been from 0.5 to 2°C at the depth of the zero annual temperature variation. Some regions have experienced substantial warming. For example, in some parts of Alaska the permafrost surface temperature has increased by up to 4°C since the mid 1970s.[73, 74, 75, 76, 77]

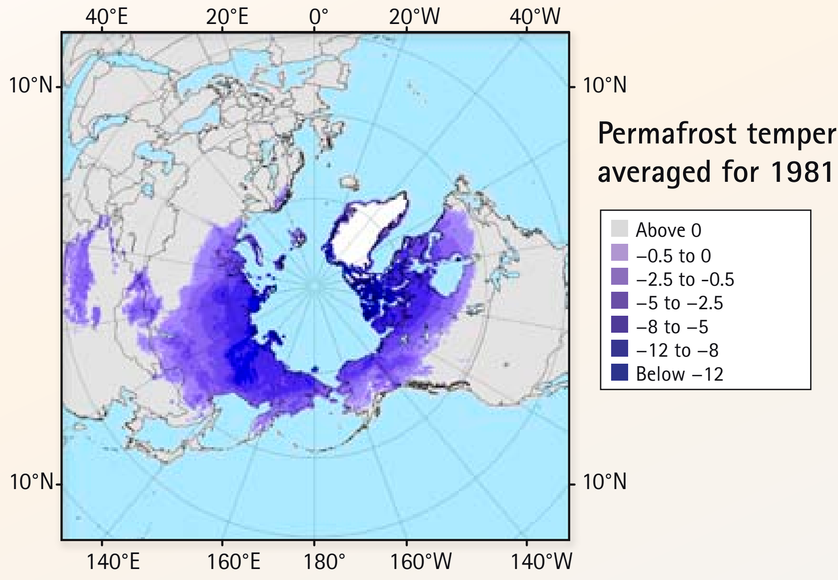


WARMING TRENDS IN PERMAFROST

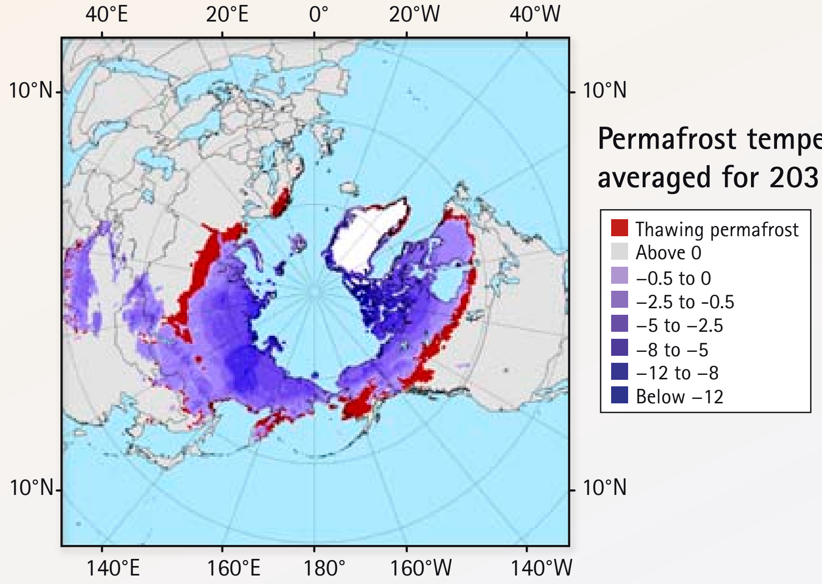
Using data from Janssonhaugen, Svalbard (northern Europe), Deadhorse (Alaska), Norman Wells (northwest Canada), Vorkuta (European Russia) and Nadym (northwest Siberia), the figure shows warming trends in permafrost around the Arctic from 1970 to the present. Permafrost plays an important role in the global carbon cycle. As thaw continues in the future, additional organic matter will decay, increasing the flux of carbon into the atmosphere, causing an accelerating feedback to climate change.

Source: Based on data from Vladimir Romanovsky, University of Alaska Fairbanks, USA, Jerry Brown, International Permafrost Association, University of Oslo, Norway & Ketil Isaksen, Norwegian Meteorological Institute, Oslo.

