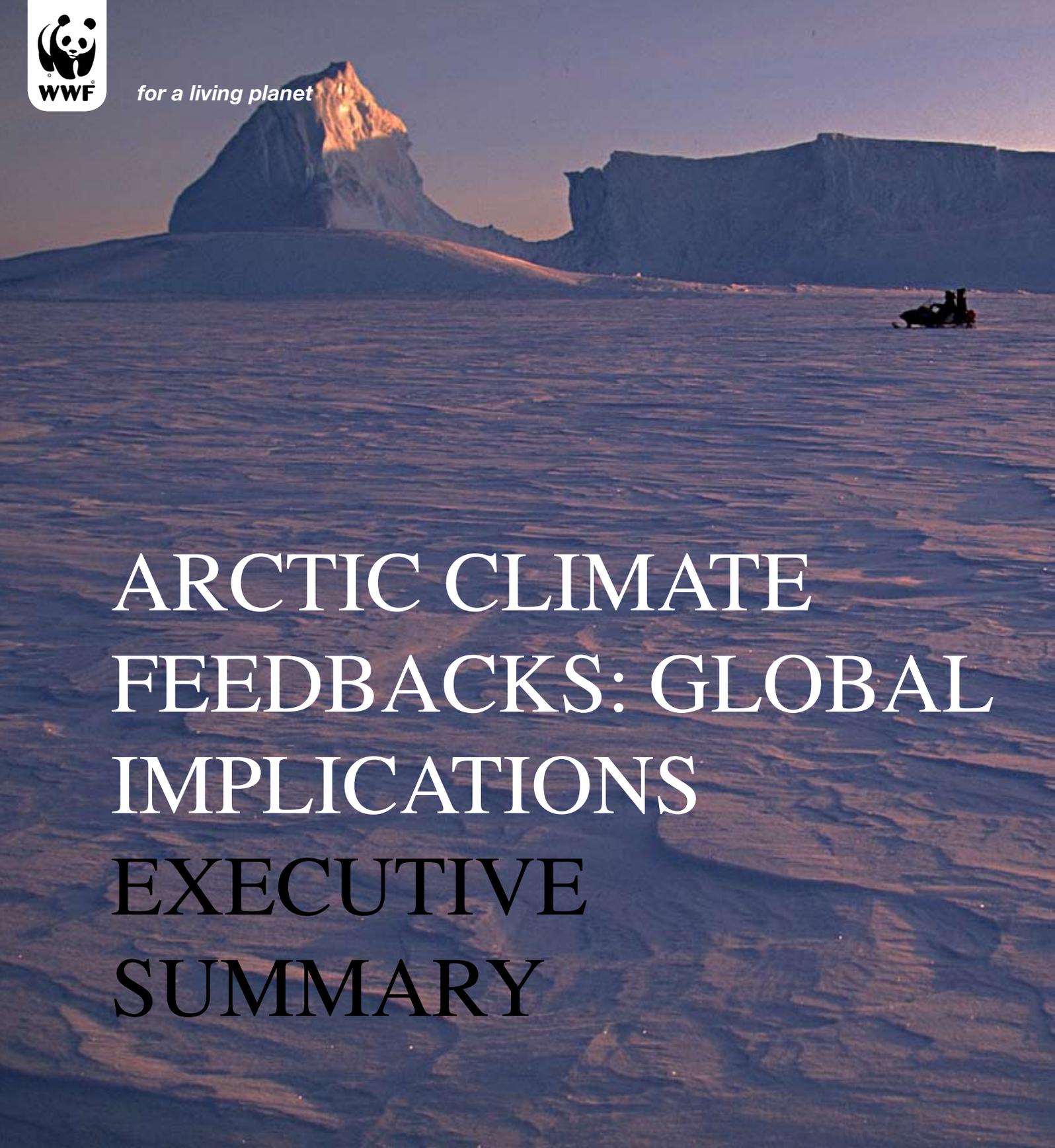




*for a living planet*

A wide-angle photograph of an Arctic landscape. In the foreground, a vast, textured expanse of sea ice stretches across the frame. In the middle ground, a small, dark boat with several people is visible on the right. In the background, a large, jagged ice formation, possibly a glacier or ice shelf, rises against a pale, hazy sky. The lighting suggests a low sun, casting a soft glow on the ice.

