for a living planet

ARCTIC CLIMATE FEEDBACKS: GLOBAL IMPLICATIONS

ARCTIC CLIMATE FEEDBACKS: GLOBAL IMPLICATIONS

Martin Sommerkorn & Susan Joy Hassol, editors

With contributions from:
Mark C. Serreze & Julienne Stroeve
Cecilie Mauritzen
Anny Cazenave & Eric Rignot
Nicholas R. Bates
Josep G. Canadell & Michael R. Raupach
Natalia Shakhova & Igor Semiletov

CONTENTS

EXECUTIVE SUMMARY

OVER 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."**

> **"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."**

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 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.

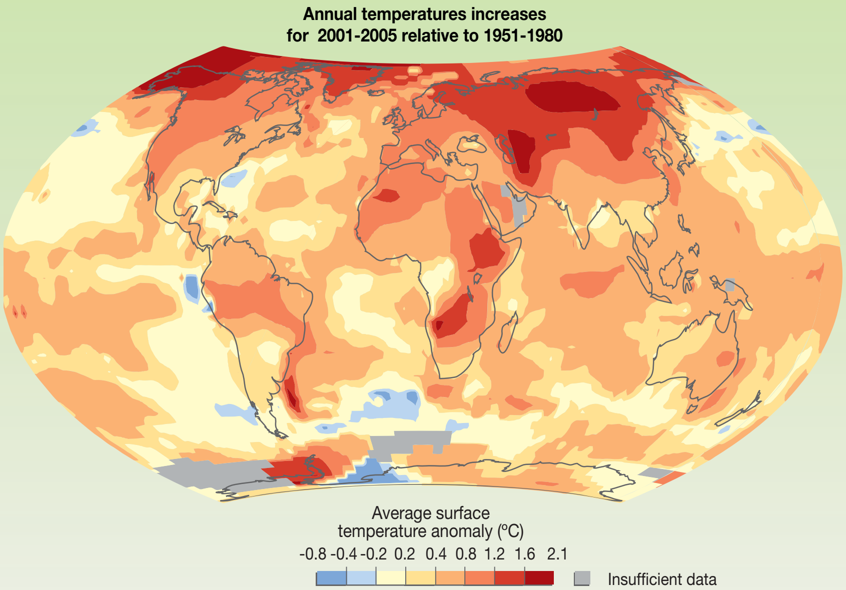
> **"Global feedbacks already arising from arctic climate change suggest that anything but the most ambitious constraints on greenhouse gas concentrations may not be sufficient to avoid dangerous interference with the climate system."**

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.

IN 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 Intergovernmental Panel on Climate Change Fourth Assessment report (IPCC 2007). 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.

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.


Annual temperatures increases for 2001-2005 relative to 1951-1980

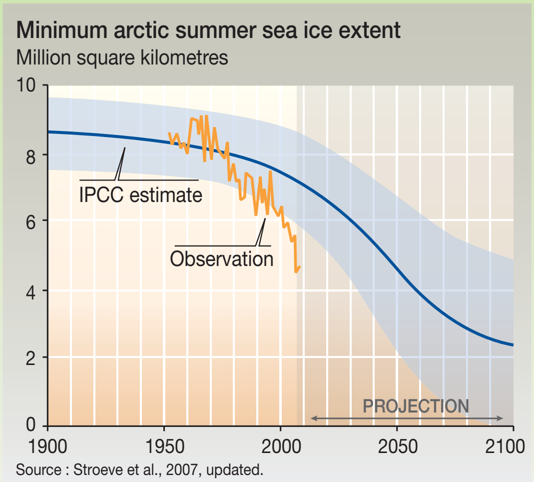
Hansen et al., Global Temperature Changes, *Proc. Natl. Acad.* Sci. 103, 2006.

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.

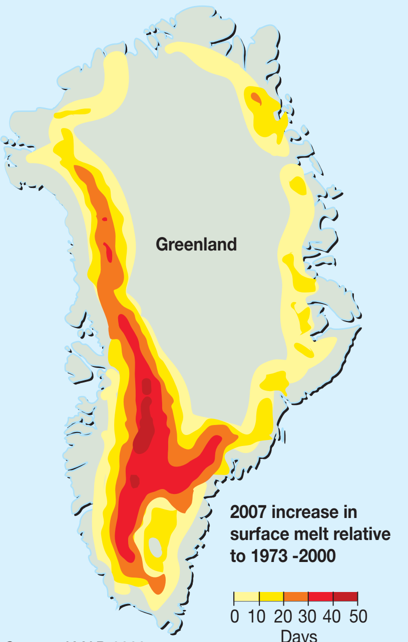

Minimum arctic summer sea ice extent

Source : Stroeve et al., 2007, updated.

Greenland Ice Sheet melting

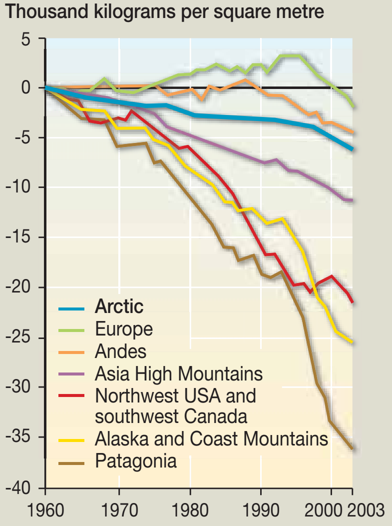
The loss of ice from the Greenland Ice Sheet has increased in recent years and is more rapid than was projected by models. The faster flow of glaciers to the sea appears to be responsible for much of the increase in mass loss. In addition, melting on the surface of the ice sheet has been increasing, 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.

Change in surface melt duration



Source: AMAP, 2009.

Glacier mass balance



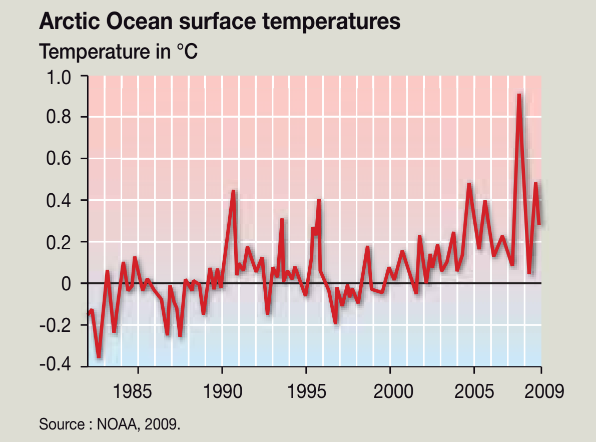
Source : Dyurgerov and Meier, 2005.

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.



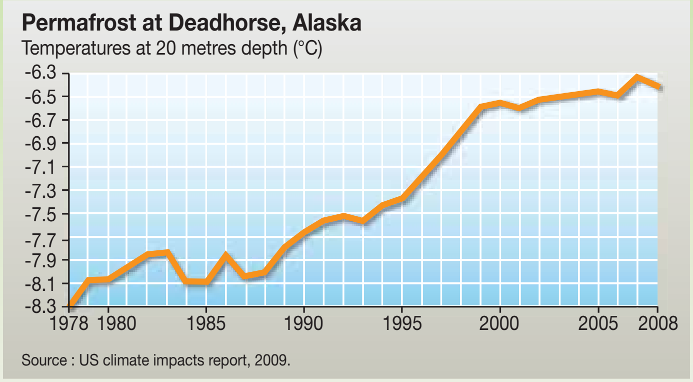
Arctic Ocean surface temperatures

Temperature in °C

Source : NOAA, 2009.

Permafrost 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.



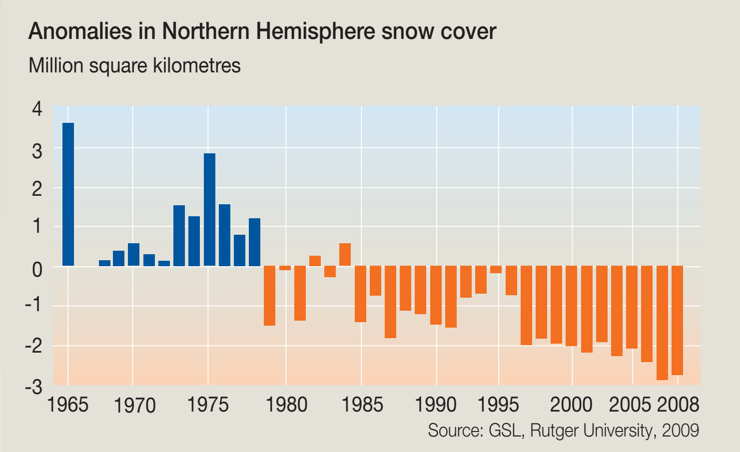
Permafrost at Deadhorse, Alaska

Temperatures at 20 metres depth (°C)

Source : US climate impacts report, 2009.

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, Rutger University, 2009

KEY FINDINGS OF THIS ASSESSMENT

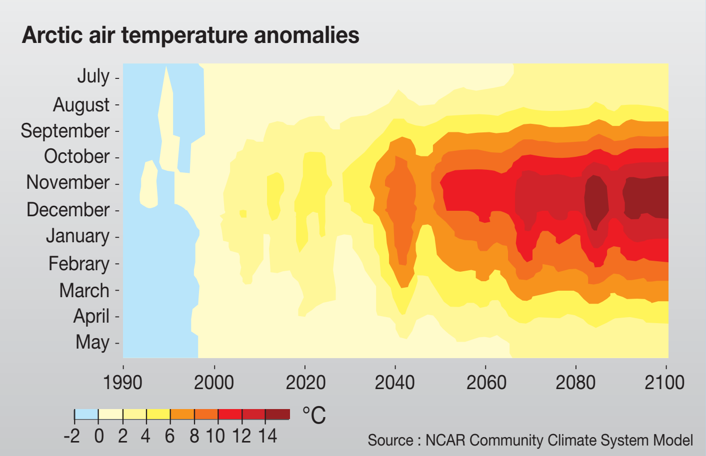
Amplification of global warming in the Arctic will have fundamental impacts on Northern Hemisphere weather and climate.

(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.



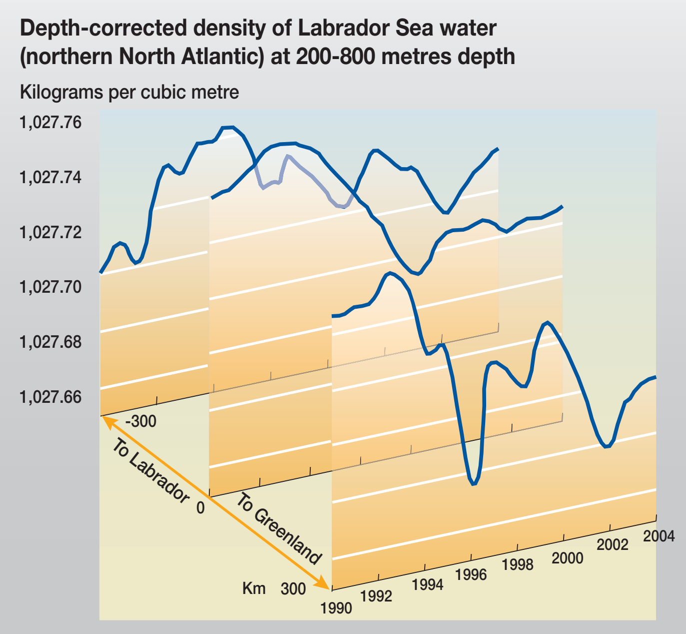
Source : NCAR Community Climate System Model

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.


Depth-corrected density of Labrador Sea water (northern North Atlantic) at 200-800 metres depth

Source: Yashayaev, 2007.

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.

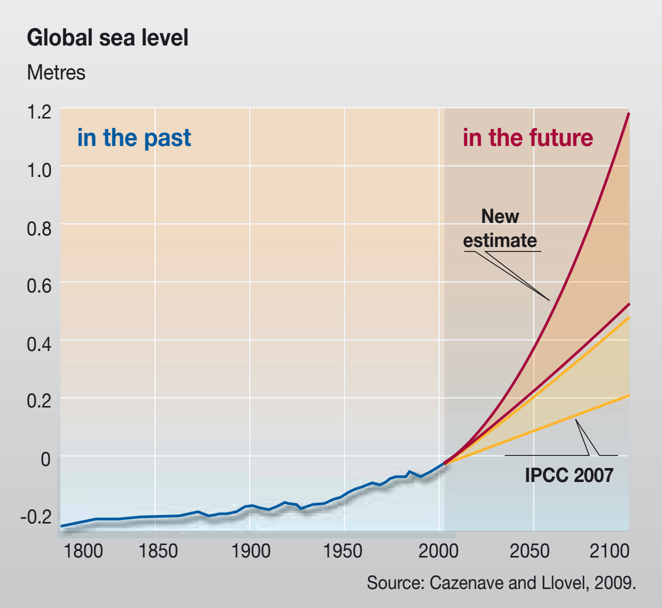
(Chapter 3, Ice Sheets and Sea-level Rise Feedbacks)

■ **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.



Source: Cazenave and Llovel, 2009.

■ **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.

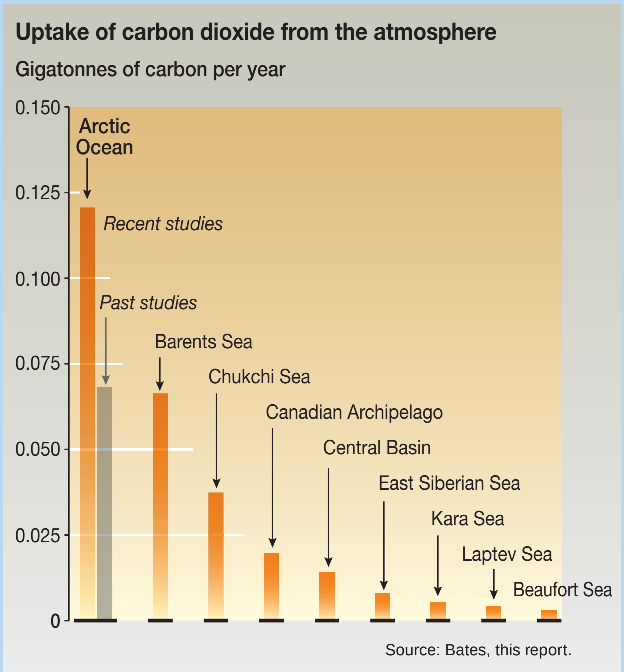
■ Arctic marine systems currently provide a substantial carbon sink but the continuation of this service depends critically on arctic climate change impacts on ice, freshwater inputs, and ocean acidification.

(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 marine plant (such as 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.



Source: Bates, this report.

■ **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 phytoplankton growth, ocean circulation and acidification, temperature effects, and river inputs, making projections uncertain.

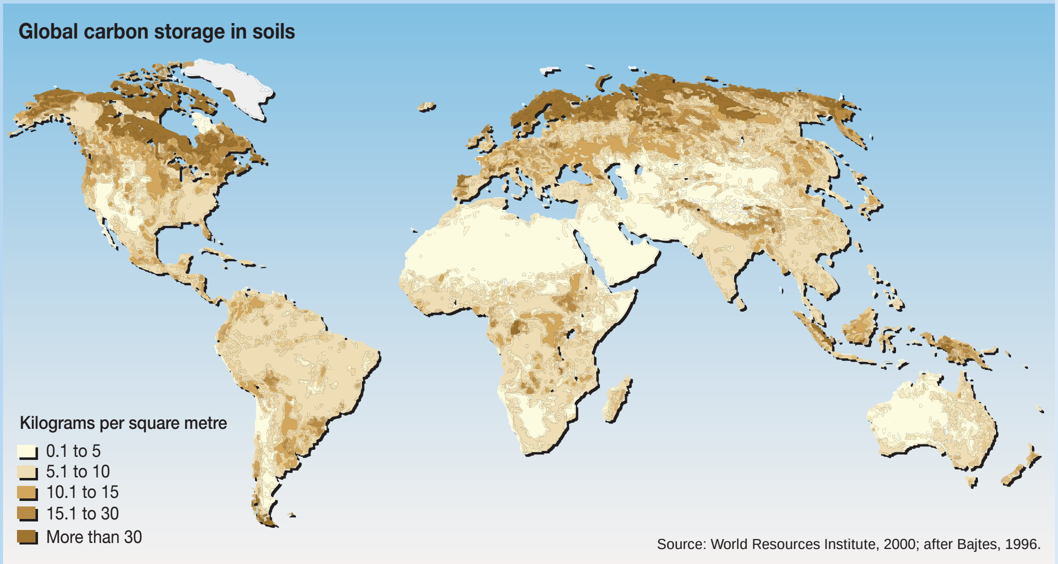
Arctic terrestrial ecosystems will continue to take up carbon, but warming and changes in surface hydrology will cause a far greater release of carbon.

(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.


Global carbon storage in soils

Source: World Resources Institute, 2000; after Bajtes, 1996.

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 destabilise when sub-sea permafrost thaws.

- **Thawing sub-sea permafrost is already releasing methane.** Current temperatures in the Arctic are 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 destabilised.** In addition, when methane hydrates destabilise, the methane within these hydrates increases tremendously in volume. The very high pressure that results may lead to abrupt methane bursts.

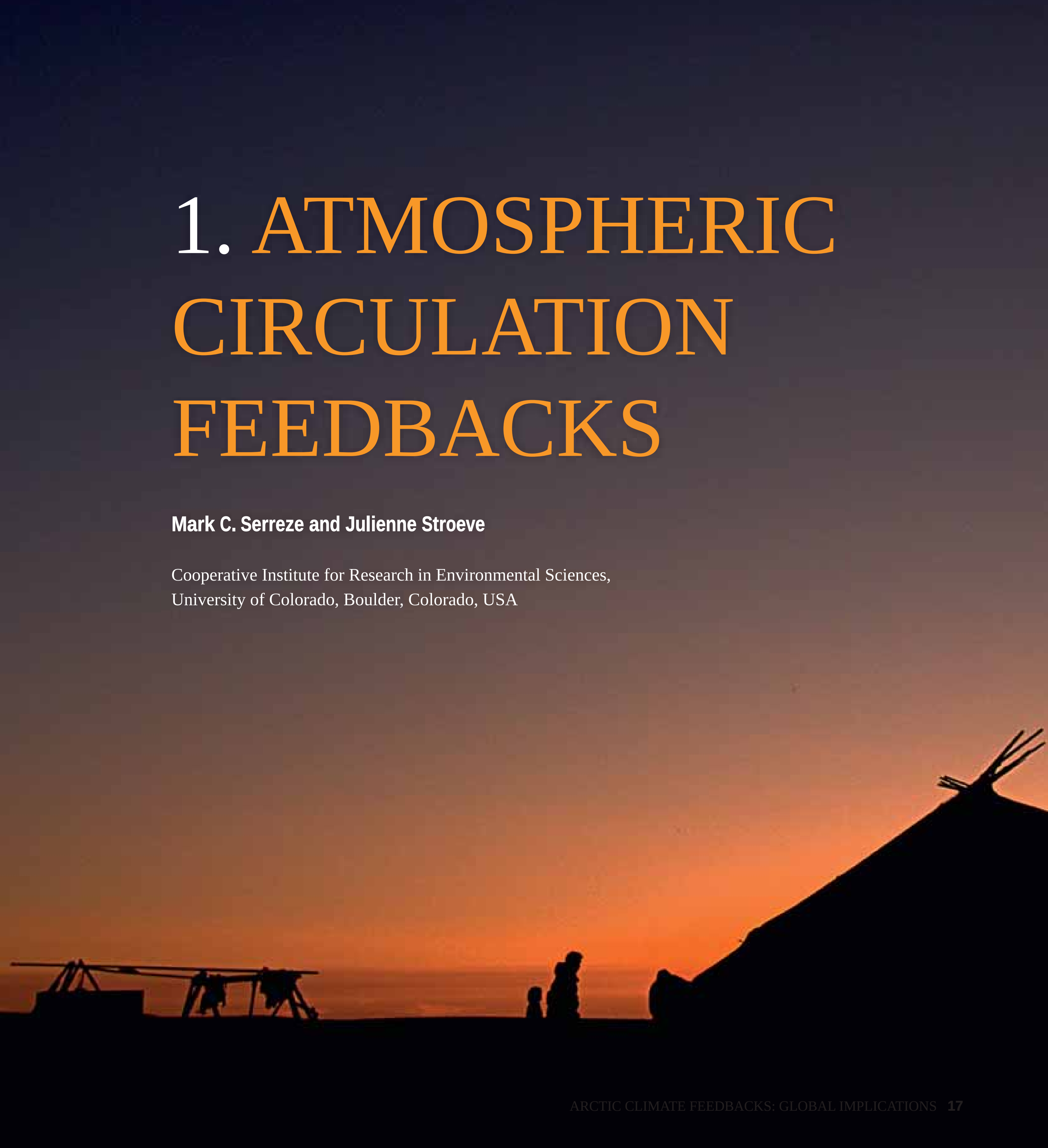
- **The most vulnerable hydrates are on the East Siberian Shelf.** The largest, shallowest, and thus most vulnerable fraction of methane deposits occurs on the East Siberian Shelf. Increased methane emissions above this shelf have been observed, but it is not yet known whether recent arctic warming is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

East Siberian Arctic Shelf contains the shallowest hydrate deposits, most vulnerable to release

Predicted hydrate deposits

Water depth less than 50 metres

Source: Soloviev et al., 2002 (top); Jakobsson et al., 2004 (bottom).