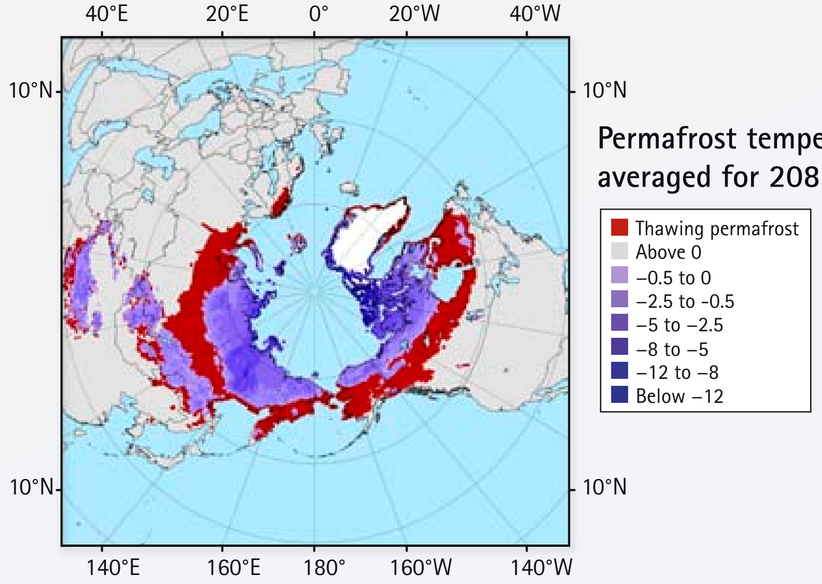
Buckled railway tracks caused by melting permafost, Chara, Russia. 2009. Photo: Kajsa Sjölander



Permafrost temperature (°C) averaged for 1981–2000



Permafrost temperature (°C) averaged for 2031–2050



Permafrost temperature (°C) averaged for 2081–2100

PROJECTIONS OF THAWING PERMAFROST

Future changes in permafrost will be driven by changes in climate, changes in surface vegetation and subsurface hydrology, among other factors. At present, there is no climate model that takes into account all these driving forces. All models do, however, show thawing of permafrost with rising temperatures. The figure show possible changes in permafrost temperatures for the entire Northern Hemisphere permafrost domain using the GIPL-1.2 permafrost model.

Source: Sergei Marchenko & Vladimir Romanovsky, Geophysical Institute, Permafrost Lab, University of Alaska Fairbanks, USA.

- During the early 2000s, permafrost warming was slowing down at many locations in Siberia and Alaska. However, over the last two to three years, very noticeable warming was recorded at the permafrost observatories located near the Arctic coasts in Eurasia and in North America.[78]
- Permafrost degradation and increases in active layer thickness are most evident in subarctic areas of discontinuous permafrost in the European north of Russia, Fennoscandia, northwestern Siberia, and interior Alaska. However, there are very few sites where long-term thawing of permafrost has been documented.
- Permafrost warming has not yet resulted in widespread permafrost thawing on a regional scale.
- The rate of downslope movement of most monitored alpine rock glaciers 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.
- There is too little information on permafrost in the Antarctic to draw conclusions about general trends, as permafrost monitoring started only very recently in this region.[79]

Outlook

Current and predicted climate changes will inevitably affect the stability of permafrost

- Future changes in permafrost will be driven by changes in climate (primarily by air temperature and changes in snow conditions), changes in surface vegetation and subsurface hydrology. Furthermore, extreme events such as forest fires have large impacts on permafrost. At present, there is no climate model that takes into account all these driving forces.
- 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 increases in air temperatures and changes in snow conditions.
- All models show thawing of permafrost with rising temperatures. Some models indicate that projected future warming will result in significant permafrost degradation by 2100, particularly for land areas south of 70 °N. However, the form and rate of permafrost degradation will differ between regions, depending on geographical location and specific environmental settings.[80]

Key implications

- Permafrost plays an important role in the global carbon cycle. Current estimates of the total amount of carbon frozen in permafrost range from 950 to 1700 Gt. The recent very high estimates equal ca. 50% of the estimated global below-ground organic carbon pool, and exceed the amount of organic carbon currently in the atmosphere by a factor of two. As active layer thaw increases in the future, additional organic matter will decay, increasing the flux of carbon into the atmosphere, causing an accelerating feedback to climate change. Observed carbon fluxes indicate that only a small amount of permafrost carbon has thawed thus far. Some of the carbon will enter the atmosphere as methane, a more powerful greenhouse gas than CO_2. Increased emissions due to soil warming are likely to be a short-term response, but in the longer-term warmer climate, longer growing periods and northward movement of productive vegetation may increase photosynthetic carbon uptake.[81, 82, 83]