# ARCTIC CLIMATE FEEDBACKS: GLOBAL IMPLICATIONS EXECUTIVE SUMMARY

**O**VER THE PAST FEW DECADES, the Arctic has warmed at about twice the rate of the rest of the globe. Human-induced climate change has affected the Arctic earlier than expected. As a result, climate change is already destabilising important arctic systems including sea ice, the Greenland Ice Sheet, mountain glaciers, and aspects of the arctic carbon cycle including altering patterns of frozen soils and vegetation and increasing methane release from soils, lakes, and wetlands. The impact of these changes on the Arctic's physical systems, biological systems, and human inhabitants is large and projected to grow throughout this century and beyond.

**“Human-induced climate change has affected the Arctic earlier than expected”**

In addition to the regional consequences of arctic climate change are its global impacts. Acting as the Northern Hemisphere's refrigerator, a frozen Arctic plays a central role in regulating Earth's climate system. A number of critical arctic climate feedbacks affect the global climate system, and many of these are now

**“There is emerging evidence and growing concern that arctic climate feedbacks affecting the global climate system are beginning to accelerate warming significantly beyond current projections”**

being altered in a rapidly warming Arctic. There is emerging evidence and growing concern that these feedbacks are beginning to accelerate global warming significantly beyond the projections currently being considered by policymakers. Recent observations strongly suggest that climate change may soon push some systems past tipping points, with global implications. For example, the additional heat absorbed by an increasingly ice-free Arctic Ocean in summer is already accelerating

local and regional warming and preventing sea ice from recovering. There is also a concern that arctic feedbacks may increase regional or global warming significantly enough that it would alter other climate feedbacks.

While the important role of the Arctic in the global climate system has long been recognized, recent research contributes much to the understanding of key linkages, such as the interactions between the Arctic Ocean and the atmosphere. At the same time, the science assessing the growing regional and global consequences of arctic climate impacts is rapidly maturing. In combination, these growing insights sharpen our awareness of how arctic climate change relates to global average warming,

and what level of global warming may constitute dangerous human interference with the climate system. Avoiding such interference by stabilising atmospheric greenhouse gases at the necessary levels is the stated objective of the United Nations Framework Convention on Climate Change. Global feedbacks already arising from arctic climate change suggest that anything but the most ambitious constraints on greenhouse gas concentrations may not be sufficient to avoid such interference. This points to the need to continually incorporate the latest science in determining acceptable limits.

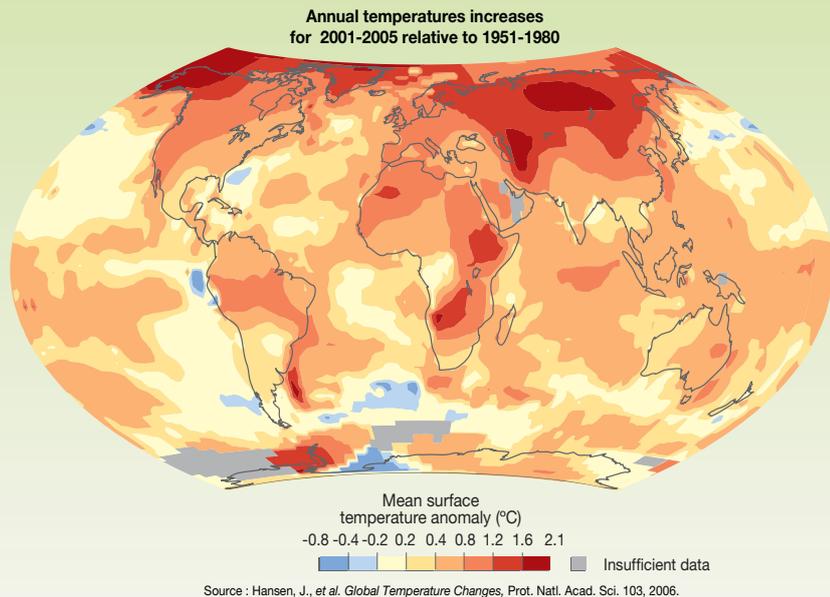
Climate change in the Arctic is affecting the rest of the world by altering atmospheric and oceanic circulation that affect weather patterns, the increased melting of ice sheets and glaciers that raise global sea level, and changes in atmospheric greenhouse gas concentrations (by altering release and uptake of carbon dioxide and methane). This report provides a comprehensive and up-to-date picture of why and how climate change in the Arctic matters for the rest of the world and is thus relevant for today's policy decisions regarding reductions in atmospheric greenhouse gases. In particular, the report describes the most recent findings regarding major arctic feedbacks of global significance for coming decades.