1. ATMOSPHERIC CIRCULATION FEEDBACKS

Mark C. Serreze and Julienne Stroeve

Cooperative Institute for Research in Environmental Sciences,
University of Colorado, Boulder, Colorado, USA

ONE OF THE MOST DRAMATIC CHANGES to the globe in recent decades has been the rapid decline of arctic sea ice. The consequences of this sea ice retreat for the global climate system are becoming increasingly understood. The decline of sea ice is amplifying warming in the Arctic, which in turn has major implications for temperature patterns over adjacent, permafrost-dominated land areas and for weather patterns across the Northern Hemisphere. These changes in weather patterns can have widespread impacts, affecting resources relied upon by society.

Key Findings

- **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 by altering the temperature gradient in the atmosphere and atmospheric circulation patterns in the Arctic and beyond. It may also affect temperature and precipitation patterns in Europe and North America. These changes will affect agriculture, forestry and water supplies.

Arctic sea ice and atmospheric circulation

Because of the Earth's orientation relative to the sun, the sun's rays strike the Earth's surface more directly at the equator than at the poles. The inequality in the amount of solar radiation received gives rise to a gradient in atmospheric temperatures, driving circulation of air in the atmosphere that transports heat from regions of low-latitude warmth to the cooler poles, heat which is then radiated to space (**Figure 1**)[1]. Much of this atmospheric heat transport is accomplished by the traveling low and high pressure systems associated with day-to-day weather that affects commerce and other human activities. Arctic sea-ice cover modifies the basic temperature gradients from the equator to the poles and hence the manner in which the atmosphere transports heat. Sea ice influences temperature gradients because of its high reflectivity and its role as an insulating layer atop the Arctic Ocean.

Arctic sea ice is at it maximum seasonal extent in spring, when it covers an area roughly twice the size of the continental United States. At this time, the reflectivity (albedo) of the freshly snow covered ice surface may exceed 80 per cent, meaning that it reflects more than 80 per cent of the sun's energy back to space and absorbs less than 20 per cent. The ice cover shrinks to about half of its spring size by September, the end of the melt season. While summer melting causes the albedo of the ice pack to decrease to about 50 per cent through exposing the bare ice and the formation of melt ponds, this is still much higher than that of the ocean and land areas, which may have albedos of less than 10 per cent. Furthermore, of the roughly 50 per cent of solar energy that is absorbed by the ice cover in summer, most is used

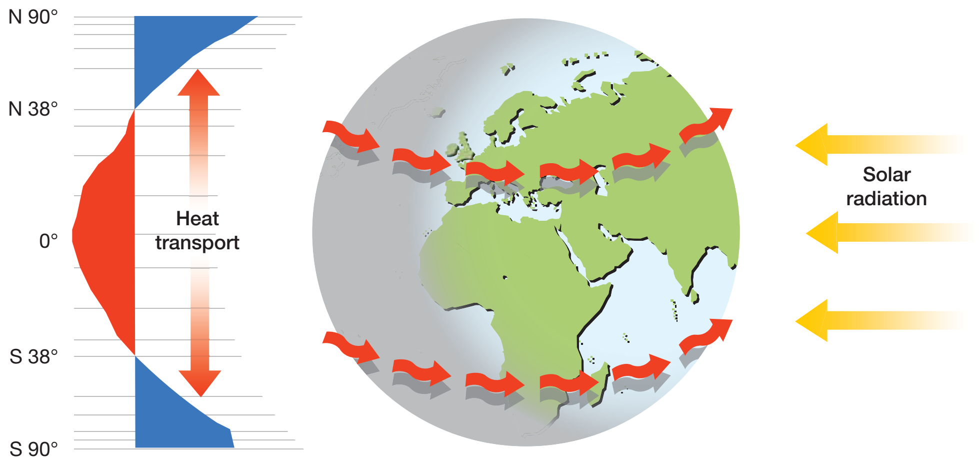


Figure 1. The sun's rays strike the surface more directly at low latitudes than at high latitudes, leading to an equator-to-pole gradient in the temperature of the atmosphere. This drives a circulation that transports heat toward the poles. Because of this transport, poleward of about 38º in each hemisphere, the Earth emits more radiation to space (as longwave, or heat radiation) than it receives from the sun as shortwave radiation. Much of the atmospheric heat transport is accomplished by weather systems travelling along the wavy jet streams of the middle and higher latitudes in each hemisphere (red arrows) [courtesy K.E. Trenberth, NCAR]

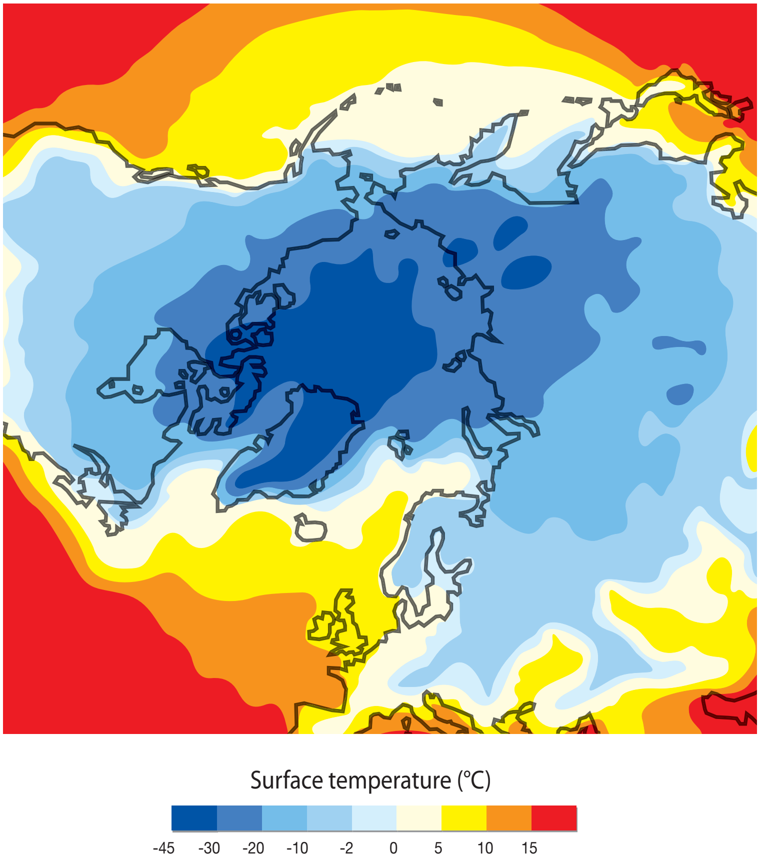


Figure 2. Surface temperatures averaged for November through March over the period 1979-1999. Strong horizontal temperature gradients in the extreme northern North Atlantic are linked to the location of the sea ice margin and cold Greenland Ice Sheet and affect the development of storms[5].

to melt ice, and the surface temperature of melting ice is fixed at the freezing point. From October through April, when there is little energy from the sun, sea ice acts as a very effective insulator, preventing heat in the Arctic Ocean from escaping upward and warming the lower atmosphere.

All of these properties of sea ice help to keep the Arctic's atmosphere cool. Without them, the atmospheric temperature gradient between the equator and the Arctic that drives weather systems would not be as strong as it is[2].

At the regional, ocean basin scale, the area between the insulating sea-ice cover and the open ocean (known as the ice margin) is characterized by particularly strong temperature gradients during winter (**Figure 2**), favoring the development of low pressure systems along the edge of the ice, as well as smaller, intense features known as polar lows that present hazards to shipping[3, 4, 5].

It follows that large changes in the distribution of arctic sea ice will affect patterns of atmospheric temperature and hence weather patterns. There is no question that ice cover is shrinking, and there is growing evidence that some of the anticipated impacts on the atmosphere have already emerged.

Observed sea ice trends

Sea-ice extent can be monitored year-round regardless of sunlight or cloud cover with satellite passive microwave sensors. Since the beginning of the modern satellite record in October 1978, the extent of arctic sea ice has declined in all months, with the strongest downward trend at the end of the melt season in September.

Since 2002, successive extreme minima in September ice extent have occurred, which have accelerated the rate of decline. Through 2001, the extent of September sea ice was decreasing at a rate of -7 per cent per decade. By 2006, the rate of decrease had risen to -8.9 per cent per decade. In September 2007, arctic sea ice extent fell to its lowest level recorded, 23 per cent below the previous record set in 2005, boosting the downward trend to -10.7 per cent per decade[6]. Ice extent in September 2008 was the second lowest in the satellite record. Including 2008, the trend in September sea ice extent stands at -11.8 per cent per decade[7] (**Figure 3**).

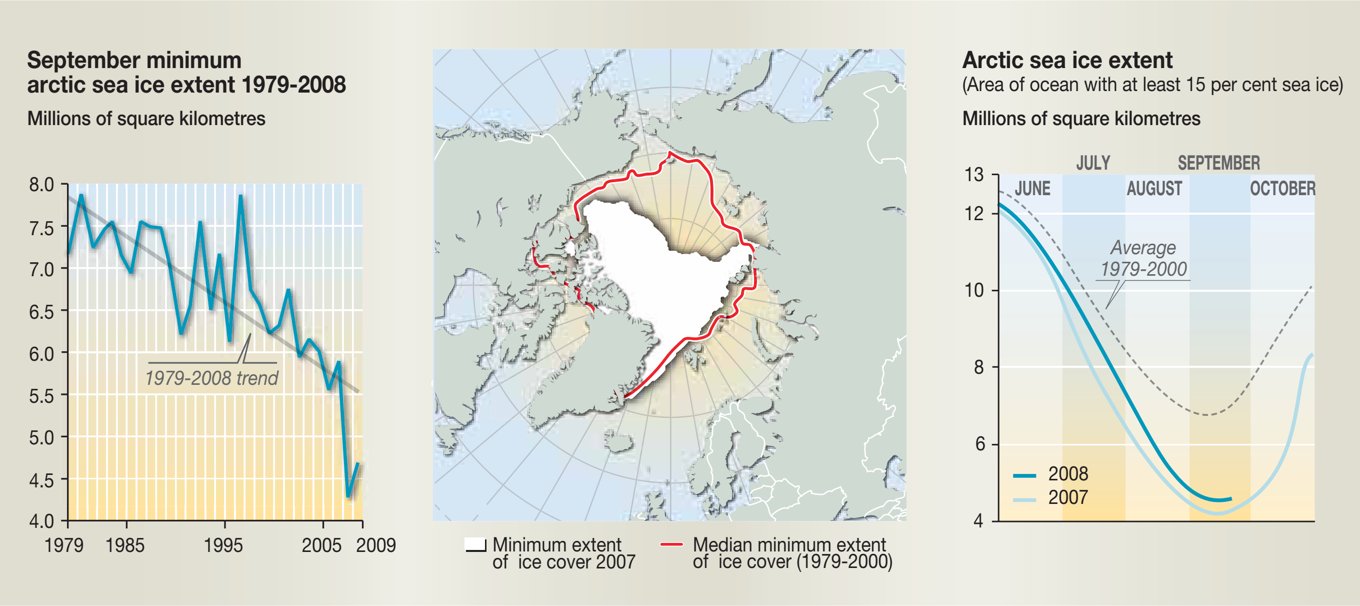
Compared to the 1970s, September ice extent has retreated by 40 per cent, an area roughly comparable to the size of the United States east of the Mississippi River.

The decreases in sea ice extent are best explained by a combination of natural variability (including changes in atmospheric and oceanic temperature and circulation) and rises in surface air temperatures linked to increasing concentrations of greenhouse gases in the atmosphere[8]. Climate models that incorporate the effects of greenhouse gas emissions from fossil fuel burning show declining September ice extent over the period of observations[7, 9, 10]. However, the model simulations mostly show smaller decreases in sea ice extent than has been observed. This argues that the models are too conservative and that ice-free summers might be realized as early as the 2030s[7, 11].

Reduced sea ice amplifies warming

Impacts of sea ice loss on atmospheric circulation can be linked to the anticipated stronger rise in arctic air temperatures compared to warming in middle latitudes, a process termed polar or arctic amplification[12, 13]. As atmospheric concentrations of greenhouse gases climb, the summer sea ice melt season will continue to lengthen and intensify, leading to less sea ice at the end of the summer. The retreat of the ice allows the dark, low-albedo ocean to readily absorb the sun's energy, increasing the summer heat content in the top 50 metres of the ocean (known as the mixed layer) (see *Ocean Circulation Feedbacks* chapter), which also further accelerates ice loss. Ice formation in autumn and winter, which is important for insulating the warm

Figure 3. Map: Median sea ice extent (1979-2000) at the date of the seasonal minimum (red line) and on 16 September 2007 (white area) when ice extent was 4.13 million square kilometres. **Left graph:** Monthly averaged September sea ice extent from 1979 to 2008**. Right graph:** Time series of ice extent from 1 June to 24 September 2008 (dark blue line), and through end of October 2007 (light blue line), and average 1979-2000 (dotted line). Data from National Snow and Ice Data Center, USA.



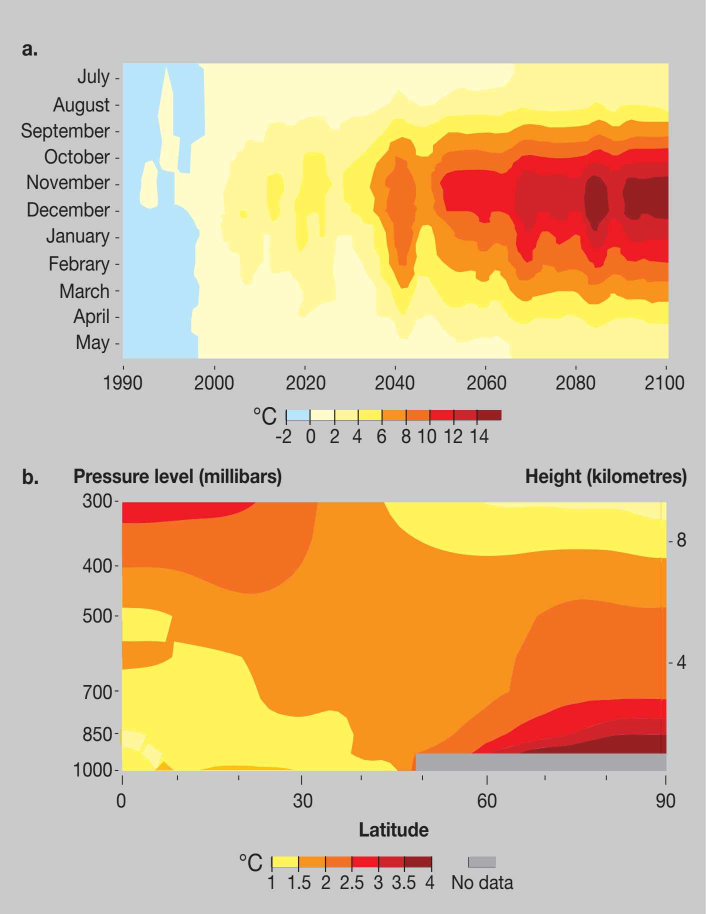


Figure 4. Depictions from the NCAR CCSM3 global climate model of: (a) near surface (2 metre) temperature deviations by month and year over the Arctic Ocean; (b) latitude by height plot of October-March temperature deviations for 2050-2059. Deviations are relative to 1979-2007 average. The simulation uses the IPCC A1B emissions scenario for this century and observed greenhouse gas concentrations for the 1990s[13].

ocean from the cooling atmosphere, is delayed. This allows for a large upward heat transfer from the ocean to the atmosphere. Simply phrased, the insulating effect of the ice that keeps the arctic atmosphere cool becomes less effective with time and the atmosphere warms significantly as a result.

Arctic amplification depicted from one of the climate models participating in the Intergovernmental Panel on Climate Change Fourth Assessment Report (IPCC 2007) is summarized in **Figure 4**. The pattern of cold-season warming over the Arctic Ocean growing with time is obvious. The high-latitude warming becomes stronger from the lower troposphere (the lower part of the atmosphere) toward the surface, a pattern that in this model simulation emerges by the decade 2020-2029 and grows in prominence with time. An analysis of 16 different climate models participating in the IPCC 2007 reveals consistency in the basic seasonality and vertical structure of warming over this century, but with different timings, magnitudes and spatial patterns of change[14]. This, in part, reflects model-to-model scatter in rates and spatial patterns of ice loss through the end of this century[8, 9, 10]. Other contributing factors include differences in patterns of atmospheric heat transport, vertical mixing, and effects of clouds and water vapor. Through transport by atmospheric circulation, warming associated with the loss of the summer arctic sea ice is likely to spread over high-latitude land areas (**Figure 5**), hastening degradation of permafrost that is likely to lead to the release of carbon presently locked in frozen solids, and thus further global warming[15] (see *Land Carbon Cycle Feedbacks* chapter).

"Arctic amplification is already occuring. Autumn Arctic Ocean surface air temperatures have increased 3 to 5°C higher in recent years."

Heating the atmosphere over the Arctic Ocean through a considerable depth will alter both the change in temperature with elevation (the atmosphere's static stability) and the gradient of atmospheric thickness from the equator to the poles. Atmospheric thickness is the separation, in metres, between two adjacent pressure levels in the atmosphere, and it increases with increasing atmospheric temperature. The weaker the thickness gradient toward the poles, the weaker the vertical change in wind speed (known as wind shear). As the arctic atmosphere warms, the thickness gradient between the poles and the equator will decrease. Taken together, these changes will affect the development, tracks and strengths of weather systems, and the precipitation that they generate.

An analysis of atmospheric data sets[16, 17] reveals that anticipated arctic amplification is already occurring[14]. Consistent with recent extreme September sea ice minima, Arctic Ocean surface air temperatures are 3 to 5°C higher in autumn (October to December) for 2002 to 2007 compared to the 1979-2007 average. The warming extends through a considerable height of the atmosphere and, while centred over the areas of ice loss, also influences adjacent land and ocean areas.

Weather patterns are altered

The expected and observed decline of summer sea ice extent will affect heating in the lower atmosphere and, as a result, atmospheric circulation. These changes will influence temperature and precipitation patterns that affect transportation, agriculture, forestry and water supplies.

> **“The additional warming in the Arctic will alter atmospheric circulation and, through it, weather patterns, affecting transportation, agriculture, forestry, and water supplies.”**

Observational evidence for responses of atmospheric circulation to declining ice extent is just beginning to emerge. Varying summer ice conditions can be associated

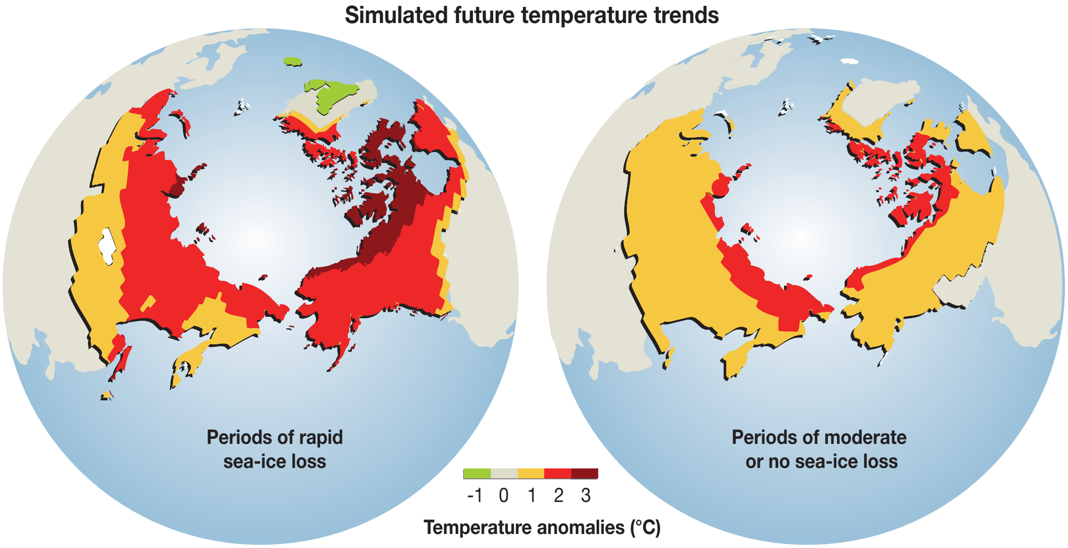


Figure 5. Expected surface air temperature trends associated with periods of rapid sea ice loss (left) and moderate or no ice loss (right) during this century. Rapid ice loss promotes strong warming over the Arctic Ocean, but atmospheric circulation spreads the heat out to influence land areas, potentially leading to thawing of permafrost and release of stored carbon to the atmosphere. Results are based on a simulation with the NCAR CCSM3 model[14].