- Subsea permafrost is poorly understood, due mainly to the lack of direct observations. However, it is known that large volumes of methane in gas hydrate form can be retained within or below permafrost. Degradation of subsea permafrost and the consequent destabilization of gas hydrates could significantly – possibly dramatically – increase the flux of methane to the atmosphere. Observations of seepage of methane from off-shore permafrost areas on the continental shelves in the Arctic have been reported. Warmer ocean temperatures may thaw or cause instability of off-shore permafrost areas.[81]
- The occurrence and thawing of ground ice close to the surface makes permafrost lands extremely sensitive to destructive processes such as the development of thermokarst. The increased development of thermokarst is likely to lead to more wetlands and surface instability, landslides, and erosion, which can significantly accelerate permafrost degradation. At the same time, further development of the thermal erosion network may lead to accelerated drainage and disappearance of already existing thermokarst lakes, new permafrost formation on the drained lake bottoms, and, as a result, to a temporary stabilization of Arctic landscapes.
- Warming of permafrost will continue to adversely affect infrastructure in permafrost regions. Warming will reduce the stability of permafrost, particularly in steep alpine areas, and thus will cause increased rock falls and catastrophic ice avalanches and mud flows.[84]
- Meltwater from permafrost could become an increasingly important source of freshwater in regions that are dependent on meltwater from glaciers that are now receding. On the other hand, thawing permafrost can lead to increased drainage and drying of lakes and ponds in some regions of the Arctic, reducing freshwater supplies for people.
- Thawing permafrost is prone to erosion. Ice-rich, coastal shorelines will be especially susceptible to erosion as the ice-free season and storminess increase. For example, the rate of erosion along a stretch of Alaska's northeastern coastline has doubled over the past 52 years.[85]
- Other implications of permafrost thawing include changes triggered in ecosystems rendering ecosystem function and biodiversity vulnerable to natural and anthropogenic influences.

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Permafrost thawing has destroyed a four-storey apartment building in Yakutia, Russia, 2001. All photos: Vladimir Romanovsky

A house affected by melting ice in degrading permafrost. Fairbanks, Alaska, USA, 2004.

This sinkhole was formed when a large ice pocket within the permafrost melted. Fairbanks, Alaska, USA, 2005.

Collapse caused by thawing permafrost. Fairbanks, Alaska, USA, 2009.

River and lake ice

Tana River, Norway, 1996. Photo: Arvid Sveen

Large regions of the Northern Hemisphere are experiencing shorter durations of river and lake ice cover. Spring break-ups occur earlier and autumn freeze-ups take place later, particularly over the last 50 years. Continued decreases in the river and lake ice season are projected.

Trends

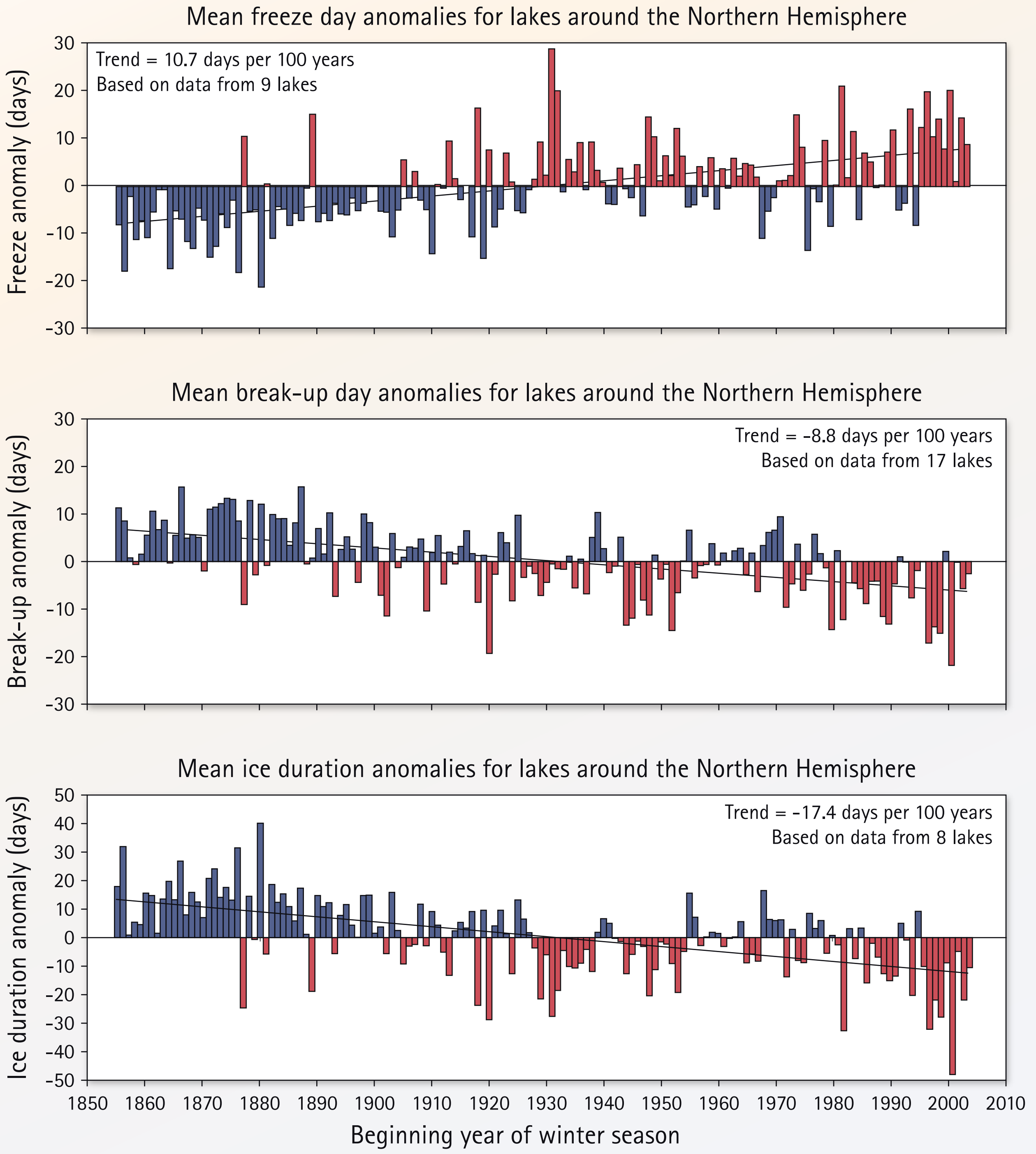
Significant changes in river and lake ice development have occurred in the Northern Hemisphere, particularly with respect to the timing of ice break-up in some regions