**I**N SUM, important aspects of the global climate system, which directly affect many people, are already seeing the effects of arctic climate change. This assessment of the most recent science shows that numerous arctic climate feedbacks will make climate change more severe than indicated by other recent projections, including those of the IPCC 2007 assessment. Some of these feedbacks may even interact with each other. Up-to-date analyses of the global consequences of arctic change highlight the need for ongoing critical review of the thresholds of dangerous human interference with the climate system, and demand increased rigour to stay below these thresholds through an ambitious global effort to reduce atmospheric greenhouse gases.

**“Global feedbacks already arising from arctic climate change suggest that anything but the most ambitious constraints on greenhouse gas concentrations may not be sufficient to avoid dangerous interference with the climate system”**

# Arctic Climate Change

The Arctic climate feedbacks that are the focus of this report are taking place in the context of rapid and dramatic climate change in the Arctic. Rising temperatures, rapidly melting ice on land and sea, and thawing permafrost are among the sweeping changes being observed. The following is a brief summary of these changes that define the starting point for the discussion of arctic climate feedbacks and their implications for the world.

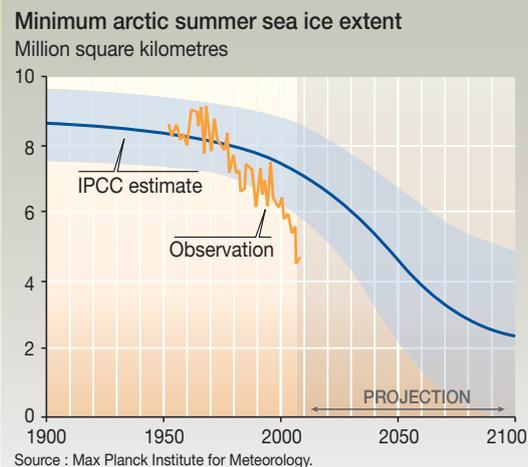


## Air temperatures rising

Arctic air temperatures have risen at almost twice the rate of the global average rise over the past few decades. This “arctic amplification” of global warming is largely a result of reduced surface reflectivity associated with the loss of snow and ice, especially sea ice. The year 2007 was the warmest on record in the Arctic. Recent research has concluded that this warming contains a clear human “fingerprint”. Precipitation is also increasing in the Arctic, and at a greater rate than the global average, an expected result of human-caused warming.

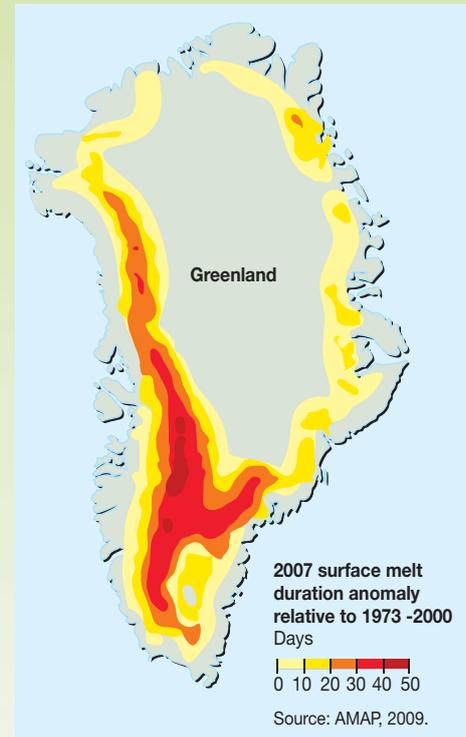
## Sea ice declining

Sea ice extent has decreased sharply in all seasons, with summer sea ice declining most dramatically — beyond the projections of IPCC 2007. Nearly 40 per cent of the sea ice area that was present in the 1970s was lost by 2007 (the record low year for summer sea ice), and ice-free conditions existed in 2008 in both the Northeast and Northwest passages for the first time on record. Sea ice has also become thinner. Thick ice that persists for years (multi-year ice) has declined in extent by 42 per cent, or 1.5 million square kilometres, about the size of Alaska, between 2004 and 2008 alone. As this multi-year ice is replaced by young ice, arctic sea ice is becoming increasingly vulnerable to melting.