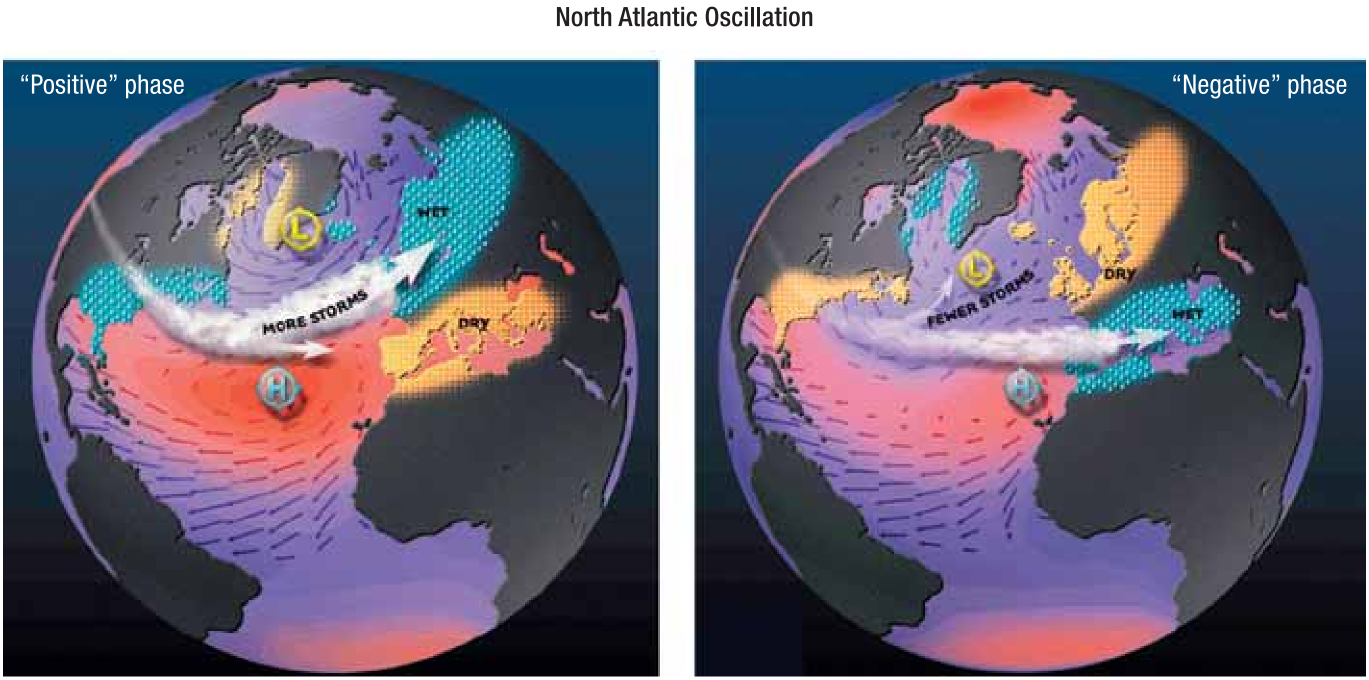


Figure 6. The “positive” (**left**) and “negative” (**right**) phases of the North Atlantic Oscillation (NAO) and anomalies in precipitation. In the positive NAO phase, the Icelandic Low (marked L) and Azores High (marked H) are both strong. Westerly winds between the two pressure centres are strong (winds indicated by arrows), bringing storms and wet conditions into northern Europe; southern Europe is drier than normal. In the negative phase of the NAO, both pressure centres are weaker, and the storm track is shifted south. Northern Europe is drier than normal, while southern Europe is wetter than normal [courtesy http://www.ldeo.columbia.edu/res/pi/NAO/].

with large-scale atmospheric anomalies (deviations from the average) during the following autumn and winter that extend beyond the boundaries of the Arctic[18]. The autumn sea level pressure fields following summers with less arctic sea ice extent exhibit higher pressures over much of the Arctic Ocean and North Atlantic, compensated by lower pressures in middle latitudes. The pattern in the North Atlantic is similar to what is known as the negative phase of the North Atlantic Oscillation (NAO).

The NAO describes a correlation in the strengths of the Icelandic Low (the semi-permanent low pressure cell centred near Iceland) and the Azores High (the semi-permanent high pressure cell centred near the Azores) — the major atmospheric “centres of action” in the North Atlantic. When both centres are strong (a deep low and a strong high), the NAO is in its positive phase. When both centres are weak (a shallow low and a weak high), the NAO is in its negative phase (**Figure 6**).

Changes in the NAO are tied to shifts in storm tracks and associated patterns of precipitation and temperature[19]. During the positive NAO phase (when both centres are strong), dry conditions typically occur over much of central and southern Europe and the Mediterranean, while stormier, wetter than normal weather conditions occur over Northern Europe. Temperatures in northern Eurasia tend to be above normal, and temperatures in northeastern North America tend to be below average. During negative NAO phases, the precipitation and temperature deviations are roughly reversed.

NAO phase	**North Atlantic storm track**	**Northern Europe**	**Southern Europe**	**Canada**	**Northeastern North America**
"Positive"	More northerly	Warmer and wetter than normal	Drier than normal	Cooler than normal	Cooler than normal
"Negative"	More southerly	Cooler and drier than normal	Wetter than normal	Warmer than normal	Warmer than normal

However, it is difficult from observations to unambiguously isolate circulation responses to declining ice extent from other factors. In recognition, the past decade has seen a growing number of studies addressing circulation responses to altered arctic sea conditions using climate models. The basic approach is to essentially tell the climate model what the sea ice conditions are (ice conditions are "prescribed") and then examine how the atmosphere responds to the prescribed conditions. Comparisons between simulations with one set of prescribed ice conditions (e.g., observed extent for the late 1900s) and another (e.g., expected ice extent by the end of this century), while keeping other factors, such as greenhouse gas concentrations, the same, isolates the effect of changing the ice[20].

While a more negative NAO phase with reduced winter ice extent finds support in a number of modeling experiments [21, 22, 23, 24], this is by no means a universal finding. One study finds that altered sea ice conditions in the Pacific sector (specifically in the Sea of Okhotsk) leads to a significant atmospheric response not only locally in the Sea of Okhotsk, but extending downstream over the Bering Sea, Alaska, and North America, with consequent changes in precipitation and temperature[25]. While another recent effort[26] concludes that parts of the Arctic and Europe may experience greater precipitation as the Arctic transitions toward a seasonally ice-free state; yet another emphasizes less rainfall in the American West[27]**.** A comprehensive study showed that although the loss of sea ice is greatest in autumn, winter is likely to see the strongest responses in temperature and precipitation. Snow depths may increase over Siberia and northern Canada because of increased precipitation[19]. Warming on land is mainly a result of warm air transport from the Arctic Ocean open-water areas.

> **"The transition to a seasonally ice-free Arctic may occur sooner than previously thought, affecting weather and precipitation patterns sooner than anticipated."**

Summary

Arctic sea ice extent is declining in all months, with the strongest downward trend observed for the end of the melt season in September. Since the observed September trend exceeds that in simulations from most current global climate models, the transition to a seasonally ice-free Arctic may occur sooner than previously thought, affecting weather and precipitation patterns sooner than anticipated.

Today, amplified atmospheric warming in autumn over the Arctic Ocean is already evident, and this warming extends through a through a considerable depth of the atmosphere. Changes in the temperature structure of the arctic atmosphere are expected to become more pronounced in coming decades as the Arctic Ocean continues to lose its summer sea ice cover. These include alterations in static stability (the change in the atmosphere's temperature with height), the poleward gradient in atmospheric thickness and the vertical change in wind speed (wind shear). These changes will invoke responses in atmospheric circulation. While there is no universal consensus regarding the spatial patterns of change that will emerge, a common thread between different modeling studies is that changes may be significant and affect areas well beyond the boundaries of the Arctic.

References

1 Trenberth, K.E., J.T. Fasullo and J. Kiehl 2009. Earth's global energy budget. *Bull. Amer. Meteor. Soc*. 90: 311-323.

2 Serreze, M.C., A.P. Barrett, A.J. Slater, M. Steele, J. Zhang and K.E. Trenberth 2007. The large-scale energy budget of the Arctic. *J. Geophys. Res.* 112: D11122, doi:10.1029/2006JD008230.

3 Shapiro, M.A., L.S. Fedor, and T. Hempel 1987. Research aircraft measurements of a polar low over the Norwegian Sea, *Tellus*,*Ser. A,* 39: 272-306.

4 Deser, C., J.E. Walsh and M.S. Timlin 2000. Arctic sea ice variability in the context of atmospheric circulation trends. *J. Climate* 13: 617-633.

5 Tsukernik, M., D.N. Kindig and M.C. Serreze 2007. Characteristics of winter cyclone activity in the northern North Atlantic: Insights from observations and regional modeling, *J. Geophys. Res.* 112: D03101, doi:10.1029/2006JD007184.

6 Stroeve, J., M. Serreze, S. Drobot, S. Gearheard, M. Holland, J. Maslanik, W. Meier, and T. Scambos 2008. Arctic sea ice extent plummets in 2007. *EOS Trans. AGU* 89(2): 13-14.

7 National Snow and Ice Data Center. Arctic Sea Ice News & Analysis. http://nsidc.com/news/press/20081002_seaice_pressrelease.html

8 Stroeve, J., Holland, M.M., Meier, W., Scambos, T., and Serreze, M. 2007. Arctic sea ice decline: Faster than forecast, *Geophys. Res. Lett.* 34: L09501, doi:10.1029/2007GL029703.

9 Zhang, X. and Walsh, J.E.: Toward a seasonally ice-covered Arctic Ocean 2006. Scenarios from the IPCC AR4 model simulations. *J. Climate* 19: 1730-1747.

10 Arzel, O., Fichefet T., and Goose, H 2006. Sea ice evolution over the 20th and 21st centuries as simulated by current AOGCMs, *Ocean Modeling* 12: 201-415.

11 Wang M., and J.E. Overland 2009. A sea ice free summer Arctic within 30 years?, *Geophys. Res. Lett.* 36: L07502, doi:10.1029/2009GL037820.

12 Holland, M.M., and C.M. Bitz 2003. Polar amplification of climate change in coupled models. *Clim. Dynam.* 21: 221-232.

13 Serreze, M.C., and J. Francis 2006. The Arctic amplification debate. Climatic Change, doi:10.10007/s10584-005-9017.

14 Serreze, M.C., A.P. Barrett, J.C. Stroeve, D.N. Kindig and M.M. Holland 2009. The emergence of surface-based Arctic amplification, *The Cryosphere* 3: 11-19.

15 Lawrence, D.M., A.G. Slater, R.A. Tomas, M.M. Holland and C. Deser 2008. Accelerated Arctic land warming and permafrost degradation during rapid sea ice loss. *Geophys. Res. Lett.* 35: L11506, doi:10.1029/2008GL033985.

16 Kalnay, E. et al. 1996. The NCEP/NCAR 40-year reanalysis project. *Bull. Amer. Meteor. Soc.* 77: 437-471.

17 Onogi, K., Tsutsui, J., Koide, H., Sakamoto, M., Kobayashi, S., Hatsushika, H., Matsumoto, T., Yamazaki, S., Kamahori, H., Takahashi, K., Kadokura, S., Wada, K., Kato, K., Oyama, R., Ose, T., Mannoji, N., and Taira, R. 2007. The JRA-25 reanalysis. *J. Met. Soc. Japan* 85: 369-432.

18 Francis, J.A., W. Chan, D.J. Leatehrs, J.R. Miller and D.E. Veron 2009. Winter Northern Hemisphere weather patterns remember summer Arctic sea ice extent. *Geophys. Res. Lett.* 36: L07503, doi:10.1029/2009GL037274.

19 Hurrell, J.W. 1995. Decadal trends in the North Atlantic Oscillation: Regional temperatures and precipitation. *Science* 269: 676-679.

20 Deser, C., R. Thomas, M. Alexander, and D. Lawrence 2009. The seasonal atmospheric response to projected Arctic sea ice loss in the late 21st century. *J. Climate* (in press).

21 Alexander, M.A. . U.S. Bhatt, J.E. Walsh, M.S. Timlin, J.S. Miller and J.D. Scott 2004. The atmospheric response to realistic Arctic sea ice anomalies in an AGCM during winter. *J. Climate* 17: 890-905.

22 Deser, C., G. Magnusdottir, R. Saravanan, and A. Phillips 2004. The effects of North Atlantic SST and sea ice anomalies on winter circulation in a GCM, Part II: Direct and indirect components of the response, *J. Climate* 17: 877-889.

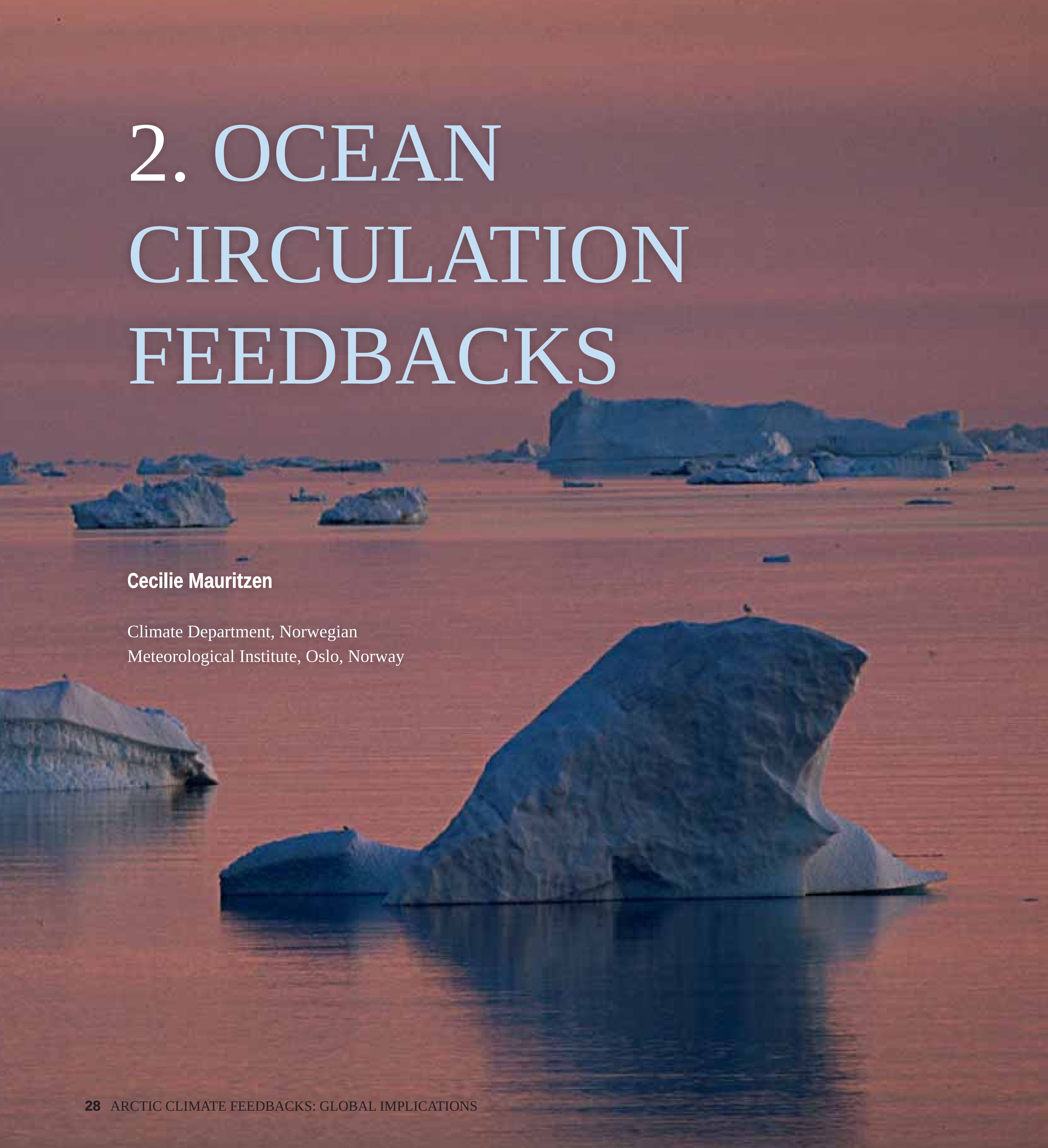
23 Magnusdottir, G., C. Deser, and R. Saravanan 2004. The effects of North Atlantic SST and sea ice anomalies on the winter circulation in CCSM3, Part I: Main features and storm track characteristics of the response. *J. Climate* 17: 857-876.

24 Seierstad, I.A. and J. Bader 2008. Impact of a projected future Arctic sea ice reduction of extratropical storminess and the NAO. *Climate Dynamics* doi10.1007/s00382-008-0463-x.

25 Honda, M., K. Yamazaki, H. Nakamura, and K. Takeuchi 1999. Dynamic and thermodynamic characteristics of atmospheric response to anomalous sea ice extent in the sea ice Okhotsk. *J. Climate* 12: 3347-3358.

26 Singarayer, J.S., J.. Bamber, and P.J. Valdes 2006. Twenty-first century climate impacts from a declining Arctic sea ice cover. *J. Climate* 19: 1109-1125.

27 Sewall, J.O., and L.C. Sloan 2004. Disappearing Arctic sea ice reduces available water in the American west. *Geophys. Res. Lett.* 31: doi:10.1029/2003GL019133.



2. OCEAN CIRCULATION FEEDBACKS

Cecilie Mauritzen

Climate Department, Norwegian
Meteorological Institute, Oslo, Norway

IN THE PAST, CHANGES IN OCEAN CIRCULATION have had wide-ranging impacts, including altering fisheries, weather patterns, and global air temperature. It is, therefore, not surprising that the potential for a significant change in global ocean circulation is considered one of the greatest threats to Earth's climate: It presents a possibility of large and rapid change, even more rapid than the warming resulting directly from the build-up of human-induced greenhouse gases in the atmosphere. And changes in ocean circulation are likely to cause societal impacts such as changes in access to important resources. For example, the El Niño phenomenon in the tropical Pacific Ocean has wide-ranging influences affecting local fisheries, regional weather patterns that span the Americas, and even global temperature; the warmest year so far was 1998, a record El Niño year.

Key Findings

- **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.

Changes in ocean circulation matter to people

Ocean circulation likely played a role in rapid climate change in the past. During the Younger Dryas cold spell (about 12,000 years ago, when the Earth was coming out of the last ice age), the Earth was warming up, and then suddenly, within a few decades, the global temperature dropped. During that period, indirect evidence indicates that the deep ocean circulation was reduced. The leading explanation is that as the great ice-age glaciers melted, a large inland meltwater lake built up on the North American continent, dammed by the glacier around the edges. When the glacier dam broke, freshwater flooded the North Atlantic, preventing the ocean from delivering heat to higher latitudes efficiently. As a result, the global air temperature probably went down by several degrees, and remained this way for more than a thousand years.

Such a dramatic change in ocean circulation has not been seen in recent history, but smaller ocean circulation changes are assumed to be involved in important periods like the medieval warm period (about 800-1300 AD) and the little ice age (about 1400-1800 AD), in combination with other effects such as volcanic eruptions and changes in the amount of energy the Earth receives from the sun. These periods involved global temperature anomalies of less than a degree, yet the consequences, at least in Atlantic sector, were staggering.

Ocean circulation can affect climate on even shorter timescales: Most climate models display large variability in the atmospheric temperature record on 5 to 10 year timescales, without any direct forcing mechanism that can explain it. It is likely that the ocean is actively contributing to setting these timescales, through releasing and taking up heat. The ocean is the largest storehouse of heat on Earth, and no other system has such a large amplitude in heat storage variability. These swings can confound the understanding and attribution of climate change, which is a good reason why climate is generally considered on timescales of 25 years and longer.

As discussed in the chapter on *Atmospheric Circulation Feedbacks*, changes in the Arctic can disturb the global atmospheric energy balance. By changing the atmospheric circulation in other places on Earth (for instance over the Indian and Pacific Oceans) the changing Arctic can indirectly modify ocean circulation in these remote places.

But there is a much more direct way in which the changing Arctic can modify the ocean circulation globally: through changes in its density structure (determined by temperature and salinity patterns). The most important Arctic contribution to climate, the ice-albedo feedback (see chapter on *Atmospheric Circulation Feedbacks*), contributes to this: as snow and ice melt into the ocean, freshwater is added and

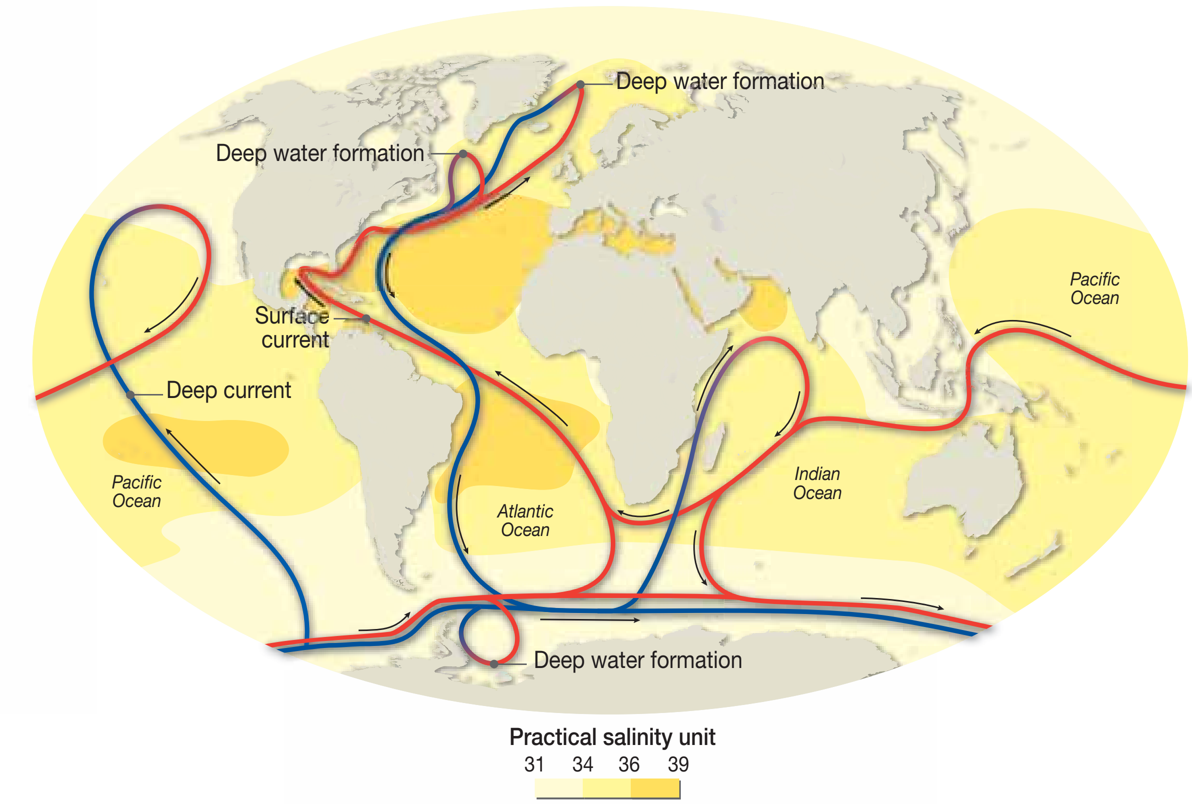
> **"If the large-scale ocean circulation is disturbed by processes altering heat and salinity in the Arctic Ocean, the consequences may be felt worldwide."**

the ocean water in those areas becomes less salty. When density changes, ocean circulation is altered.