- Historical evaluations of changes in river ice regimes suggest that some significant changes have occurred, particularly in the latter half of the 20th century. Studies of 27 long-term (about 150-year) records from across the Northern Hemisphere show that freeze has been delayed by about six days per 100 years and spring break-up has advanced at a similar rate, resulting in an almost two-week per century reduction in the ice-covered season.[86]
- Over the last 150 years, later freeze-up and earlier break-up has shortened the duration of ice cover on lakes around the Northern Hemisphere. More rapid changes have been observed for the most recent 30 years from 1975/76 to 2004/05, with a study of lake ice cover in North American and northern European lakes showing duration declining by 6 days, freeze-up occurring 1.6 days later, and break-up 1.9 days earlier per decade.[87, 88, 89, 90, 91]
- There are indications that the rate of reduction in lake ice duration is higher in the north than in the south. Remote sensing observations of lake ice in Canada over the last two decades, for example, indicate that the rate of reduction for the Canadian Arctic Archipelago is several times greater than that for more southerly continental locations. Other studies show the greatest rates of change to the south for lakes with an already short ice season.[92, 93]
- The changes in river and lake ice broadly correlate with those for general warming patterns. Similarly, certain evidence points to some regional thinning of ice covers but exceptions occur.
- There are fewer frozen lakes and rivers in the Southern Hemisphere, and no significant information is available for this area.

Outlook

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

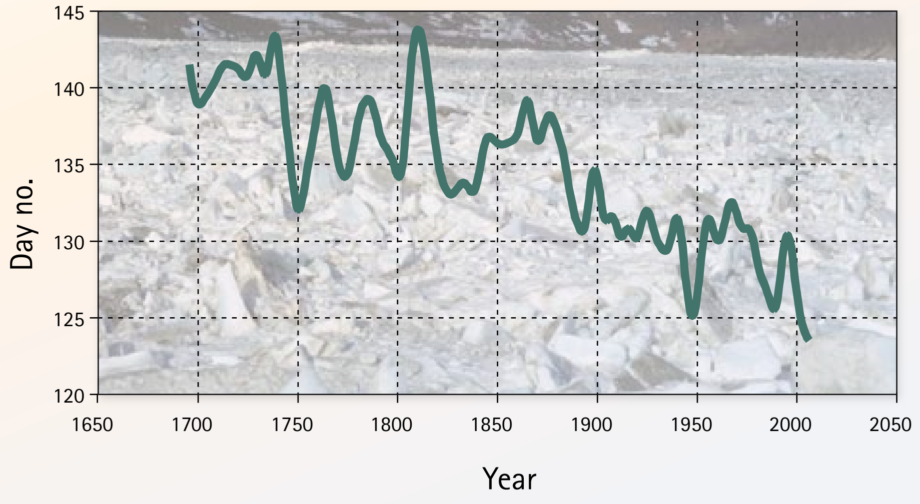
- More frequent occurrence of mid-winter river break-up and associated jamming is a major effect that can be predicted with some confidence for regions where such events are currently rare or unknown.[86]
- Declines in lake ice cover are expected to continue. Shorter ice growth seasons and higher winter air temperatures will likely lead to reductions in ice thickness, though increases in snow and snow ice could lead to greater ice thickness in some areas.[89, 93]



FREEZE, BREAK-UP AND DURATION OF LAKE ICE COVER

The figure shows mean anomalies for freeze and break-up dates and ice cover duration for lakes around the Northern Hemisphere from the winters of 1855/56 to 2004/05. Blue bars represent earlier than average freeze-ups, later than average ice break-ups, and longer than average ice cover durations. These predominate earlier in the record. Orange bars represent later than average freeze-ups, earlier than average ice break-ups, and shorter than average ice cover durations. These predominate later in the record. Note that the number of lakes with available data differs for each panel.