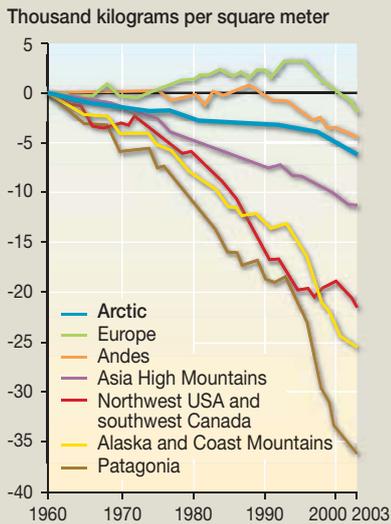


## Greenland Ice Sheet melting

The loss of ice from the Greenland Ice Sheet has increased in recent years and is more rapid than was projected by models. The faster flow of glaciers to the sea appears to be responsible for much of the increase in mass loss. In addition, melting on the surface of the ice sheet has been increasing, with 2007 melting being the most extensive since record keeping began. The area experiencing surface melt was 60 per cent larger than in 1998, the year with the second-largest area of melting in the record.



## Glacier mass balance



Source : Dyurgerov and Meier, 2005.

## Glacier retreat accelerating

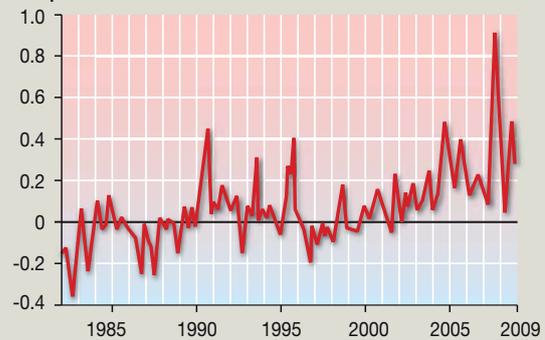
Glacier mass loss has been observed across the Arctic, consistent with the global trend. Some glaciers are projected to completely disappear in the coming decades. Alaska's glaciers are shrinking particularly rapidly. Until recent years, glaciers in Scandinavia were reported to be increasing in mass while those on Svalbard showed no net change as increased winter snowfall outpaced or equalled summer melting in those areas. This has reversed in recent years, with glaciers in both Scandinavia and on Svalbard now clearly losing mass.

## Ocean surface warming

Consistent with the rapid retreat of sea ice, the surface waters of the Arctic Ocean have been warming in recent years, because declining sea-ice cover allows the water to absorb more heat from the sun. In 2007, some surface water ice-free areas were as much as 5°C higher than the long-term average. The Arctic Ocean has also warmed as a result of the influx of warmer water from the Pacific and Atlantic oceans.

## Arctic Ocean surface temperatures

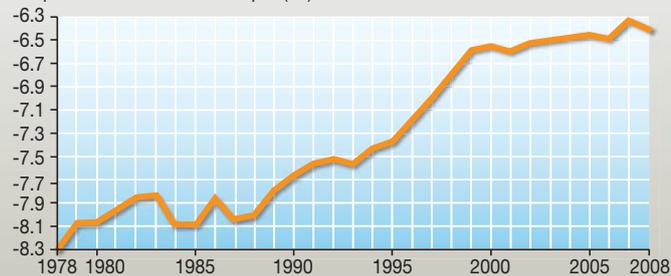
Temperature in °C



Source : NOAA, 2009.

## Permafrost at Deadhorse, Alaska

Temperatures at 20 meters depth (°C)



Source : US climate impacts report, 2009.