The Arctic Ocean (**Figure 1**) experiences much less exchange with the atmosphere than other oceans; momentum exchange (wind drag), heat exchange and freshwater exchange are limited due to the sea ice cover. Nevertheless, there is vigorous circulation at all depths of the Arctic Ocean, starting with the ice-driven transpolar drift near the surface (circulating from the Pacific toward the Atlantic), beneath which the circulation is around the pole and counter-clockwise. The deeper circulation is not directly forced in the Arctic Ocean (it cannot, since it doesn't interact with the air-ice-sea interface in the Arctic) and results only as a consequence of the global nature of large-scale ocean circulation.

And precisely this global nature of large-scale ocean circulation gives rise to the most important avenue through which changes in the Arctic can affect the global ocean: If the large-scale ocean circulation is disturbed by processes altering heat and salinity in the Arctic Ocean, the consequences may be felt worldwide. The mechanism involved is the world-encompassing meridional overturning circulation (MOC) (**Figure 2**).

Figure 1. The Arctic Ocean



(1 psu = 1 gram of salt per kilogram of water)

Figure 2. In this schematic of the MOC, warm surface currents are shown in red, and cold deep currents are shown in blue. The surface currents are transformed to deep currents at high latitudes both in the South and in the North (adapted from NASA).

The Arctic Ocean connections are changing

The Arctic Ocean connects to the global ocean through the Nordic Seas and the Canadian Archipelago, which connect to the Atlantic Ocean, and through the Bering Strait, which connects to the Pacific Ocean. These connections will be affected differently in a warming climate.

The Pacific connection is quite shallow and brings water from the upper ocean in the Pacific into the Arctic. As the Pacific water warms, so do the inflowing waters. A warming layer of water in the Pacific Ocean (which began increasing in temperature in the early 1990s from a relative steady state from the 1950s to 1980s), is already affecting sea ice cover on the Arctic's Pacific side[1].

The Canadian Archipelago connection is almost as shallow as the Bering Strait, and brings upper-ocean arctic waters, as well as sea ice, out of the Arctic. As the sea ice cover shrinks and precipitation increases, more and more freshwater is exported to the Atlantic through this connection. An increase in liquid freshwater export through the archipelago during recent years has already been observed[2].

The Nordic Seas connections are the most complicated, because this is a much deeper and wider opening, which allows a much larger exchange of water with the Arctic than the other two connections. This opening allows the MOC to extend not only to the northern North Atlantic, but into the Arctic proper, filling a subsurface layer of relatively warm water between 100 metres and 800 metres depth. Like the Pacific inflow, this inflow of warm Atlantic water is warming, and a series of pulses of unusually warm water (anomalies sometimes larger than 1ºC) has been observed to propagate into the Arctic along the Eurasian continent since the early 1990s[3, 4, 5]. (**Figure 3**)

To balance the water budget, the Nordic Seas also export arctic waters. The return flow southward into the North Atlantic Ocean is very cold (typically less than 1ºC), which normally would make it very dense if it weren't for the other factor affecting the ocean's density: salt. Some of the cold return water is relatively salty, and therefore very dense. This dense return flow sinks to several thousand metres depth as soon as it passes the Greenland-Scotland Ridge (which is 860 metres at the deepest) and is part of the MOC. Some of the cold return flow is not very salty, and it is therefore not dense enough to sink as it passes the Greenland-Scotland Ridge. This return flow supplies the upper North Atlantic (the Labrador Sea) with less salty, cold polar waters.

The cold return waters are mainly a product of cooling and reducing the salinity of the northward-flowing warm Atlantic waters. The return flow from the Arctic Ocean proper exits in the Fram Strait and flows along the coast of Greenland, where it picks up return water from the Nordic Seas along the way. This current is referred to as the East Greenland Current. Like the Canadian Archipelago connection, this

The Meridional Overturning Circulation (MOC)

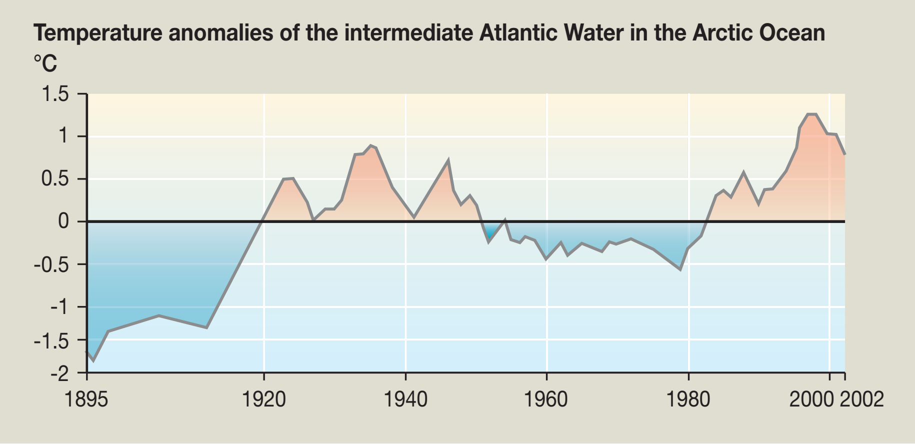
The sun heats the Earth more at the equator than at the poles, and the global-scale atmospheric and ocean circulations redistribute this heat, minimizing the temperature gradients. The meridional overturning circulation (MOC) is the main oceanic component of this system (**Figure 2**). Because the global ocean consists of connected ocean basins, the pathways of the MOC are more complicated than simply bringing warm surface waters from the equator toward the poles. For instance, in the South Atlantic, warm surface waters are brought toward and across the equator. These warm waters are eventually cooled in the North Atlantic, in particular in the Subpolar Gyre and the Nordic Seas, and return southward in the deep ocean. Some of these waters return to the surface already in the Atlantic Ocean, some return in the Southern Ocean, while some travel all the way to the northern Pacific Ocean before returning to the surface. The latter have been insulated from the atmosphere for hundreds of years.

The ocean is many thousands of metres deep (3,000 metres on the average), and the basins are thousands of kilometres wide. As a result, the strength of the MOC is measured in only a few key places, and there are no direct measurements of its long-term variability. The qualitative description of the MOC's pathways, however, goes back nearly a hundred years, based on the distinct differences in the temperature, salinity and oxygen content in the various water masses constituting the MOC. In order to maintain the Earth's current climate, the strength of the MOC must be somewhere between 15 and 30 million cubic metres per second.

While it was recognized more than 200 years ago that the oceans' cold subsurface waters originated at high latitudes[21], it wasn't suggested until the middle of the 1900s that the strength of the deep ocean circulation might be varying over time, or that the MOC may be important for Earth's climate. Since the 1950s, studies have revealed that changes in both temperature and salinity affect density and thereby ocean circulation, with the potential to change it radically. Models also revealed that the ocean circulation system appeared to be particularly vulnerable to changes in the freshwater balance, either by the direct addition of freshwater or by changes in the water cycle[22,23, 24, 25]. A strong case emerged for the hypothesis that rapid changes in the Atlantic MOC were responsible for rapid climate change in the past.

Even today the strength of the MOC has only been measured at a few places and for a very short time. Generally, inferences must be made about the strength of ocean circulation based on indirect evidence. For example, the strength of bottom currents is often inferred from the size of gravel and stones it moves. And the intensity of surface currents is often inferred from temperature. By analyzing ocean cores, paleo-oceanographers determine how ocean circulation changed in the past. The Younger Dryas cold spell is one of the periods in which there were likely large changes in deep ocean circulation. When freshwater flooded the North Atlantic after the ice dam broke, ocean circulation could have been affected in two ways: either by freezing at the surface, cutting off contact between the warm MOC and the atmosphere (similar to the situation in the Arctic Ocean today) or by changing the density of the MOC by adding freshwater such that the direction or strength of the MOC changed. Either way the bottom circulation would have changed, because the MOC itself would have changed. In the first case, because the cooling of the MOC would have stopped farther south and, as a result, the return flow would not have been quite as dense and therefore not as deep. And either way, the global air temperature would have dropped, because the heat loss from the ocean to the atmosphere would have been reduced significantly.

Figure 3. Temperature anomalies of the intermediate Atlantic Water in the Arctic Ocean[5].



export route is expected to carry more freshwater and sea ice as climate warms, but so far there is little indication that either is true[6, 7]. However, it appears that the 2007-2008 winter had unusually high ice export compared to the long-term average[8].

Global ocean circulation will not change abruptly, but it will change significantly, in this century

Since there are no long-term measurements of the MOC (see box *The Meridional Overturning Circulation*), the best assessment of its long-term variability is through model analysis. The long-term variability in sea surface temperatures in the Atlantic Ocean has been associated with small (less than 1 million cubic metres per second and not observable with current equipment) but persistent changes in the strength of the MOC over the course of decades[9]. The change is likely to become larger during this century.

The current melting of ice has been watched with great concern by oceanographers because the salinity of the North Atlantic has been decreasing for the last 50 years[10, 11, 12]. If the 1965-1995 rate of decrease were to continue for a hundred years, significant changes in ocean circulation would occur[12]. An event similar to the Younger Dryas cold spell is not likely to occur, because there are no large melt-water lakes currently building up in Greenland.

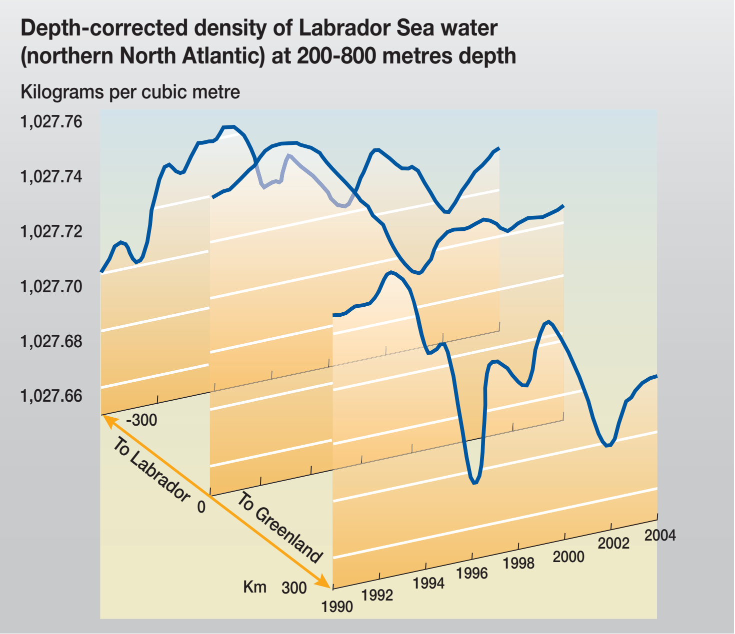
Since the mid-1990s, the salinity has been increasing rather than decreasing in the subpolar North Atlantic[13]**.** That is because hand-in-hand with the melting ice comes an increase in evaporation at lower latitudes and an increase in precipitation at higher latitudes. In a warmer climate, the water cycle speeds up, such that the resulting change in the North Atlantic is a product of increased salinity originating in the south and increasing freshwater content originating in the north.

Nevertheless, the ocean's density has continued to decrease (**Figure 4**) [14], just as it did in the 1960-1990 timeframe, because the temperature increase has been stronger than the salinity increase (higher temperature reduces ocean density whereas higher salt content increases ocean density). Since density is a more important factor than salinity for determining ocean circulation, it is realistic to assume that the MOC strength is already decreasing. Two observational studies suggest that the MOC is now weaker in strength than in 1992, with one study estimating a 30 per cent reduction by 2004[15] (note that this estimate is controversial) and another estimating a roughly 15 per cent reduction[16]. However, it should be noted that measuring the MOC is notoriously difficult (see box *The Meridional Overturning Circulation*).

It is also realistic to assume that the strength of the MOC will continue to decrease during this century and beyond as a consequence of climate change. IPCC 2007[17] global climate models consistently project a reduction in the MOC during this century (but not an abrupt collapse). The models diverge significantly in their estimates of MOC strength. This is likely related to the models themselves rather than to the emission scenarios. Using the A1B scenario, the IPCC models indicate, on average, a 25 per cent reduction in MOC strength during this century (**Figure 5**).

One consequence of the reduced MOC is a delayed warming in Atlantic sector. This delay is present in all the IPCC 2007 future scenario runs (see the "eye" in the North Atlantic in **Figure 6**) and becomes more pronounced toward the end of the century. Such a delay in warming could be a benefit to the ecosystems involved because the warming would occur more slowly, allowing more time to adjust. But the geographic range of this influence would be limited. It is not clear that continental Europe, for example, would benefit from this delay. It is also not obvious what other consequences the reduced MOC strength will have for the climate system, but it is very likely to have an impact on ecosystems and on the ocean's heat and carbon dioxide uptake.

Figure 4. Depth-corrected density of water in an upper layer (200-800 metres) of the Labrador Sea, northern North Atlantic[14].



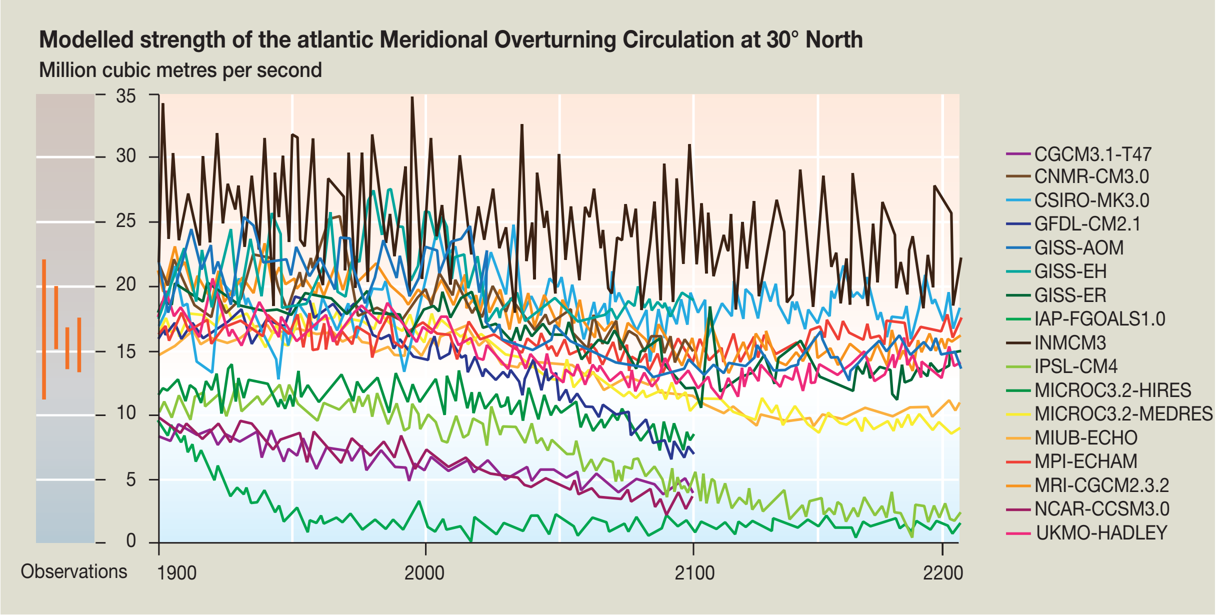


Figure 5. MOC strength in a suite of coupled climate models. IPCC 2007, WG1, Figure 10.15[18].

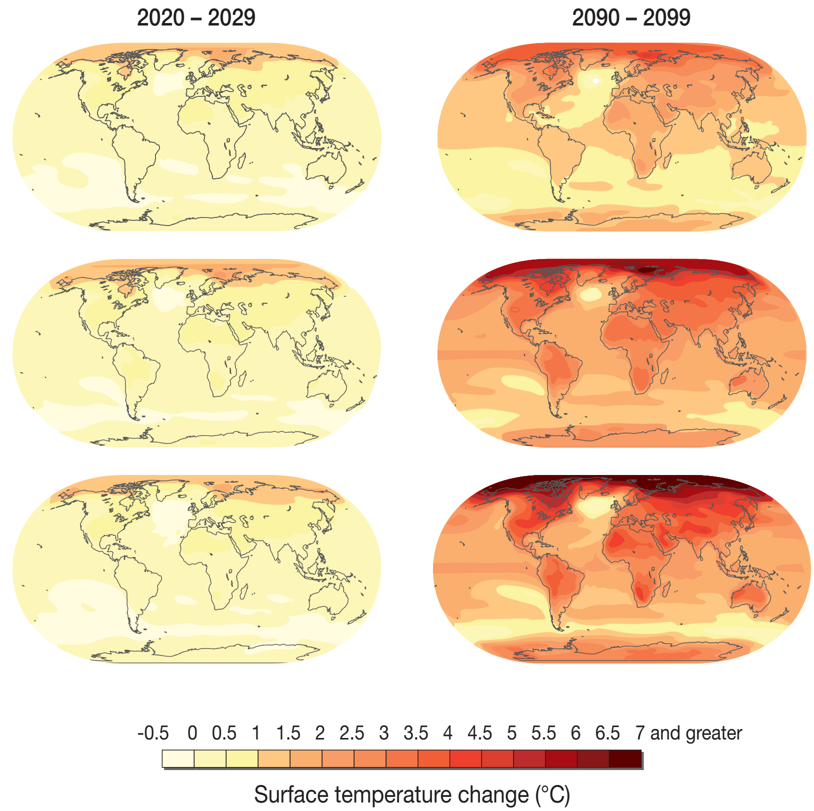


Figure 6. Projected surface temperature changes for the early **(left)** and late (**right**) part of this century relative to the period 1980–1999. The two panels show the multi-model average projections for the B1 **(top)**, A1B **(middle)** and A2 **(bottom)** SRES scenarios averaged over the decades 2020–2029 **(left)** and 2090–2099 **(right)**. IPCC 2007 WG1, Figure SPM.6[17].

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

Society is not only affected by a change in ocean circulation strength, but also by pathway changes. For example, when a nutrient-rich ocean current takes an unusual path far away from shore, the fish adjust by changing their migration patterns, affecting fisheries and other marine resources. Ocean pathway changes are possible as a consequence of arctic sea ice melting, because despite uncertainties, a consistent finding from climate models is that the reduced ice cover is likely to change the storm tracks across the North Atlantic Ocean (see chapter *Atmospheric Circulation Feedbacks*).

The position of the storm tracks over the North Atlantic Ocean affects weather and climate, ecosystems and human activities in the North Atlantic sector. Unusually cold winters over Europe and North America coinciding with unusually warmer winters over Greenland are associated with more southerly storm tracks, whereas the opposite happens during more northerly tracks. When such a situation persists for several years there is normally a significant ocean response: In the case of a southerly storm track, warmer than normal water builds up in the Subpolar Gyre, and the Gulf Stream runs on an unusually southerly track[19], a consequence that is likely to affect ocean ecosystems. In that case, the number of cod would likely increase in the Labrador Sea and decrease on the northern European side[20]. In the case of a northerly track, the situation would be the opposite.

> **“When a nutrient-rich ocean current takes an unusual path far away from shore, the fish adjust by changing their migration patterns, affecting fisheries and other marine resources.”**

References

1 Shimada, T. Kamoshida, M. Itoh, S. Nishino, E. Carmack, F. A. McLaughlin, S. Zimmermann, and A. Proshutinsky 2006. Pacific Ocean inflow: Influence on catastrophic reduction of sea ice cover in the Arctic Ocean. *Geophys. Res. Lett*. **33:** L08605, doi:10.1029/2005GL025624.

2 Våge, K. et al. 2008. Surprising return of deep convection to the subpolar North Atlantic Ocean in winter 2007–2008. *Nature Geosciences*; doi:10.1038/NGEO382.