Source: Barbara J Benson & John J Magnuson, updated 2007. Global Lake and River Ice Phenology Database, National Snow and Ice Data Center / World Data Center for Glaciology, University of Colorado at Boulder, USA.



TORNIONJOKI RIVER ICE BREAK-UP

The figure illustrates an example of the significant changes to river ice regimes that have occurred, particularly in the latter half of the 20th century. It shows the ice break-up day for the longest free-flowing river (510 km) in Europe, the Tornionjoki River, on the border between Finland and Sweden. Observations of this river go back to 1694, making it one of the oldest records of ice break-up available. In the known history of the river, its ice break-ups are now earlier than ever. Over the last 50 years the thaw begins about one week earlier.

Source: Øyvind Nordli, Norwegian Meteorological Institute, Oslo. Based on data from Korhonen 2006.[ix]

Key implications

- The rise in river level that is caused by ice cover is fundamental to ice-related hydrological impacts, such as floods caused by freeze-up and break-up ice jams, low winter flows caused by water storage during freeze-up, and sharp waves generated by ice-jam releases. Ice thickness and strength, both controlled by weather conditions, also play major roles.[86]
- In remote areas frozen rivers and lakes serve as transport corridors. Longer ice-free periods mean reduced or more expensive access to communities and industrial developments. Many northern people depend on frozen lakes and rivers for access to traditional hunting, fishing, reindeer herding, or trapping areas. On the other hand, as ice cover lasts for shorter periods, there will be longer periods of access to open waters.
- Shorter lasting and thinner lake ice cover limit the use of lakes for winter recreation such as skating, skiing, ice boating, ice fishing, snowmobiling, and winter festivals.
- Ice formation on rivers and lakes is a key factor controlling biological production, and changes in the length and timing of ice cover will consequently influence the ecosystems. For example, a more even temperature level along north-flowing rivers in the Northern Hemisphere may lead to reductions in ice-jam flooding. This has potentially negative ecological consequences for deltas where annual flooding is needed to maintain ponds and wetlands, but could also reduce the negative consequences of erosion related to ice jams. Shorter lasting ice cover has led to earlier thermal stratification and warmer summer surface waters in large lakes. More generally, when a lake no longer freezes, wind-driven mixing continues throughout the winter, also leading to changes in lake ecosystem functioning.[94, 95, 96]

Dog sledding on the frozen Tana River, Norway, 2009. Photo: Rudi Caeyers

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Uncertainties, knowledge gaps, and the way forward

How snow and ice will continue to respond to a changing climate is uncertain, as is how these changes will affect natural and social systems. To a large degree these uncertainties can only become less uncertain by filling basic knowledge gaps through continued research, monitoring, and further assessments. Reducing uncertainties about causes and consequences of future climate change in the cryosphere is critical for making sustainable mitigation and adaptation strategies. What follows is a selected listing of the most important uncertainties related to the melting of snow and ice.

Climate models are still not projecting changes in snow and ice adequately

Uncertainties

- Climate models have improved significantly over time, and the role of snow and ice in the climate system is currently better integrated into the models than before. However, a number of key cryospheric processes and issues need to be more adequately integrated into the models to more accurately and realistically project future change with widespread global importance.

Knowledge gaps

- To enable adequate validation of models and strengthen the models' ability to project the evolution of the cryosphere, more baseline data and process studies are needed. Although recent initiatives, such as the International Polar Year, have provided for extensive data collection, there are still large gaps in ongoing data collection for assessing the status of the cryosphere and for validating models.

The way forward

- Several aspects of climate models need further development. Much of the uncertainty in cryosphere change projections can be attributed to an insufficient knowledge of many of the physical processes active in this sphere, and basic research is still a fundamental requirement that needs support. Enhancing the interactive coupling between ice, snow, permafrost, atmosphere, and ocean models is also necessary. Furthermore, there are temporal, spatial, and disciplinary gaps in observation records, and data are often difficult to obtain or even unavailable.
  More emphasis must be placed on better linking global/regional climate models with regional/local impact models.
- There must be an increased effort to maintain, extend, and better coordinate long-term scientific monitoring and sustained observations of the world's cryosphere, and make this multi-disciplinary information available in a timely manner to track and understand the rapidly evolving changes in the cryosphere. The response of the cryosphere must then be incorporated in climate models in better ways than we are capable of today.