## Permafrost warming and thawing

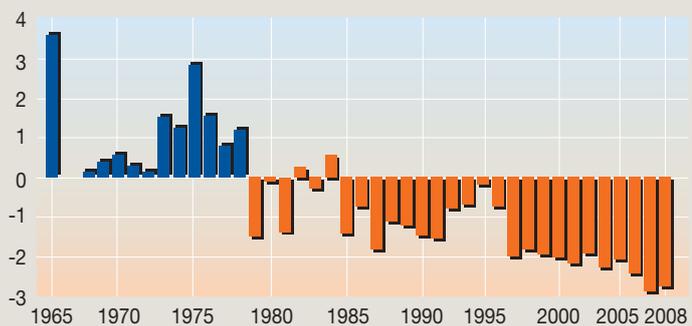
Permafrost has continued to warm and to thaw at its margins. The depth of the active layer, which thaws in the warm season, is increasing in many areas. Degrading permafrost is significantly affecting wetlands. Projections show widespread disappearance of lakes and wetlands even in formerly continuous permafrost zones.

## Declining snow, river and lake ice

Snow cover extent has continued to decline and is projected to decline further, despite the projected increase in winter snowfall in some areas. The lengthening of the snow-free season has a major impact in accelerating local atmospheric heating by reducing the reflectivity of the surface. Ice cover duration on rivers and lakes has continued to decline. This is especially apparent in earlier spring ice break-up.

## Anomalies in Northern Hemisphere Snow Cover

Million square kilometres



Source: GSL, Rutgers University, 2009

# Key Findings of this Assessment

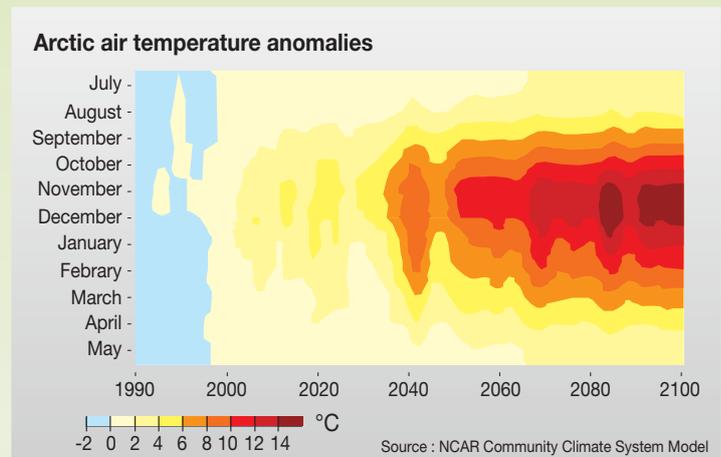
## ■ Amplification of global warming in the Arctic will have fundamental impacts on Northern Hemisphere weather and climate.

*(Chapter 1, Atmospheric Circulation Feedbacks)*

■ **Reduced sea ice amplifies warming.** Reduced sea ice cover is already amplifying warming in the Arctic earlier than projected. This amplification will become more pronounced as more ice cover is lost over the coming decades.

■ **Amplified warming spreads over land.** Amplified atmospheric warming in the Arctic will likely spread over high-latitude land areas, hastening degradation of permafrost, leading to increased release of greenhouse gases presently locked in frozen soils, leading to further arctic and global warming.

■ **Weather patterns are altered.** The additional warming in the Arctic will affect weather patterns in the Arctic and beyond by altering the temperature gradient in the atmosphere and atmospheric circulation patterns. It may also affect temperature and precipitation patterns in Europe and North America. These changes will affect agriculture, forestry and water supplies.



## ■ The global ocean circulation system will change under the strong influence of arctic warming.

(Chapter 2, Ocean Circulation Feedbacks)

■ **Changes in ocean circulation matter to people.** From dramatic climate shifts to decade-to-decade climatic fluctuations, the oceans contribute to Earth's varying climate.

■ **A changing Arctic can modify ocean circulation globally.** By causing atmospheric changes that affect the ocean outside the Arctic, and through the direct ocean circulation connection between the Arctic Ocean and the global ocean, changes in the Arctic can alter the global ocean circulation.