3 Quadfasel, D. A., A. Sy, D. Wells, and A. Tunik 1991. Warming in the Arctic, *Nature* 350*:* 385.

4 Schauer, U., B. Rudels, E. P. Jones, L. G. Anderson, R. D. Muench, G. Björk, J. H. Swift, V. Ivanov, and A.-M. Larsson 2002. Confluence and redistribution of Atlantic water in the Nansen, Amundsen and Makarov basins. *Ann. Geophys*. 20: 257–273.

5 Polyakov, I. V. *et al.* 2005. One more step toward a warmer Arctic, *Geophys. Res. Lett*. 32**:** L17605, doi:10.1029/2005GL023740.

6 Edmond Hansen, Norw. Polar Inst., personal communication

7 Rabe, B., U. Schauer, A. Mackensen, M. Karcher, E. Hansen, and A. Beszczynska-Moller 2009. Freshwater components and transports in the Fram Strait – recent observations and changes since the late 1990s. *Ocean Sci.* 5: 219–233.

8 Smedsrud, L., Sorteberg, A. & Kloster, K. 2008. Recent and future changes of the Arctic sea-ice cover. *Geophys. Res. Lett*. 35: L20503.

9 Knight, J.R., et al. 2005. A signature of persistent natural thermohaline circulation cycles in observed climate. *Geophysical Research Letters* 32: doi:10.1029/2005GL024233.

10 Brewer, P. G., W. S. Broecker, W. J. Jenkins, P. B. Rhines, C. G. Rooth, J. M. Swift, and T. Takahashi 1983. A climatic freshening of the deep North Atlantic (north of 50° N) over the past 20 years. *Science* 222: 1237-1239.

11 Lazier, J.R.N. 1995. The salinity decrease in the Labrador Sea over the past thirty years. In: *Natural climate variability on decade-to-century time scales*, Martinson, D.G., K. Bryan, M. Ghil, M.M. Hall, T.M. Karl, E.S. Sarachik, S. Sorooshian and L. Talley (eds), National Academy Press, Washington D.C., 295-302.

12 Curry, R., C. Mauritzen 2005. Dilution of the northern North Atlantic Ocean in recent decades. *Science* 308 (5729): 1772-1774.

13 Hátún, H., A. B. Sandø, H. Drange, B. Hansen, and H. Valdimarsson 2005. Influence of the Atlantic Subpolar Gyre on the Thermohaline Circulation, *Science* 309: 1841-1844.

14 Yashayaev, I. 2007. Hydrographic changes in the Labrador Sea, 1960-2005. *Progress in Oceanography* 73: 242-276.

15 Bryden, H.L., et al. 2005. Slowing of the Atlantic meridional overturning circulation at 25ºN. *Nature* 438: 655-657.

16 Wunsch, C. and P. Heimbach 2006. Estimated Decadal Changes in the North Atlantic Meridional Overturning and Heat Flux 1993-2004. *J. Phys. Oceanogr.,* 36(11): 2012–2024, doi:10.1175/JPO2957.1.

17 IPCC (2007) Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 996 pp.

18 Schmittner, A., Latif, M. and Schneider, B. 2005. Model projections of the North Atlantic thermohaline circulation for the 21st century assessed by observations. *Geophysical Research Letters* 32: 10.1029/2005GL 024368.

19 Visbeck M.H., Chassignet E.P., Curry R.G., Delworth T.L., Dickson R.R., Krahmann G. 2003. The Ocean's Response to North Atlantic Oscillation Variability. In *The North Atlantic Oscillation-Climatic Significance and Environmental Impact*, Hurrell, J.W., Kushnir, Y., Ottersen G., Visbeck M. (ed.), American Geophysical Union, Washington D.C., 1-35.

20 Drinkwater K.F., Belgrano A., Conversi A., Edwards M., Greene C.H., Ottersen G., Pershing A.J., Walker H. 2003. The Response of Marine Ecosystems to Climate Variability Associated with the North Atlantic Oscillation. In *The North Atlantic Oscillation-Climatic Significance and Environmental Impact*, Hurrell, J.W., Kushnir, Y., Ottersen G., Visbeck M. (ed.), American Geophysical Union, Washington D.C., 1-35.

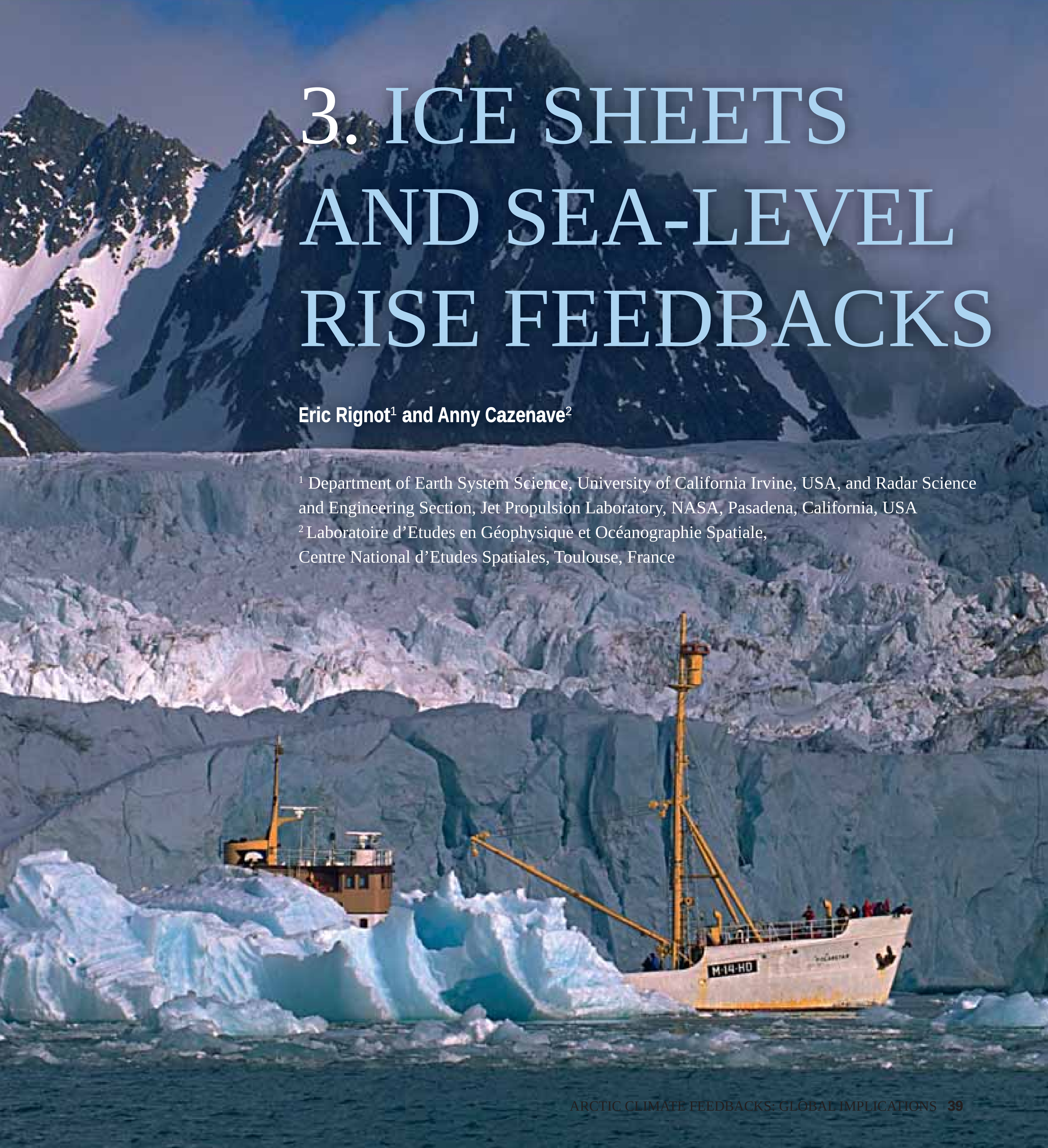
21 Warren, B.A. 1981. Deep circulation of the World Ocean. In *Evolution of Physical Oceanography*, MIT Press, 6-41.

22 Stommel, H. 1961. Thermohaline Convection with Two Stable Regimes of Flow. *Tellus* 13: 224-30.

23 Bryan, K., and M. J. Spelman 1985. The Ocean's Response to a CO2-Induced Warming. *J. Geophysical Research* 90 (11): 679-88.

24 Bryan, F.O. 1986. High latitude salinity effects and interhemispheric thermohaline circulations. *Nature*, 323: 301-304.

25 Manabe, S. and R.J. Stouffer 1988. Two Stable Equilibria of a Coupled Ocean-Atmosphere Model. *J. Climate* 1: 841-66.



3. ICE SHEETS AND SEA-LEVEL RISE FEEDBACKS

Eric Rignot[1] and Anny Cazenave[2]

[1] Department of Earth System Science, University of California Irvine, USA, and Radar Science and Engineering Section, Jet Propulsion Laboratory, NASA, Pasadena, California, USA
[2] Laboratoire d’Etudes en Géophysique et Océanographie Spatiale,
Centre National d’Etudes Spatiales, Toulouse, France

AFTER 3,000 YEARS OF LITTLE CHANGE, global average sea level has been rising over the past century as climate has warmed, with an increasing rate of rise in recent decades. As climate heats up, air and ocean temperatures rise, causing ocean water to expand, glaciers to melt, and making the ice of the ice sheets of Greenland and Antarctica melt faster into the oceans, raising sea level worldwide. There is enough ice in Greenland to raise global sea level by 7 metres and in Antarctica to raise sea level by 60 metres.

Key Findings

- **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 in 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 particularly at risk.

Sea level is a very sensitive index of climate change and variability. As the ocean warms in response to global warming, seawater expands and, as a result, sea level rises. When mountain glaciers melt in response to increasing air temperature, sea level rises because more freshwater glacial runoff discharges into the oceans. Similarly, ice mass loss from the ice sheets causes sea-level rise.

The increase of freshwater flowing into the oceans reduces its salinity, decreasing its density and affecting ocean circulation patterns that, in turn, affect sea level and how it varies from region to region.

Hence, local and regional climate changes affect sea level globally.

Arctic climate is of particular concern since it is a region where the strongest changes are expected in the future[1]. Current observations indicate that Arctic climate is changing faster than that of the rest of the world. Arctic climate change has already had a considerable effect on sea level through ice mass loss from the Greenland Ice Sheet, melting of glaciers in Alaska and on Svalbard, warming of the Arctic Ocean, thawing of permafrost in Siberia, and increased water input from arctic rivers.

> **"Arctic climate change has already had a considerable effect on sea level."**

Sea-level rise is accelerating

While the global average sea level had remained almost stable for the 3,000 years (following the approximately 120-metre sea-level rise associated with the last deglaciation), tide gauge measurements available since the late 1800s have reported significant sea-level rise during the 1900s, especially since 1950, increasing an average of 1.7 millimetres per year over the past 50 years[2, 3, 4]. Since early 1993, sea level variations have been accurately measured by satellite altimetry (Topex/Poseidon, Jason-1 and Jason-2 missions). This 15-plus year data set shows that average global sea level is currently rising at a rate of about 3.3 millimetres per year

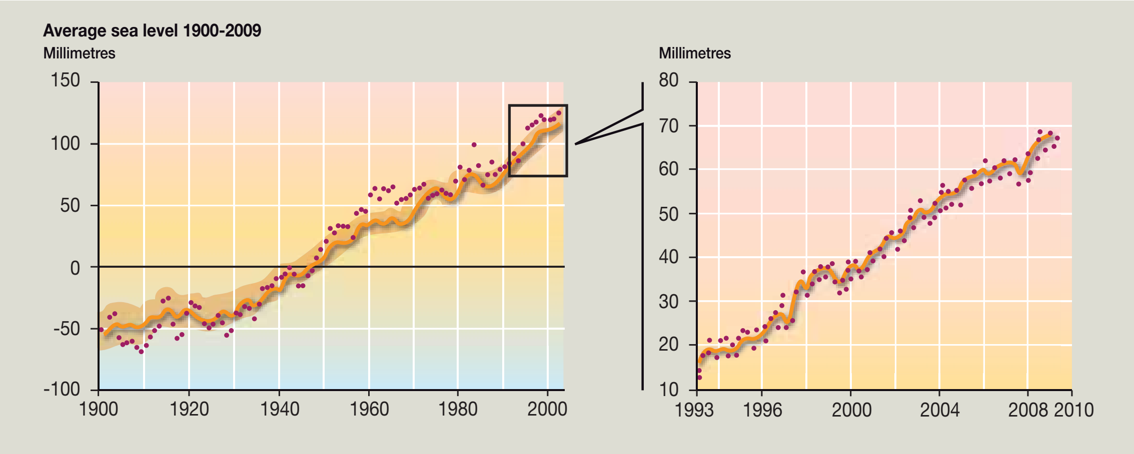


Figure 1. Change in average sea level during the 1900s from tide gauges (**left**)[2,4]. Global average sea level since 1993 measured by satellite altimetry (**right**)[7].

(plus or minus 0.4 millimetres)[4, 5, 6, 7], roughly twice the average rate recorded by tide gauges over the previous decades (**Figure 1**).

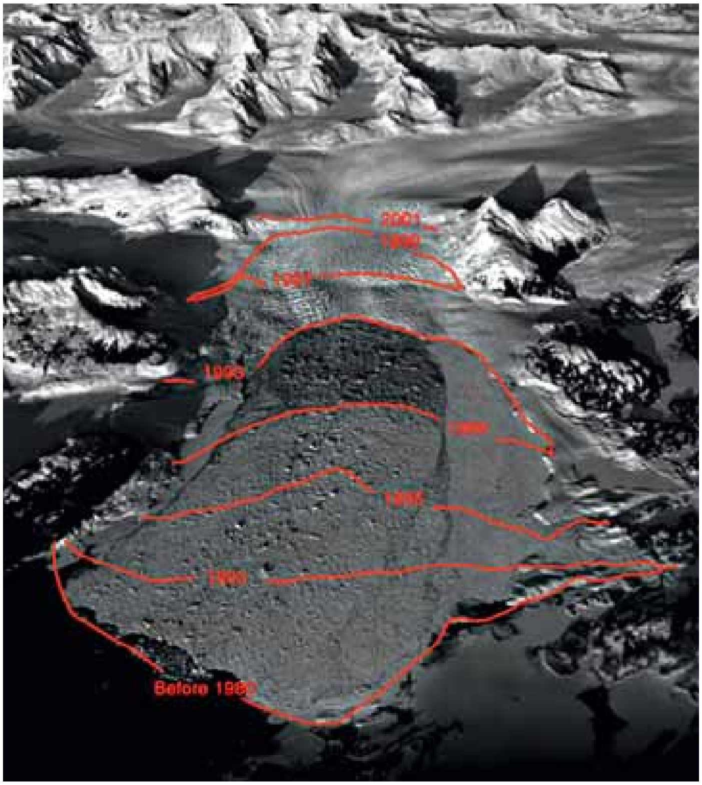
Ocean warming

Analyses of *in situ* ocean temperature data from the past 50 years, collected by ships and recently by profiling floats, indicate that ocean heat content, and hence ocean thermal expansion, has significantly increased since 1950. Ocean warming explains about 25 per cent of the observed sea-level rise of the last few decades[8, 9, 10]. This number is likely a lower bound, because of the lack of hydrographic data in remote regions of the Southern Hemisphere and in the deep ocean (below 1,000 metres)[8]. A steep increase in thermal expansion was observed during the decade 1993-2003. Since about 2003, the thermal expansion rate has decreased, but this likely reflects short-term natural variability rather than a new long-term trend. On average, over the period 1993 to 2008 (the satellite altimetry era), ocean warming has accounted for about 30 per cent of sea-level rise[9, 10].

Glaciers melting

Highly sensitive to global warming, mountain glaciers and small ice caps have retreated worldwide during the recent decades, with significant acceleration during the 1990s. From mass balance studies of a large number of glaciers, estimates have been made regarding the contribution of glacier ice melt to sea level[11, 12, 13]. For the period 1993 to 2008, melting glaciers and ice caps explain about 30 per cent of the observed sea-level rise, with melting glaciers in Alaska accounting for about one-third of this[11, 13] (**Figure 2**).

Figure 2. The recent retreat of the Columbia Glacier, Alaska.



History of Columbia retreat (R.M. Krimmel, USGS)


NASA

Columbia Glacier c. 1980


NASA

Columbia Glacier 2005

The ice sheets are losing mass

As climate heats up, air and ocean temperatures rise, the melting of ice at the surface of the Greenland Ice Sheet increases, and glaciers flow faster to the ocean and melt. Even

Figure 3. Images of Antarctica **(left)** and Greenland **(right)** to scale. Antarctica is 50 per cent larger than the United States or Europe. Greenland is 7 times smaller than Antarctica. There is enough ice in Antarctica to raise global sea level by 60 metres and 7 metres in Greenland.

in Antarctica, where air temperatures remain below freezing and melting is limited to the low-lying regions of the Antarctic Peninsula, ocean warming has triggered changes in ice mass that are comparable in magnitude to what is being observed in Greenland. As glaciers flow and melt faster into the oceans, sea level is rising worldwide. There is enough ice in Greenland to raise global sea level by 7 metres and in Antarctica to raise sea level by 60 metres (**Figure 3**).

In the last interglacial (a period between ice ages), about 120,000 years ago when global air temperatures were only 2 to 3°C above present temperatures, sea level was 4 to 6 metres higher[14]. During that period, a large part of the ice sheets on Greenland and West Antarctica had melted into the sea. It is almost certain that if the Earth experienced the same climate again, it would only be a matter of time before these ice sheets melt into the sea again[15].

The knowledge of the evolution of Greenland and Antarctica in a warming climate has evolved significantly since the 2007 Intergovernmental Panel on Climate Change Fourth Assessment report (IPCC 2007).

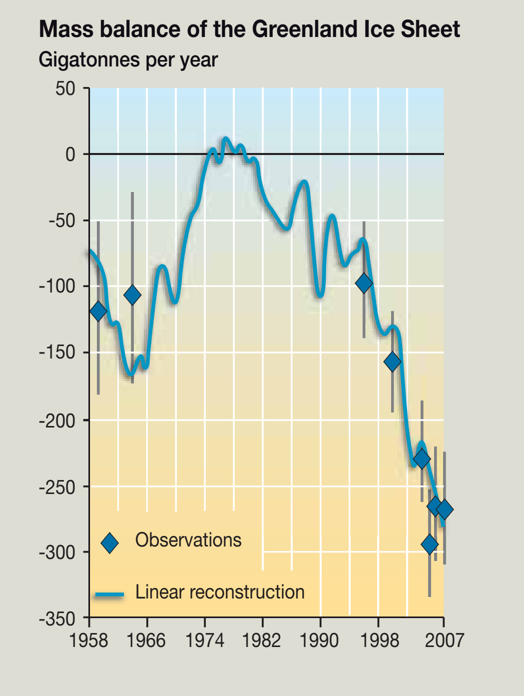


Figure 4. Changes in mass of the Greenland Ice Sheet from 1958-2007[16]. The blue diamonds are observations of ice discharge and snowfall combined. The blue curve fills in data gaps by using a linear reconstruction of anomalies in ice discharge from anomalies in surface runoff (snow and ice melt).

Greenland Ice Sheet

Observations from the ground, airborne platforms and satellites show that the Greenland Ice Sheet is losing an excess ice mass to the ocean compared to what is needed to maintain the ice sheet in a state of mass equilibrium (i.e., no net growth or shrinkage). In 2008, this mass loss was about 280 gigatonnes per year[16] (**Figure 4**). One gigatonne per year is the amount of water consumed annually by the city of Los Angeles, California, and its 8 million inhabitants. Thus, each year the Greenland ice sheet loses the amount of water required to supply 280 cities like Los Angeles with freshwater. While this number is large at the human scale, it only represents a small fraction of the total ice volume in Greenland.

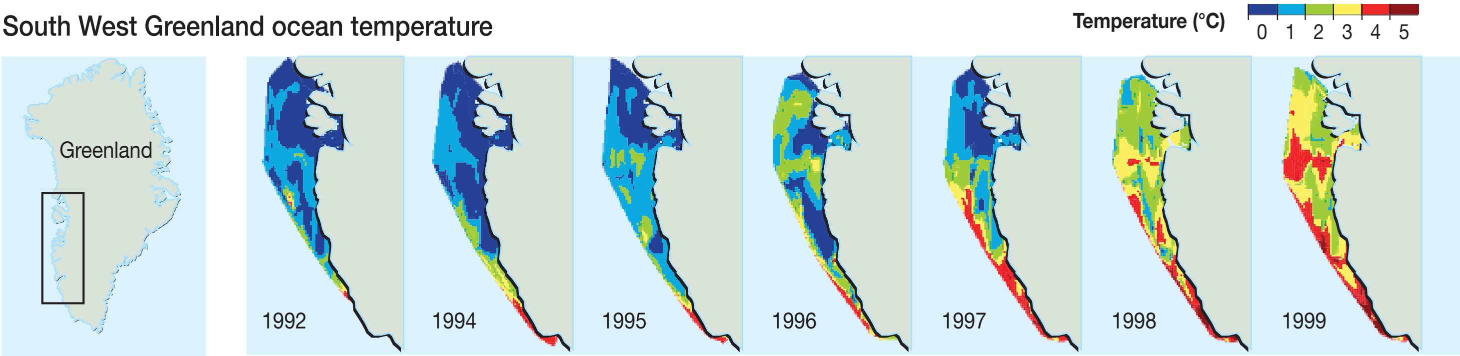
More important, the ice sheet loss has been increasing over the last 20 years (**Figure 4**). This is shown by approaches comparing accumulation versus perimeter loss; or direct measurements of mass changes using time-variable gravity[17, 18]. The ice sheet was near balance in the 1970-1980s, when climate was colder than it is today. Since then, the ice sheet loss has increased by about 20 gigatonnes every year. If the ice sheet continues to lose mass at this rate, sea level will rise worldwide by 31 centimetres from Greenland alone by the year 2100.