The basis for assessing the potentially large impact of melting glaciers on downstream societies is inadequate

Uncertainties

- Melting glaciers may strongly affect the seasonal availability of freshwater. There is growing concern that glacier changes may have grave consequences for millions of people living downstream of glacier areas, in particular in the Himalaya and Andes region, where population density is high and where many people are economically vulnerable. However, not enough data are available, in particularly in the Himalayas, which is among the regions with the least available data, to make solid quantitative assessments as to how serious and extensive this issue is.
- The relative importance of glacier contributions to runoff depends on other components of the hydrological cycle and is regionally highly variable. Relative importance is high in areas where precipitation is low during the melt season and where glacier meltwater flows into semi-arid areas. The relative importance of glacier runoff is smaller where the melting of seasonal snowpack or summer monsoon rainfall contributes significantly to water availability, which is the case in wide areas of the Himalayas. The relative importance of glacier runoff also varies between upstream and downstream regions.

Knowledge gaps

- Understanding the impact of climate changes on glaciers and glacier-fed rivers requires long-term glaciological, meteorological, and hydrological monitoring, accessible atmospheric data, and information from satellites. In addition to the basic lack of data, several bottlenecks hamper data collection, for example, geographical, administrative, or political restrictions and the lack of human resources and equipment.

The way forward

- The potential ramifications of glacier melt in some regions of the world could be large, but have not been quantified. Ongoing comprehensive glacier monitoring is sparse, and further data gathering both with regard to glacier dynamics and dependency on glacier runoff is needed.
- To better assess the downstream effects of glacier melt it may be appropriate to take a basin-wide approach across political borders. Legal aspects of water apportionment between upstream and downstream countries need to be further studied and streamlined, and regional cooperating organizations should be considered to avoid any trans-boundary problems.
- Issues related to administrative/political restrictions of access need to be dealt with to enhance data collection, and remote data collection technology should be further developed and used for monitoring in a more operational way.

The near-future contribution of ice sheets to sea level is highly uncertain but potentially large

Uncertainties

- Global climate models likely under-predict future sea level rise because ice dynamics and melt processes are not well represented in current climate models. Existing ice sheet models do not adequately reproduce the observed changes in ice sheets, and the exact level of future change is consequently uncertain even though it is clear from paleoclimatic evidence that ice sheets shrink and sea level rises whenever the planet warms for an extended period of time.
- Recent satellite and ground observations indicate increasing rates of ice sheet thinning and melting. While changes during this century may remain relatively low, continued warming over time would thin and weaken the ice sheets to a point where more rapid reduction of the Greenland and West Antarctic ice sheets could take place in the centuries to come, significantly influencing sea level. This would be of major concern as these two ice sheets contain enough water to raise sea level by 7 m and 5 m, respectively. Projections of future ice sheet related rises in sea level should therefore be regarded as a lower boundary. The reaction of the ice sheets to climate change also depends on the long-term history of the ice sheet, including the past mass balance.

Knowledge gaps

- One of the main weaknesses in current models is that they fail to take into account changes at the ocean interface, which have a dramatic impact on the thickness of the fringing ice shelves and their resistance to seaward flow of the grounded ice sheet. Recent rapid changes at the edges of the ice sheets show acceleration of flow and thinning, with the velocity of some glaciers increasing significantly. It is unclear whether it is a short-term natural adjustment or a response to recent climate change, but processes causing accelerations are enabled by warming, so these adjustments will very likely become more frequent in a warmer climate.

The way forward

- Further research is needed to better understand the dynamics of ice sheets in a changing climate. However, even though there is still need for more research and improved understanding, and even though different groups may come to slightly different projections of global sea level rise caused by ice loss, this should not cloud the overall picture, in which even the lower end of the projections would have very serious effects. Unless significant mitigation actions are undertaken with urgency, the climate could cross a threshold during the 21st century that commits the world to a sea level rise of meters, which will have serious repercussions for people, communities, cities, and even entire states around the world.

The amount and role of greenhouse gases released from thawing permafrost remain uncertain

Uncertainties

- Serious concerns are associated with the potential impact that thawing permafrost may have on the global climate system. Warming and associated thawing of permafrost alters carbon sources and sinks in organic terrain, resulting in the release of additional carbon to the atmosphere. Warming of subsea permafrost can also release significant amount of methane, which is currently stored in gas hydrates.

Knowledge gaps

- Many knowledge gaps need to be filled to decrease the uncertainties related to the total net effect of greenhouse gas release from frozen ground. Recent studies have indicated that the total amount of greenhouse gases held in frozen ground has been hugely underestimated, and while estimates likely are improving, the levels remain uncertain. Few data are available on methane hydrates under the Arctic Ocean and their processes are still poorly understood. Methane hydrates in subsea permafrost is one of the biggest wild cards in the climate system.