■ **The Arctic Ocean connections are changing.**

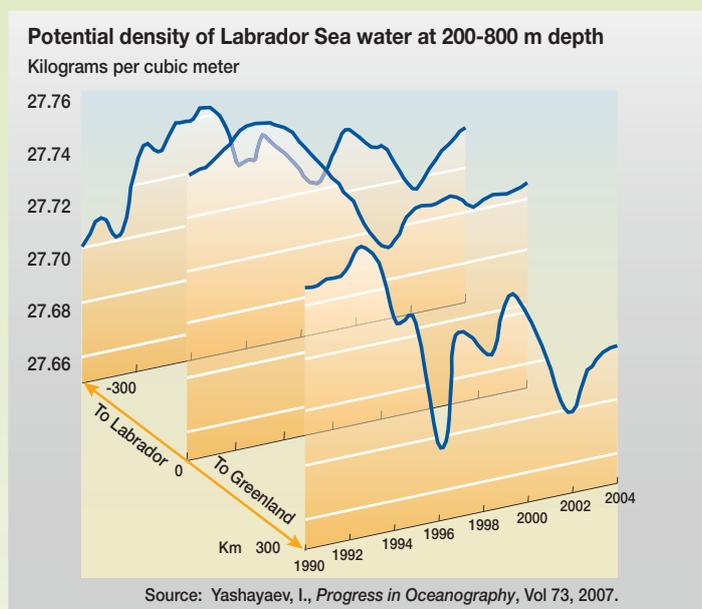
The Arctic Ocean is connected to the global ocean through the Atlantic and the Pacific Oceans. Water flowing into the Arctic Ocean from both the Pacific and Atlantic has warmed over the past decade. Although there has been an increase in freshwater input into the Arctic Ocean from melting ice and increased precipitation and river flows, so far there are few indications of an increase in freshwater export from the Arctic. Changes in temperature and salinity and their effects on density are among the concerns because of their potential to alter the strength of the global ocean circulation.

■ **Global ocean circulation will not change**

**abruptly, but it will change significantly, in this century.** There are only few indications that changes in the global overturning circulation are already occurring. However, it is likely that the circulation strength will change in the future. This assessment supports the IPCC 2007 projection of a 25 per cent average reduction of the overturning circulation by 2100.

■ **People are affected not only by changes in ocean circulation strength, but also by**

**changes in circulation pathways.** This assessment highlights the potential for currents in the North Atlantic Ocean to alter their paths. Different ocean currents transport waters with different characteristics, supporting different ecosystems. Therefore, changes in ocean circulation pathways will affect fisheries and other marine resources.



## ■ The loss of ice from the Greenland Ice Sheet has increased and will contribute substantially to global sea level rise.

*(Chapter 3, Ice Sheets and Sea-level Rise Feedbacks)*

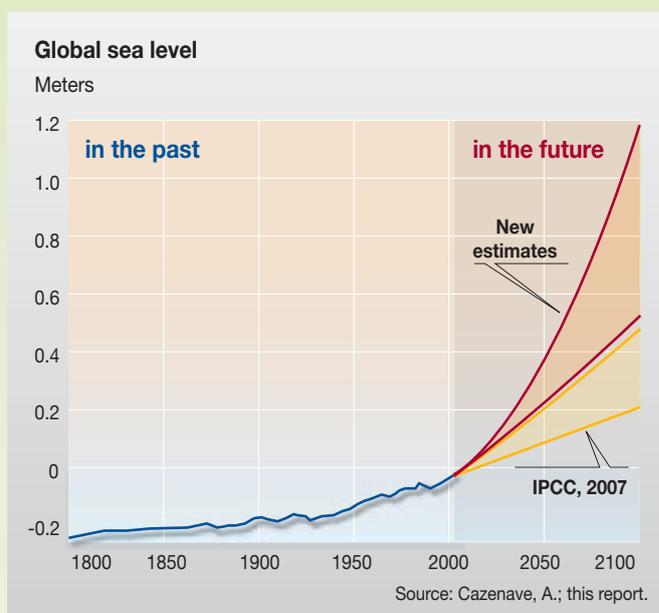
■ **Sea-level rise is accelerating.** Sea level has been rising over the past 50 years, and its rate of rise has been accelerating. The rate of rise in the past 15 years is about double that of the previous decades.

■ **Thermal expansion and melting of land-based ice are driving sea-level rise.** Ocean warming and increased water inputs from melting glaciers and ice sheets are the primary contributors to sea-level rise. Over the past 15 years, thermal expansion, glacier melting and ice sheet mass loss have each contributed about one-third of the observed sea-level rise.

■ **The ice sheets are melting.** The ice sheets on Greenland and Antarctica are melting into the ocean faster than expected. Melt rates are sensitive to climate and are accelerating as both land and ocean temperatures rise.

■ **Ice sheet melt will be the major contributor to future sea-level rise.** With ongoing warming, ice sheet melting is projected to continue irreversibly on human timescales and will be the primary contributor to sea-level rise far into the future, well beyond this century.