One-third of the ice sheet loss is caused by increased surface melting or runoff. In the last 15 years, runoff has increased by 50 per cent. Places that used to melt only rarely now melt every year.

Glacier flow rates are accelerating

Yet increased surface melting and runoff is not the largest change observed in Greenland. The other two-thirds of the ice sheet loss is caused by the acceleration of glaciers. Glaciers discharge ice from the island to the ocean, flowing like rivers that discharge rainfall from their catchment basin into the sea. Their rate of flow is affected by climate. They flow faster under warmer conditions. Warmer conditions

South West Greenland ocean temperature



include warmer air temperatures, which affect the glacier surface, and warmer ocean conditions that affect the submerged parts of the glaciers that reach the ocean.

Initially, meltwater was assumed to be the prime cause of glacier acceleration, making its way to the ground beneath ice sheets, lubricating it and causing the glaciers to flow more quickly to the sea[19] (**Figure 5**). However, this process only accelerates ice flow by about 20 per cent, which, while important, is not enough to explain the observed rate of ice loss[20, 21].

What was realized in recent years is that the primary cause of glacier acceleration is the pressure change that occurs near the glacier fronts as a glacier melts. As ocean and land temperatures rise (**Figure 6**), the ice at the front of glaciers (where the ice meets the ocean and produces icebergs) melts and thins more rapidly, causing the glacier frontal regions to retreat inland, which reduces the backpressure (or resistance to flow) on the inland ice. The reduced pressure causes them to flow more quickly into the sea, much like removing the cork from a bottle[22]. Acceleration rates of several hundred per cent can result from this mechanism.

Nearly all the large glaciers in south Greenland sped up when the ocean waters warmed up by several degrees during the mid-1990s[23]. This has resulted in the collapse of floating ice tongues and in the retreat of glacier terminus, which has in turn triggered glacier acceleration. A wave of acceleration is then transmitted upstream, over vast distances (measured in hundreds of kilometres), affecting the entire catchment basin.

Ice sheet numerical models used in IPCC 2007 were not able to explain the observed speed up of Greenland glaciers for various reasons, but mostly because the mechanisms of destabilisations of the glaciers in a warmer climate were not sufficiently well understood. While it is certain is that the ice sheets will continue to lose mass at an increasing rate in a warmer climate; predicting those rates remains a serious scientific challenge at present[24, 25, 26].

Places that are most vulnerable to change are glaciers grounded below sea level, because the glacier frontal regions remain in contact with ocean waters during the retreat, which maintain high rates of iceberg production and submarine melting


Braithwaite, 2002

Figure 5. Meltwater moulin on the Greenland Ice Sheet.

Figure 6. Time series of ocean temperature along the coast of west Greenland that show a transition from cold to warm (+3°C) in the mid-1990s that is held responsible for the subsequent acceleration of the glaciers[23]. The warm waters melted the submarine portion of the glaciers, which reduced resistance to flow and allowed glaciers to slide faster to the sea. Some of the glaciers doubled or tripled their speeds within one year. The floating ice tongue of Jakobshavn Isbrae disappeared completely in year 2002, the same year the fjord was classified as World Heritage Site by UNESCO.

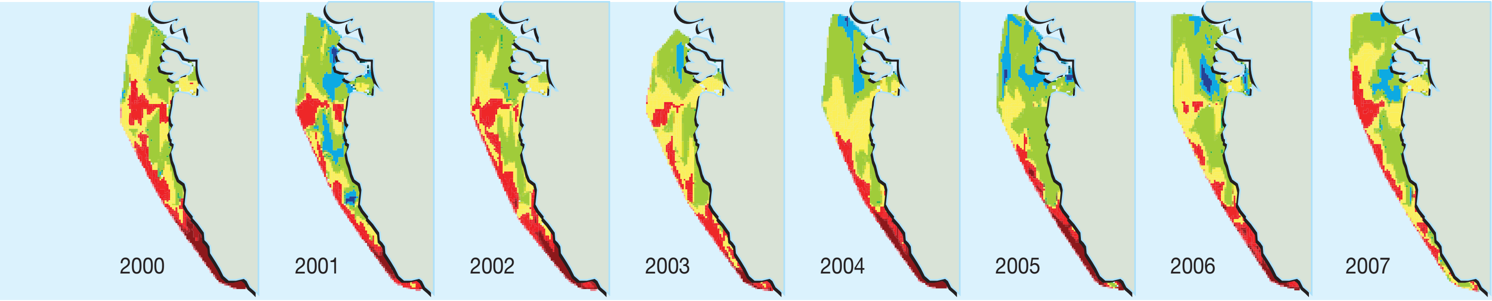
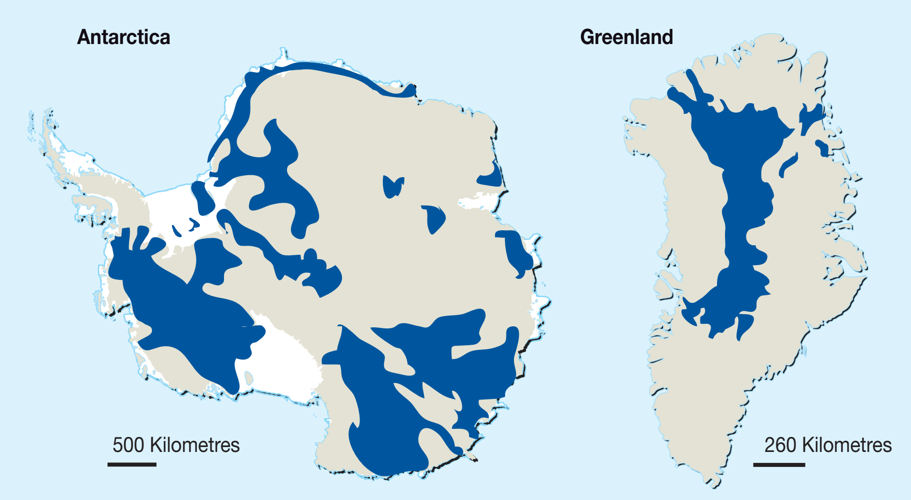


Figure 7. Maps of Greenland and Antarctica showing sectors grounded below sea level (in blue). These sectors are most sensitive to climate change and have the potential for rapid retreat; but ice sheet retreat may still occur in regions grounded above sea level.

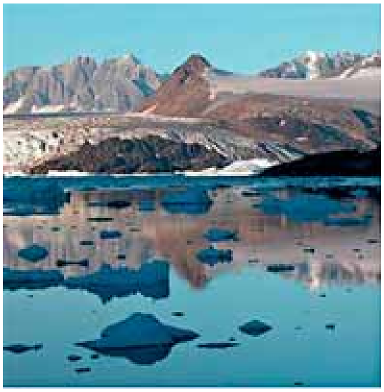


compared to glaciers terminating on land. As frontal regions thin faster than interior regions, the glaciers are stretched across their length and become steeper, which increases ice flow and propagates ice thinning inland. Much of northern Greenland is grounded below sea level **(Figure 7)**. The deep channel that underlies Jakobshavn Glacier, which collapsed around the year 2000, is also grounded below sea level; it is the largest glacier in Greenland and discharges 10 per cent of the Greenland ice sheet. As climate warming continues, existing models agree that the ice sheet will melt almost completely if local warming exceeds 4 to 5°C[15].

Currently, the ice sheet is changing nearly three times faster than anticipated by existing numerical models and the contribution of Greenland to sea level is larger than expected. A rapid decay of Greenland glaciers will increase freshwater input to the North Atlantic, which may disrupt global ocean circulation and global climate.

For a long time, conventional wisdom held that Antarctica was too cold to see substantial melting and that it would instead gain ice mass due to increasing snowfall, even as climate warmed. Reality has unfolded quite differently. It is now clear that Antarctica has been warming slowly over the past 50 years, and it has not seen an increase in snowfall[27, 28]. As in Greenland, however, glacier flow rates in Antarctica have been increasing in some regions. In the Antarctic, ice does not melt from the top because temperatures are too cold, but it melts from the bottom where it is in contact with the ocean. While only some sectors of Greenland are grounded below sea level and at risk of collapse, the vast majority of West Antarctica is grounded below sea level, as are significant sectors of East Antarctica **(Figure 7)**. These sectors are most sensitive to changes in ocean temperature at the periphery of Antarctica.

Figure 8. Image of a glacier in Kangerdlugssuaq Fjord, in Greenland. Glaciers discharge meltwater and icebergs to the North Atlantic ocean. Freshwater discharges may affect the thermohaline circulation (based on the ocean water's temperature and salinity affecting its density), which in turns affects global climate.



J. Dowdeswell, 2006

Ice sheet melt will be the major contributor to future sea-level rise

Sea-level rise from ice sheets is only beginning

In 2008, Antarctica lost nearly as much ice as Greenland, a net loss of about 220 gigatonnes per year[29, 30] (**Figure 9**). This is only 10 per cent of its annual input of mass from snowfall to the continent (i.e. a much smaller fraction than for Greenland). This means that the Antarctic continent holds a much greater potential for rapid sea level rise in the future, as more regions of Antarctica are destabilised by climate change.

As in Greenland, the mass loss from Antarctica is accelerating[29] (**Figure 9**). In the Amundsen Sea sector of West Antarctica (currently Antarctica's largest contributor to sea-level rise), Pine Island glacier has been thinning more rapidly and its flow rate has been accelerating more every year for the past 35 years[31]. The glacier will continue to accelerate until it becomes ungrounded from its ice plain and begins calving from a much deeper bed[22]. At that point, which could be only a few years away, the glacier will abruptly speed up by a factor of 2 to 3, break up into icebergs over a much wider front, and continue its retreat — even if climate were to slowly come back to the colder conditions of the 1970s. This sector of West Antarctica alone contains enough ice to raise sea level by an additional metre. Ground, airborne and satellite surveys indicate that ice in this region is beginning to collapse, the likely result of a warmer ocean. The contribution to sea level from this sector of Antarctica is not included in the IPCC 2007 projections.

In sum, accelerated ice mass loss in coastal regions of Greenland and West Antarctica contributed about 30 per cent to the 1993-2008 sea-level rise, with an almost equal amount from Greenland and West Antarctica. From 1993 to 2003, the ice sheet contribution was less than 15 per cent, but it has increased significantly since 2003. Although none of the climate factors discussed above change linearly with time, on average over the 1993-2008 period, ocean warming, glacier melting and ice sheet mass loss have each contributed about 30 per cent to global average sea-level rise.

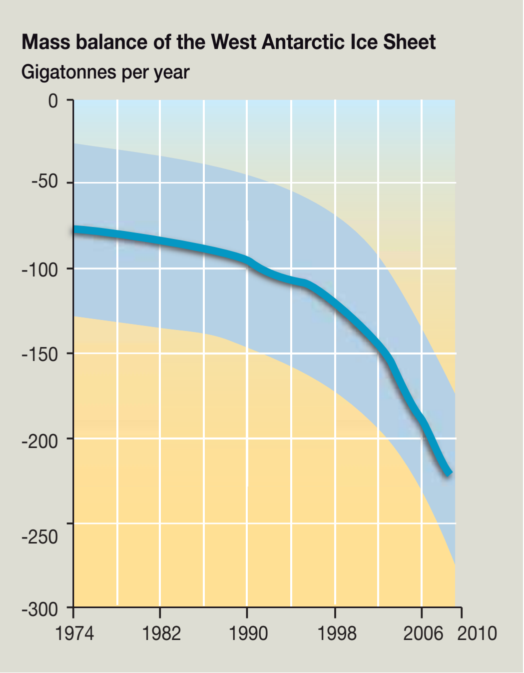


Figure 9. Increase in mass loss by the West Antarctic ice sheet[32]. The mass loss has been steadily increasing since the 1970s as a result of accelerations in glacier flow; snowfall has not changed significantly in Antarctica over the past 50 years[30].

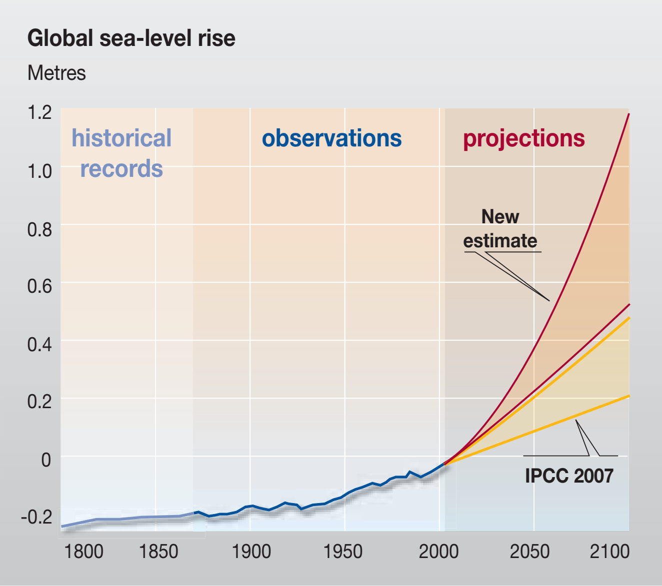
Sea level will rise more than previously expected

Exactly how much ice sheet melt will affect sea level in the future is difficult to predict.

However, sea level is expected to rise more than previously thought. IPCC 2007 projections based on coupled climate models indicate that sea level is likely to be higher than today's level by about 40 centimetres by 2100 (within a range of plus or minus 20 centimetres because of differences between models and uncertainty about future greenhouse gases emissions)[32]. However, this amount of rise is likely a lower bound because it accounts only for future ocean warming and glacier melting; it excludes rapid changes from ice sheets because it did not appear possible to predict them at the time. The complex ice sheet dynamics by which glaciers flow into the ocean, which are responsible for a large proportion of Greenland and West Antarctica ice mass loss have begun to be understood only recently and thus were not taken into account in the IPCC 2007 sea-level projections.

To address this complex problem, more advanced numerical ice sheet models and more complete observations of key physical processes are needed, for instance of rising ocean temperature in contact with glacier ice. Because ice sheet losses are currently increasing faster than any other system contributing to sea-level rise, it is likely that ice sheets will be the primary contributor to sea-level rise during this century. As further progress is made in understanding and modelling the mechanisms of destabilisation of glaciers and ice sheets, improved predictions will be possible.

Figure 10. Future sea-level rise based on simple relationship between rate of sea-level rise and global average temperature[33].



An alternative approach to predict future sea level rise has been proposed. It estimates that sea level will rise by 60 to 120 centimetres by 2100, much more than IPCC 2007 projections[33, 34] (**Figure 10**). This projection is based on a simple relationship established for the 1900s that relates the observed average rate of global sea-level rise and the observed average global temperature of the Earth. Using global average temperature projections, it can project future global average sea level. While future sea level rates may not necessarily follow the past century's dependence on the average global temperature (in particular if ice sheet dynamics play a larger role in the future), the approach offers insight to plausible ranges of future sea-level rise.

Sea level will continue to rise after 2100. A certain amount of climate change and associated sea-level rise is already locked in for the next several decades based on past emissions

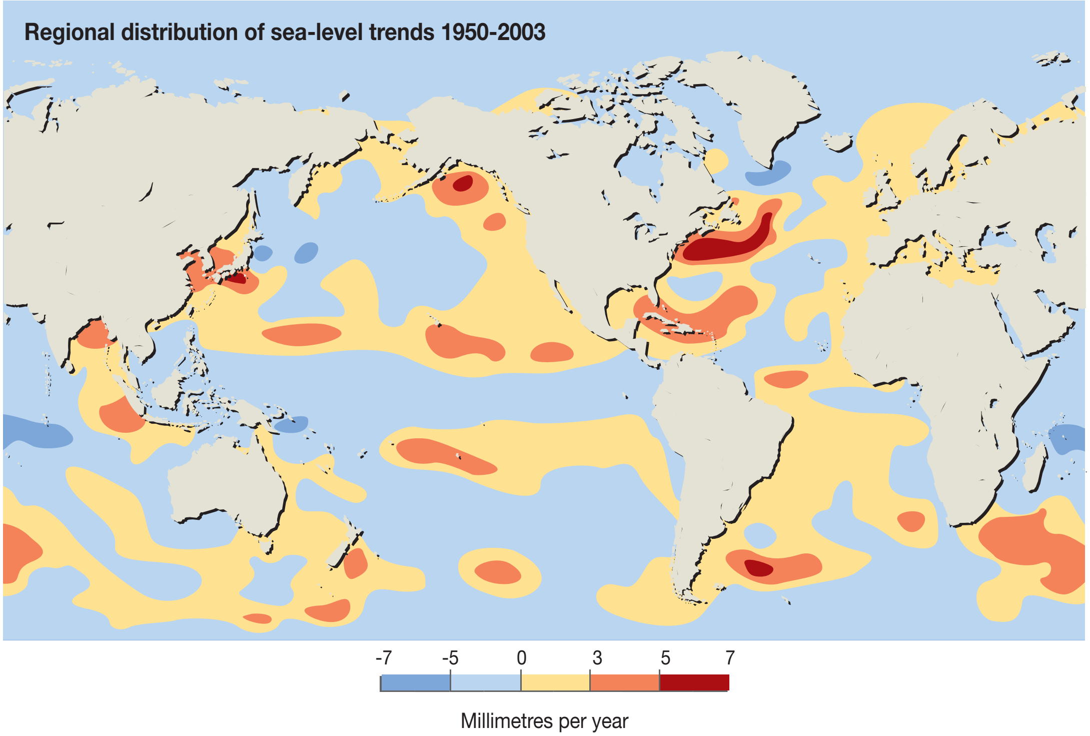


Figure 11. Past sea level reconstruction (1950-2003) based on tide gauges and an ocean circulation model[37].

of greenhouse gases. What is at stake now is how severe climate change will be in the middle and end of this century and beyond.

Some of the changes that have taken place are irreversible on a human timescale. For example, satellites witnessed the collapse of the Larsen B ice shelf in Antarctica in March 2002 after 10,000 years of continuous existence. It would take several hundred years to rebuild this ice shelf from its current state to what it was in year 2000. As climate warming progresses farther south in the Antarctic Peninsula, more ice shelves are expected to collapse. The irreversible character of such changes implies that observed changes in polar regions could have very significant impacts.

Sea-level rise is not uniform

Satellite altimetry data has revealed that sea level is not rising uniformly **(Figure 11)**. In some regions (e.g., western Pacific), rates of sea-level rise are faster by up to 3 times the average global rate. In other regions, rates are slower than the global average (e.g., eastern Pacific). Spatial patterns in sea-level trends mainly result from large-scale changes in the density structure of the oceans associated with temperature and salinity changes[8]. To date, the largest regional changes in sea-level trends result from ocean temperature change (i.e., from change in heat content of the oceans), but local changes in water salinity also can be important[35]. Observations of ocean temperature over the past few decades show that trend patterns in thermal expansion are not stationary, but fluctuate both in space and time in response to natural perturbations of the climate system (such as a result of the El Niño-Southern Oscillation, North Atlantic Oscillation and Pacific Decadal Oscillation)[36]. As a result, sea-level trend patterns observed by satellites over the last 15-plus years are different from those observed over the last 50 years[2, 37]. Such decade-to-decade oscillations are not reproduced well by coupled climate models.

Like the present, sea-level rise is not expected to be uniform around the world in the future. The regional sea level map for 2090-2100 provided by IPCC 2007 (average of 16 models for one emission scenario)[1] shows higher than average sea-level rise in the Arctic Ocean and along a narrow band in the South Atlantic and South Indian oceans. However, as noted in IPCC 2007[1], geographical patterns of sea-level change from different models generally are not similar, reflecting current model deficiencies in modelling regional changes, in particular those associated with decade-to-decade and multi-decade natural variability.

IPCC 2007 regional projections are different from present-day observed patterns of sea-level rise (compare **Figure 11** and **Figure 12**), a result of temporal variability in spatial trend patterns.