The way forward

- Further knowledge and understanding of these issues is essential to understanding future climate change trends and impacts. Although estimates regarding the rate and extent of permafrost formation and degradation improve over time, there are still no climate models that take into account all the driving forces that affect permafrost development, such as temperature, snow, vegetation, and hydrology. A sustainable network of nationally-supported permafrost observatories would enhance observations and enable validation of models.

Our understanding of the magnitude of the role of black carbon in the changing cryosphere is weak

Uncertainties

- Black carbon has the potential to accelerate changes in the cryosphere specifically and climate warming in general through direct and indirect processes in the atmosphere, snow, and ice. There is still, however, considerable uncertainty regarding the magnitude of their effects, especially in relation to the surface albedo.

Knowledge gaps

- Our ability to quantify the effects of black carbon in climate models is severely limited, in particular due to uncertainties about the level of emissions. Knowledge gaps regarding fundamental properties shaping the life cycle of black carbon (emission, transport and transformation, and finally deposition) also interfere with our predictive skills. For example, models vary greatly with respect to how much black carbon is transported and how much is deposited in the Arctic. There is a general lack of proper data on the distribution of black carbon in snow and ice. Measurement techniques are marred by uncertainties and a lack of standardization. The basic processes related to black carbon in snow and ice, for example, the fate of black carbon during melting, are not well understood.
- Black carbon trends in the Arctic are inconsistent because of limited sampling: conclusions are based on single ice cores in one place or single pollution episodes propagating into the Arctic. There is a pressing need for a pan-Arctic observational network for climatically active substances as well as more studies of ice cores and other proxy records (for example, lake sediments) for black carbon.[97, 98]

The way forward

- While it is important and necessary to fill these knowledge gaps, it is also vital to cut emissions of black carbon to slow down short-term climate change. Inhalation of black carbon is hazardous to health, making mitigation desirable regardless of climate change. Measures or technology that would curb emissions from diesel-powered vehicles, domestic fuel burning (coal and biomass), and agricultural and forestry practices to mitigate biomass burning are relevant policy areas to consider in this context.

Glossary

Active layer: The highly mobile layer of soil, subject to periodic thawing, located above the permafrost, ranging in depth from a few centimeters to 3 m. The thickness of the layer depends on factors such as slope angle and aspect, drainage, rock or soil type, depth of snow cover, and ground-moisture conditions. Thawing may occur daily or only in summer.

Albedo: The fraction of solar energy (shortwave radiation) reflected from the Earth back into space. It is a measure of the reflectivity of the Earth's surface. Ice, especially with snow on top of it, has a high albedo: most sunlight hitting the surface bounces back towards space. Water and ground not covered by ice or snow are much more absorbent and less reflective.

Anthropogenic: Caused by humans.

Biomass burning: The burning of biological material such as wood and other plant material, waste, and alcohol fuels. It does not include organic material such as coal or petroleum that have been transformed by geological processes.

Black carbon: Black carbon is emitted during the burning of coal, diesel fuel, natural gas, and biomass and is part of the composition of soot.

Cryosphere: The cryosphere consists of the frozen portions of the globe, and includes ice sheets, glaciers, ice caps, icebergs, sea ice, snow cover and snowfall, lake and river ice, permafrost and seasonally frozen ground.

Depth of zero annual temperature variation: With increasing depth in the ground, the seasonal difference in temperature decreases. The point at which there is no discernable change in temperature is the depth of zero annual temperature variation.

Feedback process: In a feedback process, some of the output of a system returns as input. Climate feedback processes are positive when they amplify climate change and are negative when they diminish change. The climate system is characterized by strong positive and negative feedback loops between processes that affect the state of the atmosphere, ocean, and land. A simple example is the ice-albedo positive feedback loop whereby melting snow exposes more dark ground (of lower albedo), which in turn absorbs heat and causes more snow to melt.

Gas hydrates: Gas hydrates occurring beneath the continental shelves of the world and associated with deep permafrost represent the single largest known source of mobile carbon. Methane hydrate, thought to be the most common form of gas hydrate, is only stable under specific conditions of low temperature and moderate pressures. When these conditions are changed by processes such as climate warming or fluctuations in sea level, there is a significant risk of an increased flux of methane into the atmosphere.

Glacier: A glacier is a perennial mass of snow and ice that moves over land. A glacier forms in locations where the mass accumulation of snow and ice exceeds loss over many years. See also ice cap.

Glacier lake outburst flood: A glacial lake outburst flood can occur when a lake contained by a glacier or a terminal moraine dam fails. This can happen due to erosion, a buildup of water pressure, an avalanche of rock or heavy snow, an earthquake, volcanic eruptions under the ice, or if a large enough portion of a glacier breaks off and massively displaces the waters in a glacial lake at its base.