■ **Sea level will rise more than previously expected.** Sea level will rise more than 1 metre by 2100, even more than previously thought, largely due to increased mass loss from the ice sheets. Increases in sea level will be higher in some areas than in others. Low-lying coastal areas around the world are at particular risk.



## ■ Arctic marine systems currently provide a substantial carbon sink but the continuation of this service depends critically on arctic climate change impacts on ice, freshwater inputs, and ocean acidification.

(Chapter 4, Marine Carbon Cycle Feedbacks)

### ■ The Arctic Ocean is an important global carbon sink.

At present, the Arctic Ocean is a globally important net sink for carbon dioxide, absorbing it from the atmosphere. It is responsible for 5 to 14 per cent to the global ocean's net uptake of carbon dioxide.

■ **A short-term increase in carbon uptake by the Arctic Ocean is projected.** In the near-term, further sea-ice loss, increases in phytoplankton growth rates, and other environmental and physical changes are expected to cause a limited net increase in the uptake of carbon dioxide by arctic surface waters.

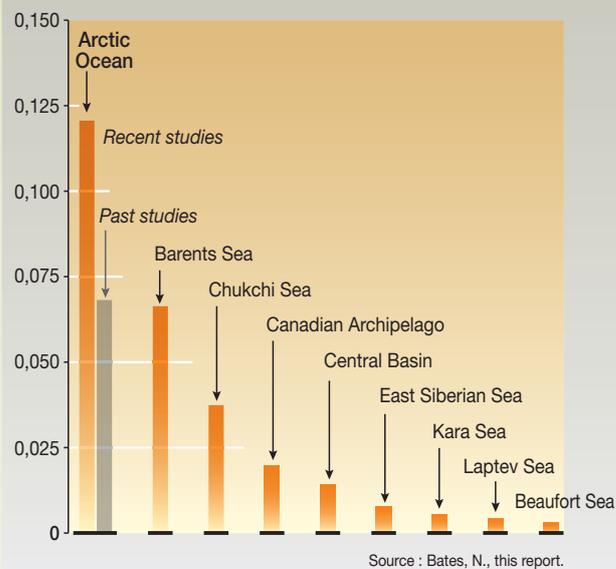
### ■ In the long term, net release of carbon is expected.

Release of large stores of carbon from the surrounding arctic landmasses through rivers into the Arctic Ocean may reverse the short-term trend, leading to a net increase of carbon dioxide released to the atmosphere from these systems over the next few centuries.

### ■ The Arctic marine carbon cycle is very sensitive to climate change.

The Arctic marine carbon cycle and exchange of carbon dioxide between the ocean and atmosphere is particularly sensitive to climate change. The uptake and fate of carbon dioxide is highly influenced by physical and biological processes themselves subject to climate change impacts, such as sea ice cover, seasonal marine plant (such as phytoplankton) growth, ocean circulation and acidification, temperature effects, and river inputs, making projections uncertain.

Uptake of carbon dioxide from the atmosphere  
Gigatons of Carbon per year



## ■ Arctic terrestrial ecosystems will continue to take up carbon, but warming and changes in surface hydrology will cause a far greater release of carbon.

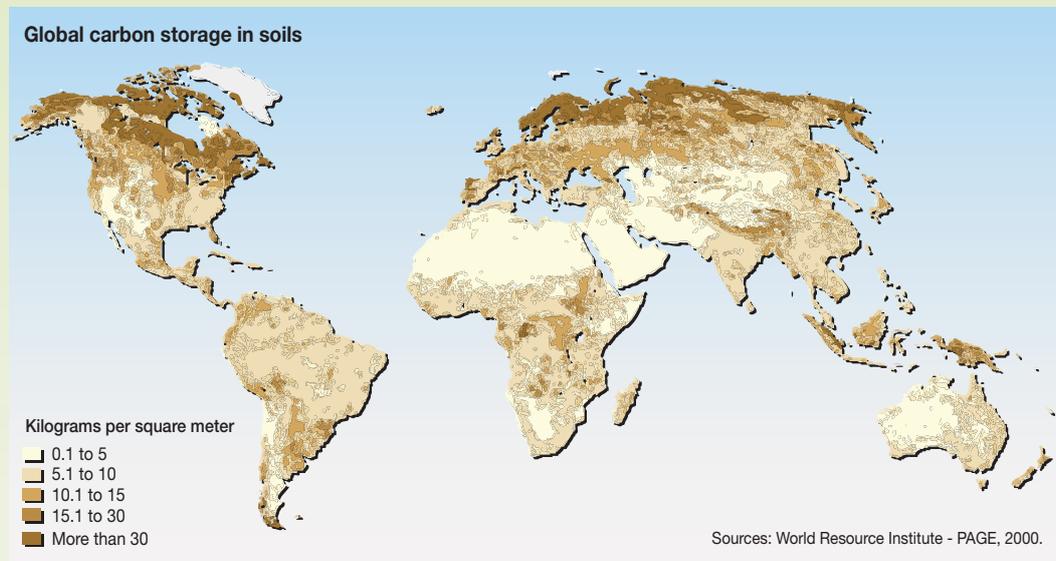
*(Chapter 5, Land Carbon Cycle Feedbacks)*