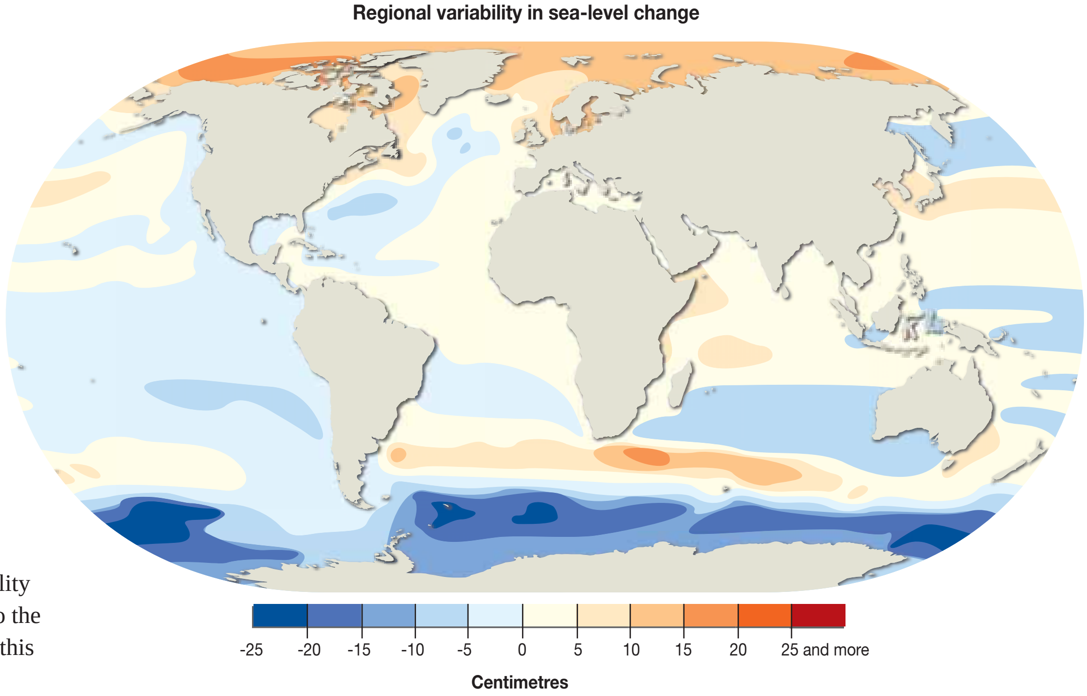


Figure 12. Regional variability in sea level change relative to the global average by the end of this century[32].

Threats to coastal regions

Sea-level rise is a major concern for populations living in low-lying coastal regions (about 25 per cent of humans), because it will give rise to inundation (both temporary and permanent flooding), wetland loss, shoreline erosion, saltwater intrusion into surface water bodies and aquifers, and it will raise water tables[38, 39]. Moreover, in many coastal regions of the world, the effects of rising sea level act in combination with other natural and/or human-induced factors, such as decreased rates of stream sediment deposition in deltas, ground subsidence (sinking) as a result of tectonic forces, groundwater pumping, and/or oil and gas extraction.

In addition to factors that modify shoreline structure and equilibrium (e.g., sediment deposition in river deltas, changes in coastal waves and currents), coastal regions are affected by relative sea-level rise (i.e., the combination of sea-level rise and vertical movement of the ground). In many coastal regions of the world, these two factors are currently of the same order of magnitude and in the opposition direction — sea level is rising and the ground is sinking. This amplifies the effect of sea-level rise in these locations, so that for example, a half-metre rise in global sea level and a half-metre of local land subsidence combines to produce 1 metre of relative sea-level rise. Accelerated ground sinking has been reported in many regions, either because of local groundwater withdrawal (e.g., Tokyo subsided by 5 metres, Shanghai by 3 metres, and Bangkok by 2 metres during the last decades[39]) or oil and gas extraction (e.g., along the Gulf of Mexico Coast in the United States where the ground subsides at a rate of 5 to 10 millimetres per year[40]). Whatever the causes, ground subsidence (sinking) directly interacts with and amplifies climate-related sea-level rise (long-term trend plus regional variability). However, if sea level continues to rise at current rates, and more likely accelerates, the climate factors (sea-level rise) will become dominant. And, as mentioned previously, IPCC 2007 sea level projections are very likely to be underestimations. In addition, climate models are not yet able to provide reliable regional variability projections that will be superimposed on the global average rise for the next few decades. Hence, it is very difficult to quantify future sea-level rise in specific regions where various factors interact in complex ways. Despite the uncertainties, sea-level rise will almost surely cause significant impacts in coastal regions around the world.

References

1 IPCC 4th Assessment Report, *Climate change 2007: The physical Science Basis. Contribution of Working Group I to the Fourth Assessment report of the Intergovernmental Panel on Climate Change* [Solomon S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, UK, and New York, USA., 2007.

2 Church J.A., N.J. White, R. Coleman, K. Lambeck, and J.X. Mitrovica 2004. Estimates of the regional distribution of sea-level rise over the 1950 to 2000 period. *Journal of Climate 17*(13): 2609-2625.

3 Holgate S.J., and P.L. Woodworth 2004. Evidence for enhanced coastal sea level rise during the 1990s. *Geophys. Res. Lett.* 31:(L07305), doi:10.1029/2004GL019626.

4 Jevrejeva S., Grinsted A., Moore J.C. and Holgate S. 2006. Non linear trends and multiyear cycles in sea level records. *J. Geophys. Res*. C09012: doi:1.1029/2005JC003229.

5 Leuliette E.W., R.S. Nerem, G.T. Mitchum 2004. Results of TOPEX/Poseidon and Jason-1 Calibration to Construct a Continuous Record of Mean Sea Level. *Marine Geodesy 27:* 79-94.

6 Nerem S., Leuliette E. and Cazenave A. 2006. Present-day sea level change*, C.R. Geosciences* 338: 1077-1083.

7 Cazenave A., and Llovel W. 2009. Contemporary sea level rise. *Annual Review of Marine Science*, in press.

8 Bindoff N., Willebrand J., Artale V. , Cazenave A., Gregory J. , Gulev S., Hanawa K., Le Quéré C., Levitus S., Nojiri Y., Shum C.K., Talley L., Unnikrishnan A. 2007. Observations: oceanic climate and sea level. In: *Climate change 2007: The physical Science Basis. Contribution of Working Group I to the Fourth Assessment report of the Intergovernmental Panel on Climate Change* [Solomon S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, UK, and New York, USA.

9 Ishii M. and M. Kimoto 2009. Re-evaluation of historical ocean heat content variations with varying XBT and MBT depth bias corrections. *Journal of Oceanography* 65(3):287-299, doi:10.1007/s10872-009-0027-7.

10 Levitus S., Antonov J.L., Boyer T.P., Locarnini R.A., Garcia H.E. and Mishonov A.V. 2009., Global Ocean heat content 1955-2008 in light of recently revealed instrumentation. *Geophys. Res. Lett*., in press.

11 Lemke P. et al. 2007. Observations : changes in snow, ice and frozen ground. In: Climate change 2007: The physical Science Basis. Contribution of Working Group I to the Fourth Assessment report of the Intergovernmental Panel on Climate Change [Solomon S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, UK, and New York, USA.

12 Meier, M.F., Dyurgerov, M.B., Rick, U.K., O'Neel, S., Pfeffer, W.T., Anderson, R.S., Anderson, S.P., & Glazovsky, A.F.. 2007. Glaciers dominate Eustatic sea-level rise in the 21st century. *Science* 317(5841): 1064-1067.

13 Cogley J.C. 2009. Geodetic and direct mass balance measurements: comparison and joint analysis. *Annals of Glaciology* 50: 96-100.

14 Jansen E. et al. 2007. Paleoclimate. In: Climate change 2007: The physical Science Basis. Contribution of Working Group I to the Fourth Assessment report of the Intergovernmental Panel on Climate Change [Solomon S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, UK, and New York, USA.

15 Jonathan M. Gregory, Philippe Huybrechts, Sarah C. B. Raper 2004. Threatened Loss of Greenland Ice Sheet. *Nature*, April 8.

16 Rignot E, et al. 2008a. Mass balance of the Greenland Ice Sheet from 1958 to 2007, *Geophys. Res. Lett.* 35: L20502.

17 Cazenave et al. 2009. Sea level budget over 2003-2008: A re-evaluation from GRACE space gravimetry, satellite altimetry and Argo. *Glob. Planet. Change* 65:83--88, doi:10.1016/j/gloplacha.2008.10.004.

18 Velicogna I, Wahr J. 2006. Revised Greenland mass balance from GRACE. *Nature* 443:329.

19 Zwally HJ, Giovinetto MB, Li J, Cornejo HG, Beckley MA, et al. 2005. Mass changes of the Greenland and Antarctica ice sheets and shelves and contributions to sea level rise: 1992--2002. *J. Glaciol.* 51:509--24.

20 Rignot E, Kanagaratnam P. 2006. Changes in the velocity structure of the Greenland ice sheet. *Science* 311:986--90.

21 Joughin I, Das SB, King M, Smith BE, Howat IM, Moon T. 2008. Seasonal speedup along the western flank of the Greenland ice sheet. *Science* 320:781--83.

22 Thomas, R.H. 2004. Force-perturbation analysis of recent thinning and acceleration of Jakobshavn Isbrae, Greenland, *J. Glaciol.* 50: 57-66.

23 Holland D, Thomas RH, De Young B, Ribergaard MH, Lyberth B. 2008. Acceleration of Jakobshawn Isbrae triggered by warm subsurface ocean waters. *Nat. Geosci.* 1:659--64, doi:10.1038/ngeo316.

24 Pfeffer et al. 2008. Kinematic constraints on glacier contributions to 21st century sea level rise. *Science* 321: 1340-1343.

25 Alley et al. 2005 (FROM USP : Alley, R.B., P.U. Clark, P. Huybrechts, and I. Joughin, 2005: Icesheet and sea-level changes ice-sheet and sea-level changes. *Science* 310(5747): 456-460.

26 Faezeh M. N., A. Vieli, I. M. Howat, and I. Joughin 2009. Large-scale changes in Greenland outlet glacier dynamics triggered at the terminus. *Nature Geoscience* 2: 110 - 114.

27 Steig E. et al. 2009. Warming of the Antarctic ice sheet surface since the 1957 International Geophysical Year. *Nature* 457: 459-461.

28 Monaghan et al. Insignificant change in Antarctic snowfall since the International Geophysical Year. *Science* 313: 827-831.

29 Rignot E. et al. 2008b. Recent Antarctic ice mass loss from radar interferometry and regional climate modeling, *Nature Geoscience* 1: 106-110.

30 Rignot, E. 2008. Changes in West Antarctic ice dynamics observed with ALOS PALSAR. *Geophys. Res. Lett.* 35: L12505.

31 Scott, J. B. T., G. H. Gudmundsson, A. M. Smith, R. G. Bingham, H. D. Pritchard, and D. G. Vaughan 2009. Increased rate of acceleration on Pine Island Glacier strongly coupled to changes in gravitational driving stress. *The Cryosphere* 3, 125-131.

32 Meehl et al., 2007. Global Climate Projections. In: Climate change 2007: The physical Science Basis. Contribution of Working Group I to the Fourth Assessment report of the Intergovernmental Panel on Climate Change [Solomon S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, UK, and New York, USA.

33 Rahmstorf, S. 2007. A semi-empirical approach to projecting future sea level rise. *Science* 315: 368.

34 Horton, R. et al., 2008. Sea level rise projections from current generation CGCMs based on the semi empirical method. *Geophys. Res. Lett.* 35.

35 Wunsch, C., R.M. Ponte and P. Heimbach 2007. Decadal Trends in Sea Level Patterns: 1993–2004, *Journal of Climate 20: 24, doi: 10.1175/2007JCLI1840.1*.

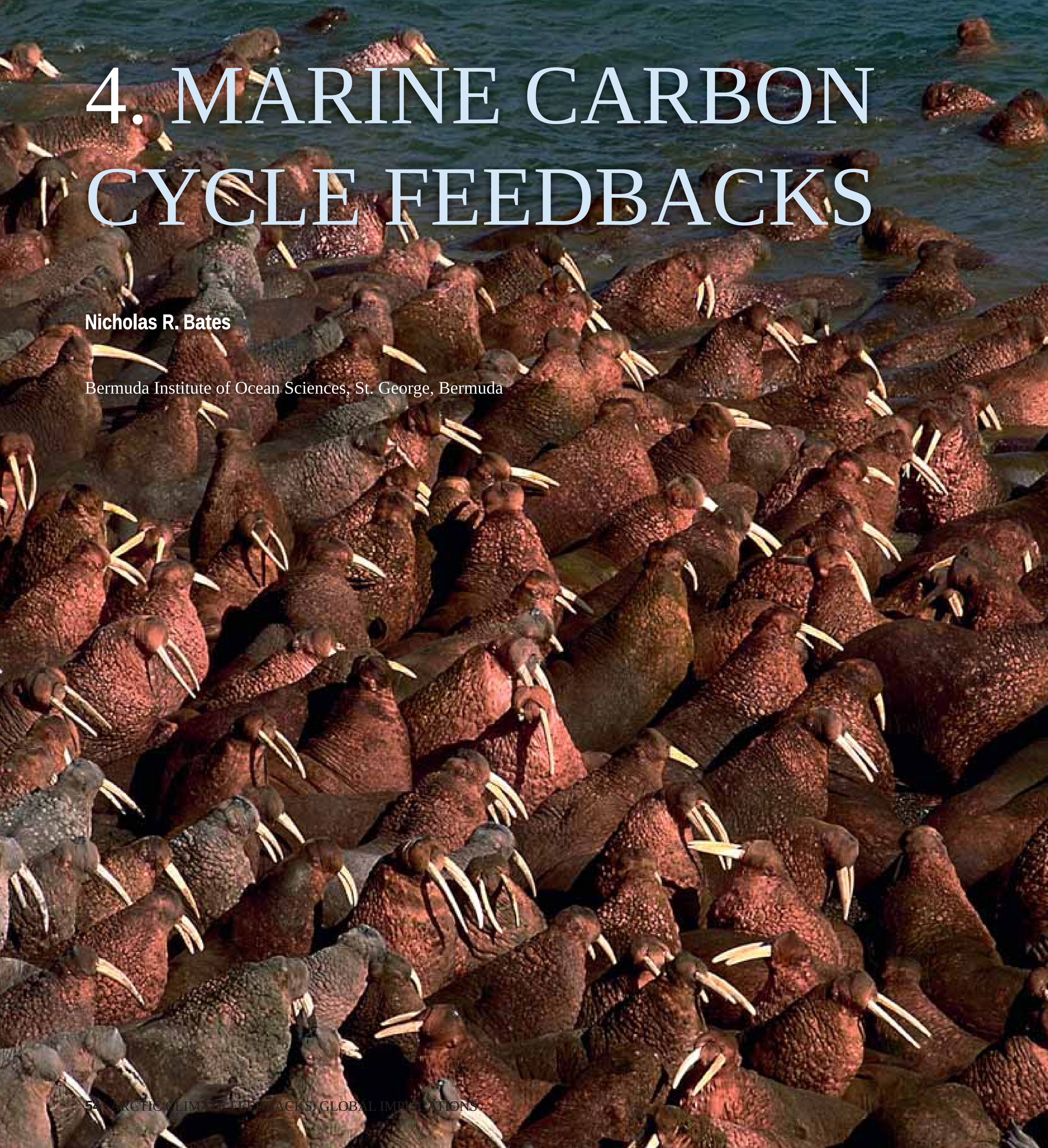
36 Lombard A., Cazenave A., Le Traon P.Y. and Ishii M. 2005. Contribution of thermal expansion to present-day sea level rise revisited. *Global and Planetary Change* 47: 1-16.

37 Llovel W., Cazenave A., Rogel P. and Berge-Nguyen M. 2009. 2-D reconstruction of past sea level (1950-2003) using tide gauge records and spatial patterns from a general ocean circulation model. *Climate of the Past* 5: 1-11.

38 Nicholls R.J. 2002. Rising sea level: potential impacts and responses. In Hester R.E., Harrison R.M. eds. Issues in Environmental science and technology; *Global Environmental Change* 17: 83-107.

39 Nicholls R.J., 2007. The impacts of sea level rise, *Ocean Challenge* 15 (1): 13-17.

40 Ericson J.P., Vorosmarty C.J., Dingman S.L., Ward L.G. and Meybeck L. 2006. Effective sea level rise and deltas: causes of change and human dimension implications, *Global and Planetary Change* 50: 63-82.



4. MARINE CARBON CYCLE FEEDBACKS

Nicholas R. Bates

Bermuda Institute of Ocean Sciences, St. George, Bermuda

AMONG ITS OTHER IMPORTANT FUNCTIONS, the Arctic Ocean absorbs carbon dioxide. But absorbing carbon dioxide produced by human activities also has downsides. It gradually reduces the ocean's ability to take up more carbon dioxide, and it leads to ocean acidification. The complexities of the Arctic Ocean and its role in the global carbon cycle are only beginning to be understood. Part of the difficulty is the dearth of measurements in this remote and not easily accessible region. Still, what is known, and what is being discovered, is creating concern among scientists studying the Arctic Ocean and its role in the global carbon cycle.

Key Findings

- **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 marine plant (such as 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 this trend over the next century, leading to a net increase of carbon dioxide released to the atmosphere from these systems.

- **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 phytoplankton growth, ocean circulation and acidification, temperature effects, and river inputs, making projections uncertain.

The Arctic plays an important role in the global climate system through interactions between sea-ice, ocean and atmosphere, global ocean circulation and the global balance of gases such as carbon dioxide and methane. Rapid environmental change in the Arctic as a result of warming[1, 2], sea-ice loss[3, 4] and other physical and biological changes[5, 6, 7, 8], are already altering the marine carbon cycle. The major finding of this chapter is that the atmosphere-ocean exchange of carbon dioxide is changing rapidly[9, 10, 11] in response to sea-ice loss and other climate-change induced processes. Arctic Ocean marine ecosystems are also particularly sensitive to the impacts of ocean acidification[12, 13, 14] that result from the ocean uptake of human-produced carbon dioxide.

"The atmosphere-ocean exchange of carbon dioxide is changing rapidly in response to sea-ice loss and other climate-change induced processes."

Geographic setting

The relatively small Arctic Ocean (about 10,700,000 square kilometres) is almost completely landlocked except for a few ocean gateways that allow limited exchanges of seawater with the Pacific and Atlantic oceans (**Figure 1**). The coastal seas of the Arctic (Barents, Laptev, Kara, East Siberian, Chukchi and Beaufort seas) overlie shallow continental shelves (less than 200 metres deep) that constitute about 53 per cent of the total area of the Arctic Ocean[15]; the remainder is a deep central basin more than 2,000 metres deep, flanked by the slightly shallower Eurasian and Canada basins. In the central basin of the Arctic, subsurface waters are relatively isolated from surface waters due to differences in seawater density that change with depth[16, 17] and limited exchanges with deep water outside of the Arctic. As such, climate change due to warming, sea-ice loss and other processes mostly affects surface waters rather than the deep, isolated and old subsurface waters in the central basin.

Surrounding the Arctic Ocean is an extensive land margin and watershed with major rivers draining Siberia and North America[5, 18]. The arctic landmasses also contain large stores of freshwater (mostly glacial ice and permafrost) (see *Ice Sheets and Sea-level Rise Feedbacks* chapter) and terrestrial carbon (see *Land Carbon Cycle Feedbacks* chapter) compared to the stores of carbon in the Arctic Ocean[15]. As such, arctic rivers contribute disproportionately large amounts of freshwater and other materials, such as carbon, compared to other ocean basins.

Sea ice in the Arctic

Atmosphere-ocean interaction, ocean circulation[19] and exchanges of water with other oceans control the seasonal sea-ice advance and retreat, year-to-year changes of sea-ice distributions and thickness, and export of sea-ice from the Arctic Ocean to the Atlantic Ocean[20]. In wintertime, the Arctic is almost completely covered by sea-ice (except for significant areas of open-water associated with ice-free areas — polynyas — and gaps between the sea ice — flaw-leads). The normally thick (3- to 7-metre) multi-year ice in the central basin and thinner seasonal sea-ice (1 to 2 metres) across

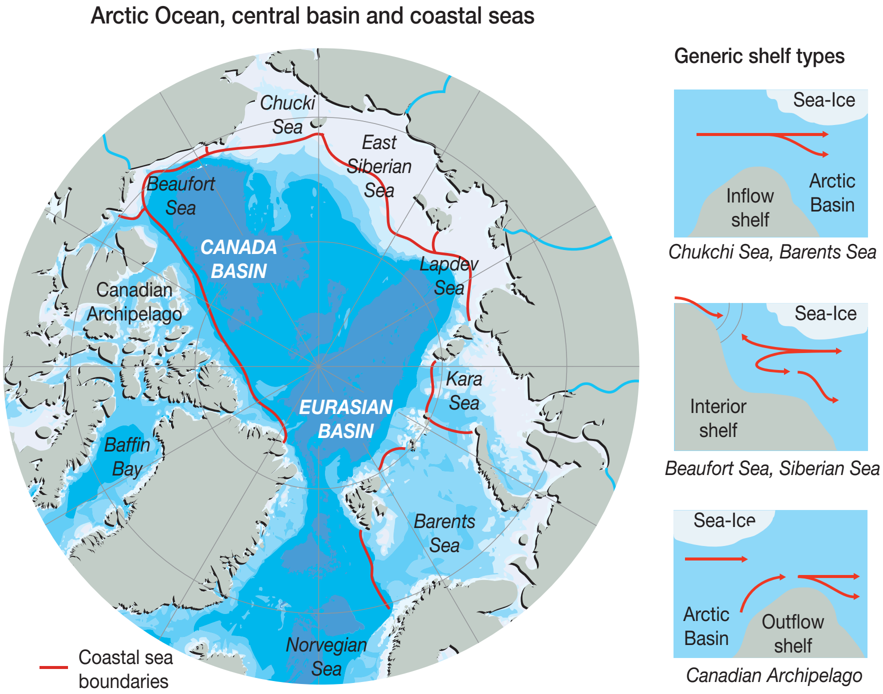


Figure 1. **Left panel:** Schematic of the Arctic Ocean, central basin (Canada and Eurasian basins) and arctic continental shelves (with approximate boundaries for each Arctic Ocean coastal sea), and major rivers draining into the region[15]. **Right panel:** The three generic types of continental shelves (i.e., inflow, interior and outflow) are shown[23].

the arctic shelves has declined dramatically since the 1990s[21]. In a self-reinforcing cycle, sea-ice loss reinforces surface warming because of reduced surface reflectivity (albedo) and increased heat absorption, which inhibits sea-ice formation in the winter and accelerates sea-ice loss during the summer[22]. This in turn, affects the chemistry and biology of the Arctic Ocean.