Greenhouse gases: Greenhouse gases are chemical compounds in the atmosphere that trap heat, through a mechanism known as the greenhouse effect. The most important greenhouse gas is water vapor, which contributes about two-thirds of the greenhouse effect. Other important natural greenhouse gases are CO_2, ozone, nitrous oxide, and methane.

Gt: A gigatonne, 10^9 (1,000,000,000) tonnes.

Ice cap: An ice cap is a large glacier that covers an entire mountain, mountain chain, or volcano. Ice caps are not constrained by topographical features and their dome is usually centered on the highest point of a massif. Ice flows away from this high point (the ice divide) towards the ice cap's periphery. See also glacier, ice dome, and ice sheet.

Ice dome: A main component of an ice sheet or ice cap. It has a convex surface form and tends to develop symmetrically over a land mass.

Ice sheet: Masses of ice covering more than 50,000 km^2.

Ice shelf: A thick, floating platform of ice that forms where a glacier or ice sheet flows down to a coastline and onto the ocean surface. Ice shelves are found in Antarctica, Greenland, and Canada only. The melting of ice shelves does not contribute significantly to sea level rise. However, ice shelves act as natural obstacles for discharge from glaciers and ice sheets, and disintegration can therefore lead to increased discharge of ice that does impact sea level.

IPCC: The Intergovernmental Panel on Climate Change (IPCC) is a scientific intergovernmental body tasked to evaluate the risk of climate change caused by human activity. The panel was established in 1988 by the World Meteorological Organization and the United Nations Environment Programme, two organizations of the United Nations. The IPCC shared the 2007 Nobel Peace Prize with former US Vice President Al Gore.

Little Ice Age: A period of cooler climate between approximately 1550 (or perhaps as early as 1300) and 1850, when mountain glaciers advanced in many parts of the world. The precise timing of the advances and retreats varied from region to region. Temperatures were not uniformly colder throughout this period, but rather showed marked variations on decadal timescales.

Mass balance: The difference between ice accumulation and ice mass loss. Mass balance is a measure of net annual change in thickness averaged over the total glacier area. Climate change may cause variations in both temperature and snowfall, causing changes in mass balance. Changes in mass balance control a glacier's long-term behavior, and mass balance is therefore the most sensitive climate indicator of a glacier.

Mid-latitudes: The mid-latitudes are between 23°26′22″ and 66°33′39″ North, and between 23°26′22″ and 66°33′39″ South. They are the Earth's temperate zones between the tropics and the Arctic and Antarctic.

Multi-year ice: Sea ice which survives the summer is classified as multi-year ice. Multi-year ice has distinct properties that distinguish it from first-year ice, based on processes that occur during the summer melt. Multi-year ice contains much less brine and more air pockets than first-year ice. Multi-year ice is much more common in the Arctic than in the Antarctic. This is because ocean currents and atmospheric circulation move sea ice around Antarctica, causing most of the ice to melt in the summer.

Rock glacier: A form of mountain permafrost in which frozen debris and/or ice underlie a layer of debris and move downslope.

Salinity: The saltiness or dissolved salt content of a body of water. It is a general term used to describe the levels of different salts such as sodium chloride, magnesium and calcium sulfates, and bicarbonates.

Sea level equivalent: Ice mass expressed as the cumulative contribution it would add to sea level if it melted.

Snowpack: The amount of seasonal or annual accumulation of snow at a given location.

Snow water equivalent: A common snowpack measurement, it is the water content obtained from melting snow (for instance, the thickness of the layer of water that would result form melting a given snow depth) typically reported in millimeters.

Thermokarst: Thermokarst forms when ground ice melts, the resulting water drains, and the remaining soil collapses into the space previously occupied by ice.

Tidewater glacier: A glacier terminating in the sea.

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People of Greenland, 2009. Photos: Camille Seaman

Humpback whale, Antarctica, 2000. Photo: Stefan Lundgren

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Melting Ice conference, Tromsø, 2009. Photo: Torgrim Rath Olsen

"Snow and ice are melting far above normal seasonal changes, and the changes are occurring at an accelerating pace. We see this happening in all snow- and ice-covered regions: Antarctica, the Arctic, Greenland, the 'third pole' of the Himalayas, and other glaciated areas throughout the world.

We strongly urge that political action be taken to ensure a globally responsible policy to substantially reduce the emission of greenhouse gases. We are not helpless against this threat.

We can:

- *Commit to deep cuts in global greenhouse gas emissions*
- *Address short-lived climate pollutants such as black carbon, methane and tropospheric ozone*
- *Work toward solutions where industrialized nations, which bear the main responsibility for the man-made climate change we have seen so far, assist the many peoples affected that cannot cope with the challenges alone*
- *Base political action on scientific findings – and ensure that science is steadily improved and updated."*

– Jonas Gahr Støre and Al Gore

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