■ **Arctic lands store large amounts of carbon.** The northern circumpolar regions, including arctic soils and wetlands, contain twice as much carbon as in the atmosphere.

■ **Emissions of carbon dioxide and methane are increasing due to warming.** Current warming in the Arctic is already causing increased emissions of carbon dioxide and methane. Most of the carbon being released from thawing soils is thousands of years old, showing that the old organic matter in these soils is readily decomposed.

■ **Carbon uptake by vegetation is increasing.** Longer growing seasons and the slow northward migration of woody vegetation are causing increased plant growth and carbon accumulation in northern regions.

■ **Carbon emissions will outpace uptake as warming proceeds.** Future arctic carbon emissions to the atmosphere will outpace carbon storage, and changes in landscape will result in more of the sun's energy being absorbed, accelerating climate change.



## ■ The degradation of arctic sub-sea permafrost is already releasing methane from the massive, frozen, undersea carbon pool and more is expected with further warming.

*(Chapter 6, Methane Hydrate Feedbacks)*

### ■ Large amounts of methane are frozen in arctic methane hydrates.

Methane is a powerful greenhouse gas. A large amount of methane is frozen in methane hydrates, which are found in ocean sediments and permafrost. There is more carbon stored in methane hydrates than in all of Earth's proven reserves of coal, oil and natural gas combined.

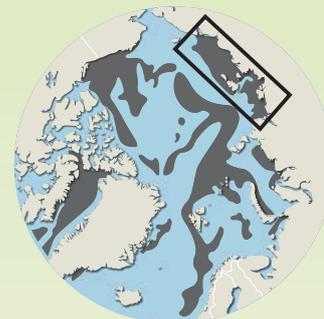
■ **Continental shelves hold most of this hydrate.** Most methane hydrates are stored in continental shelf deposits, particularly in the arctic shelves, where they are sequestered beneath and within the sub-sea permafrost. Since arctic hydrates are permafrost-controlled, they destabilize when sub-sea permafrost thaws.

■ **Thawing sub-sea permafrost is already releasing methane.** Current temperatures in the Arctic are already causing sub-sea permafrost to thaw. Thawed permafrost fails to reliably seal off the hydrate deposits, leading to extensive methane release into the ocean waters. Because of the shallow water depth of large portions of the Arctic shelves, much methane reaches the atmosphere un-oxidized (not changed to carbon dioxide). It is not yet known how much this release contributes to current global atmospheric methane concentrations. Methane is about 25 times more potent a greenhouse gas than carbon dioxide.

■ **Hydrates increase in volume when destabilized.** In addition, when methane hydrates destabilize, the methane within these hydrates increases tremendously in volume. The very high pressure that results may lead to abrupt methane bursts.

■ **The most vulnerable hydrates are on the East Siberian Shelf.** The largest, shallowest, and thus most vulnerable fraction of methane deposits occurs on the East Siberian Shelf. Increased methane emissions above this shelf have been observed, but it is not yet known whether recent arctic warming is responsible for the increase in emissions.

East Siberian Arctic Shelf,  
the most vulnerable fraction of the arctic shelf



Predicted hydrate  
deposits



Water depth  
<50 m

Source : Jacobsen et al, 2004.

ARCTIC CLIMATE FEEDBACKS:  
GLOBAL IMPLICATIONS

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