Biology of Arctic Ocean surface waters

In the shallow coastal waters of the Chukchi and Barents seas, the inflow[23] of nutrient-rich seawater from the Pacific and Atlantic oceans[24], coupled with the seasonal retreat and melting of sea ice and the abundance of light, sustains high rates of marine plant (i.e., phytoplankton) photosynthesis and growth[25, 26] in open waters each year. The seasonal growth of marine phytoplankton and zooplankton (e.g., shrimp, copepods) supports rich and diverse open-water and seafloor ecosystems[27]. These ecosystems provide critical food sources for marine mammals (e.g., grey whale, walrus, polar bears), seabirds and human populations in the Arctic.

Elsewhere in the Arctic, coastal waters of the Beaufort and Siberian seas have significantly reduced marine phytoplankton growth rates as a result of lower nutrient supplies[23, 15]. In the central basins of the Arctic (i.e., Canada and Eurasian basins), surface waters are mostly covered by sea ice with very low rates of marine phytoplankton growth[28]. Across the Arctic, marine phytoplankton and microbial (i.e., bacteria and viruses) communities in sea-ice also influence the marine carbon cycle.

The Arctic Ocean is an important global carbon sink

Seawater exchanges with other oceans, land to ocean inputs and atmosphere-ocean exchanges strongly influence the physical and chemical properties of the surface waters of the Arctic Ocean. As such, climate change will predominantly affect the pools and fluxes of carbon in surface waters of the Arctic over the next century.

The upper waters of the Arctic contain approximately 25 gigatonnes (1 gigatonne of carbon equals 1 billion tonnes of carbon) of inorganic carbon (i.e., bicarbonate, carbonate and carbon dioxide) and about 2 gigatonnes of organic carbon (in the form of living organisms, detritus and other materials). Seawater inflow of Pacific Ocean water through Bering Strait into the Chukchi Sea and Atlantic Ocean water flowing into the Barents Sea supplies an inflow of about 3 gigatonnes of inorganic carbon per year into the Arctic Ocean with a similar outflow from the Arctic through Fram Strait. Within the Arctic itself, river inputs and coastal erosion constitute a land to ocean carbon flux of about 0.012 gigatonnes of carbon per year[15]. However, there are larger uncertainties about the atmosphere-ocean fluxes of carbon and production of organic carbon by marine plant photosynthesis and its subsequent export from surface waters to deep waters and sediments of the Arctic.

Atmosphere-ocean exchanges of carbon

The exchange of gases such as carbon dioxide between the atmosphere and ocean is primarily controlled by gas concentration differences between the air and the sea and by the turbulence in the lower atmosphere[29], which arises from weather patterns and longer-term climate changes that control the variability of wind and waves. In polar seas, seasonal or permanent sea-ice cover is a potential barrier to the atmosphere-ocean exchange of gases[30] compared to open waters elsewhere.

In the last two decades, more precise and accurate carbon data have been collected in the Arctic Ocean. Recent analyses indicate that surface waters of the Arctic Ocean generally have low to very low carbon dioxide concentrations compared to its concentration in the atmosphere (including the Barents Sea, Chukchi Sea and Beaufort Sea shelves as well as the central basin of the Arctic Ocean[11]; see references listed in **Figure 2**). As such, these surface waters have the ability to absorb large amounts of carbon dioxide (about 0.066 to 0.175 gigatonnes of carbon per year, **Figure 2**).

Currently, the Arctic Ocean carbon dioxide sink potentially contributes about 5 to 14 per cent to the global balance of carbon dioxide sinks and sources[31]. Thus, it is important to the feedback between the global carbon cycle and climate. However, it should be noted that the uptake of carbon by the Arctic Ocean is relatively small

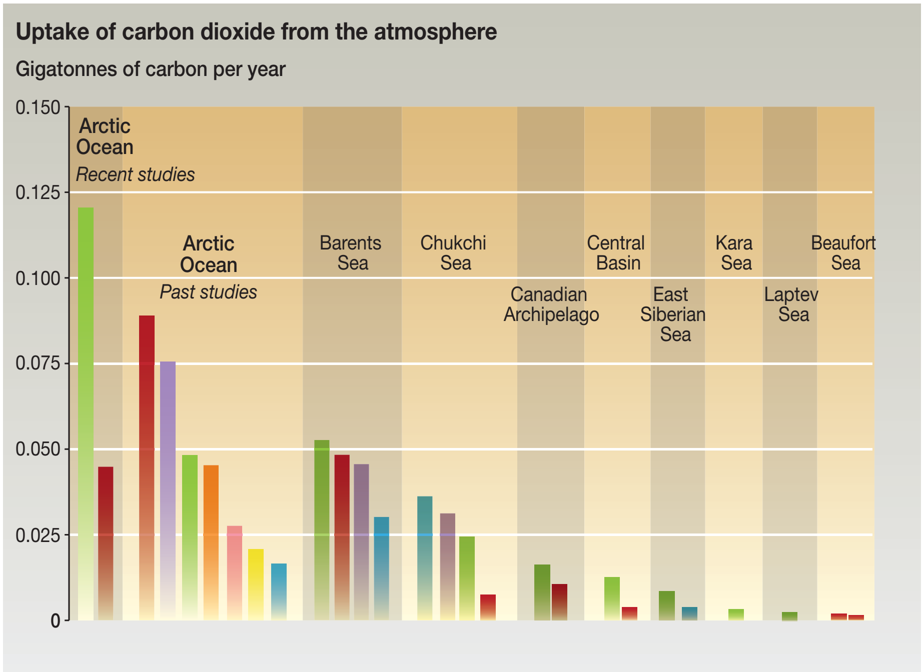


Figure 2. Annual ocean uptake of carbon dioxide expressed in gigatonnes carbon per year. Studies are referenced as follows: Barents Sea (red[44]; green[45]; blue[46]; turqoise[47]); Kara Sea (red[46]; green[48]); Laptev Sea (red[49]; green[48]); East Siberian Sea (red[50]; green[49]; blue[48]); Chukchi Sea (red[51]; green[52]; blue[41]; turquoise[53]); Beaufort Sea (red[48]; green[51]); Canadian Archipelago (red[54]; green[54]); Central Basin (red[52]; green[52, 54]); Arctic Ocean (low and high estimates), Arctic Ocean (past studies (red[55]; green[56]; blue[57]; turqoise[48]; pink[48]; yellow[58]; orange[59]).

compared to the potential release of land-based carbon to the atmosphere from surrounding arctic landmasses over the next few centuries as a result of climate change (see *Land Carbon Cycle Feedbacks* chapter).

Fluxes of carbon from surface waters to deep water and sediments

Biological and physical processes play a very important role in controlling the marine carbon cycle, fluxes of carbon from surface waters to deep water and sediments, and atmosphere-ocean fluxes of carbon dioxide. In the Chukchi and Barents seas, in particular, the concentration of carbon dioxide is decreased by the cooling that occurs when the warmer, nutrient-rich Pacific and Atlantic waters move northward and by the seasonally high rates of marine plant (phytoplankton) photosynthesis and growth during sea-ice retreat. These processes appear to be the primary reason that surface waters in the Arctic have the capacity to absorb significant amounts of carbon dioxide. In contrast, localized nearshore areas around major river inputs to the arctic shelves appear to have seawater carbon dioxide concentrations that are higher than the atmosphere[32, 33]. In these areas, inputs of carbon from the rivers to the ocean and bacterial activity combine to drive these surface waters to be potential sources of carbon dioxide to the atmosphere. In the entire Arctic Ocean, the production of organic carbon by marine plant photosynthesis and the loss of carbon from surface waters from the subsequent sinking and export of organic carbon is estimated at about 0.135 gigatonnes of carbon per year (note that this estimate has large uncertainties[15]).

The key finding from this review of the present Arctic Ocean carbon cycle is: 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 of the global ocean's net uptake of carbon dioxide.

> **"At present, the Arctic Ocean is a globally important net sink, responsible for the 5 to 14 per cent of the global ocean's net uptake of carbon dioxide."**

Vulnerability of Arctic Ocean carbon to change

The potential vulnerability of the marine carbon cycle due to natural and human-caused climate-change factors include: (1) sea-ice loss, warming, circulation and other physical changes; (2) changes in biology and ecosystem structure of the Arctic; (3) changes in the water cycle and freshwater inputs to the Arctic Ocean, and; (4) ocean acidification effects. Of these factors, sea-ice loss, phytoplankton growth, and warming appear to be the primary agents of change over the next decade or so.

In the near-term, due to the disproportionate rates of carbon fluxes, changes in atmosphere-ocean carbon fluxes and flux of biologically produced organic carbon from surface to deep waters will influence the marine carbon cycle more strongly than changes in land-to-ocean carbon fluxes.

A short-term increase in carbon uptake by the Arctic Ocean is projected

Changes in atmosphere-ocean carbon fluxes

In the near-term, sea-ice loss is expected to increase the uptake of carbon dioxide by surface waters[9, 10, 11], because the exposed surface waters have a lower carbon dioxide content than the atmosphere. The loss of sea-ice effectively removes the barrier to the atmosphere-ocean exchange of gases such as carbon dioxide, but also for other gases that are important to climate, including methane and dimethylsulfide (which is emitted to the atmosphere by marine phytoplankton and affects cloud formation).

The loss of sea-ice in the past few decades has reduced sea-ice cover by about 36,000 square kilometres per year, thereby exposing surface waters of the arctic shelves and central basin. In the early 2000s, the Arctic Ocean took up about 3 to 4 per cent more carbon dioxide per year (about 0.002 gigatonnes of carbon per year) than it had previously[10]. More recently, however, in 2007 and 2008, seasonal sea-ice extent reached a seasonal minimum, 25 per cent lower than any previously observed in the satellite record. This constituted an additional exposure of about

600,000 square kilometres of surface waters to atmosphere-ocean exchange of gases. Assuming that the carbon dioxide content of surface and subsurface waters had not changed significantly since early this century, this recent loss of summertime sea-ice cover has increased the uptake of carbon dioxide into the Arctic Ocean by an additional 0.033 gigatonnes of carbon (plus or minus 0.01 gigatonnes) per year[11]. This has increased the size of the arctic carbon dioxide sink by 20 to 50 per cent over the last several years, with potentially similar implications for other gases.

Given this scenario, the Arctic Ocean carbon dioxide sink will have increased its contribution to the global balance of carbon dioxide sinks and sources from about 5 to 14 per cent to as much as 18 per cent. This masks the global reduction of the ocean uptake of carbon dioxide over the last few decades and, thus, is increasingly important to the feedback between the global carbon cycle and climate. Over time, carbon and carbon dioxide distributions in surface and subsurface waters, atmosphere-ocean carbon dioxide gradients, and the capacity of the Arctic Ocean to uptake carbon dioxide are expected to change in response to environmental changes driven largely by climate and environmental change. This makes future predictions of the Arctic Ocean carbon dioxide sink/source trajectory beyond the next decade difficult.

The loss of sea-ice in the Arctic also is likely to result in greater open water area and increased air-sea interaction, with a variety of consequences. Increased atmospheric instability will probably result in increased wind speed and storm events over the Arctic. Although the direction of atmosphere-ocean gas exchange is forced by differences in the carbon dioxide concentration between the ocean and the atmosphere, the rate of gas exchange of carbon dioxide and other gases is primarily driven by wind speed and air and surface water interactions. Given this, even though atmosphere-ocean carbon dioxide differences might decrease, atmosphere-ocean carbon dioxide gas exchange rates can increase. This is because gas transfer speeds increase exponentially relative to wind speed[29].

Wintertime sea-ice is now thinner than in previous decades, and there may be potentially greater atmosphere-ocean gas exchange directly through sea-ice[30], as a result of the potential weakening of the sea-ice barrier to gas exchange. In the winter, wind-driven areas of open-water surrounded by sea-ice open up (in particular on the Chukchi and Laptev sea shelves[19]) and facilitate the uptake of carbon dioxide from the atmosphere[9, 10]. Thus, as openings of ice-free water surrounded by sea ice increase in size and number, the size of the carbon dioxide sink in the Arctic may increase in the near future, depending on inorganic carbon distributions and future differences in the concentration of carbon dioxide between the atmosphere and ocean.

"Further sea-ice loss, increases in phytoplankton growth rates, and other changes are expected to cause a limited net increase in the uptake of carbon dioxide by arctic surface waters."

The loss of sea-ice in the Arctic, increased open-water area, and increased shelf-basin exchanges will also increase mixing of deeper, nutrient-rich waters onto the arctic shelves. In the Chukchi and Beaufort seas, the phytoplankton-growing season has apparently increased in the last decade[7], especially as a result of reduced sea-ice extent and longer open-water conditions. As a consequence of increased phytoplankton growth, the potential for the Arctic Ocean to uptake carbon dioxide will increase.

A key finding is that 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

Other process may somewhat counteract the increase in Arctic Ocean uptake of carbon dioxide. Reduced cooling of water during its movement to the poles and increased absorption of the sun's energy that results in the warming of surface water relative to previous decades should act to increase the carbon dioxide content of seawater[34]. In the recent past (1998-2006), warming of up to 2°C had been observed in the regions of significant sea-ice loss (mainly on the "inflow" arctic shelves such as the Chukchi and Barents seas[8]). If surface waters warm by 4 to 5°C as a consequence of climate change predicted by the end of this century and if present-day carbon and carbon dioxide distributions remain unchanged, the Arctic Ocean carbon dioxide sink will significantly decrease in size as a result of warming. This process may somewhat counteract the impacts of sea-ice and increased phytoplankton photosynthesis and growth on the atmosphere-ocean exchange of carbon dioxide. If there are ecosystem shifts in the future as a result of further climate change, the export of organic carbon and interactions between the pelagic (open ocean) and benthic (seafloor) ecosystem might decrease[35], despite concurrent increases in marine phytoplankton photosynthesis and growth[7].

There are likely to be changes in the carbon pools of subsurface waters on the arctic shelves and subsurface waters of the central basin. In the central basin, density stratification generally acts as a barrier to mixing between nutrient-poor surface waters and nutrient-rich subsurface waters. Subsurface waters generally have much higher carbon dioxide content than surface waters, with low rates of mixing between these waters and the surface mixed layer[17]. The surface mixed layer typically extends to 10 to 50 metres, with depth heavily dependent on mixing due to winds and sea-ice cover. The loss of sea-ice should facilitate deeper mixing and bring nutrient and carbon dioxide-rich subsurface waters to the surface. This could either increase or decrease atmosphere-ocean carbon dioxide exchanges depending on biological responses of the Arctic Ocean surface ecosystem to the increased supply of nutrients.

The above discussion of responses of the Arctic Ocean sink of carbon dioxide as a result of physical and biological changes, including sea-ice loss and other factors, has many uncertainties and associated caveats. These studies are only applicable to the near-term future (less than a decade), because it is assumed that the driving force of atmosphere-ocean gas exchange (e.g., carbon dioxide and dissolved inorganic carbon distributions of surface and subsurface waters) will not change significantly over the residence time of surface waters in the Arctic (e.g., 2 to 30 years). However, in the era of rapid change in the Arctic, water-column carbon distributions and atmosphere-ocean carbon dioxide exchange rates are highly likely to change and be responsive to a host of other factors and feedbacks, both on local and global scales.

Release of carbon from the arctic landmasses

Finally, freshwater inputs from arctic rivers and the transport of sediment and dissolved materials such as land-derived organic carbon are also expected to increase[1] (see *Land Carbon Cycle Feedbacks* chapter). For example, the eastern Beaufort Sea shelf is highly affected by the Mackenzie River outflow of freshwater, and increased open-water through sea-ice loss may increase the photochemical breakdown of organic carbon to carbon dioxide in surface waters. Given the potentially large stores of land-based carbon that may be released to the Arctic Ocean over the next few centuries, the present Arctic Ocean carbon dioxide sink may reverse if significant amounts of terrestrial organic carbon are broken down to carbon dioxide through microbially mediated (i.e., through the activity of bacteria) and photochemical processes.

A key finding is that the release of large stores of carbon from the surrounding arctic landmasses through rivers into the Arctic Ocean may reverse the near-term trend of higher atmosphere to ocean carbon flux over the next century, leading to a net increase of carbon dioxide released to the atmosphere from this region.

> **“The release of large stores of carbon from the surrounding arctic landmasses through rivers into the Arctic Ocean may reverse the near-term trend of higher atmosphere to ocean carbon flux over the next century, leading to a net increase of carbon dioxide released to the atmosphere from this region.”**

Ocean acidification effects in the Arctic Ocean

As a consequence of the ocean uptake of human-induced carbon dioxide emissions, surface water carbon dioxide content has increased, while its *p*H has decreased (a decrease in *p*H indicates an increase in its acidity) in the upper ocean (over the last few decades in particular)[36]. This gradual process, termed ocean acidification, has long been recognized by chemical oceanographers[37], but more recently brought to general attention. The predicted ocean uptake of human-caused carbon dioxide, based on IPCC scenarios[38], is expected to increase hydrogen ion concentration (a measure of *p*H) by 185 per cent and decrease its *p*H by 0.3 to 0.5 units over the next century and beyond[39], with the Arctic Ocean impacted before other regions as a result of the relatively low *p*H of polar waters compared to other waters[12, 13]. The effects of ocean acidification are potentially far-reaching in the global ocean, particularly for organisms that secrete *p*H-sensitive shells or tests of calcium carbonate minerals (i.e., calcifying fauna)[40, 41] and those organisms that feed on calcifying fauna.

Ocean acidification and decreased *p*H reduces the saturation states of calcium carbonate minerals such as aragonite and calcite, with many studies showing decreased calcium carbonate production by calcifying fauna[40, 41] and increased dissolving of calcium carbonate in the water column and in sediments. Recently, the effects of upwelling and impingement of corrosive waters on calcium carbonate has been demonstrated[42] on the west coast of the United States. In the Arctic Ocean, potentially corrosive waters are found in the subsurface layer of the central basin[43]. On the Chukchi Sea, waters corrosive to calcium carbonate seasonally affect the shelf sediments and organisms that live near the seafloor, as a result of high rates of summertime phytoplankton growth, the upward export of organic carbon, and the buildup of carbon dioxide in subsurface waters that has been amplified by ocean acidification over the last century[14]. Given the scenarios for *p*H changes in the Arctic Ocean, the arctic shelves will be increasingly affected by ocean acidification and presence of carbonate mineral undersaturated waters, with potentially negative implications for shelled organisms that live on and near the seafloor as well as for those animals that feed on the seafloor ecosystem.

The arctic marine carbon cycle is very sensitive to climate change

At present, the Arctic Ocean continental shelves and central basin have lower carbon dioxide content than the atmosphere. There are, however, localized areas of surface seawater that are highly influenced by sea-ice melt and river inputs where the opposite is observed, and these areas are potential sources of carbon dioxide to the atmosphere. The carbon dioxide chemistry of the Arctic Ocean is highly influenced by physical and biological processes, such as seasonal marine phytoplankton photosynthesis and growth during summertime sea-ice retreat toward the pole, as well as temperature effects (both cooling and warming), shelf-basin exchanges and formation of dense winter waters, and river inputs of freshwater and land-based carbon.

At present, although seasonal sea-ice cover provides a barrier to atmosphere-ocean gas exchange, the Arctic Ocean is a sink for carbon dioxide, taking up about 0.065 to 0.175 gigatonnes of carbon per year, contributing 5 to 14 per cent to the global balance of carbon dioxide sinks and sources. The Arctic Ocean has become an important influence on the global carbon cycle, with the marine carbon cycle and atmosphere-ocean carbon dioxide exchanges sensitive to Arctic Ocean and global climate change feedbacks. In the near-term, further sea-ice loss and increases in phytoplankton growth rates are expected to increase the uptake of carbon dioxide by arctic surface waters, although mitigated somewhat by warming in the Arctic. Thus, the capacity of the Arctic Ocean to uptake carbon dioxide is expected to change in response to environmental changes driven largely by climate. These changes are likely to continue to modify the physics, biogeochemistry and ecology of the Arctic Ocean in ways that are not yet fully understood. Finally, in response to increased marine phytoplankton growth and uptake of human-produced carbon dioxide, the seafloor ecosystem of the arctic shelves is expected to be significantly harmed by ocean acidification, which reduces the ability of many species to produce calcium carbonate shells or skeletons, with profound implications for arctic marine ecosystems.

A key finding is that the arctic marine carbon cycle and exchange of carbon dioxide between the ocean and atmosphere is particularly sensitive to climate change. 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.

> **“The arctic marine carbon cycle and exchange of carbon dioxide between the ocean and atmosphere is particularly sensitive to climate change.”**

References

1 Arctic Climate Impact Assessment (ACIA), 2005. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

2 Serreze, M.C., and Francis, J.A., 2006. The Arctic amplification debate. *Climate Change* 76: 241-264.

3 Maslanik, J.A., Drobo, S., Fowler C., Emery, W., and Barry R., 2007. On the Arctic climate paradox and the continuing role of atmospheric circulation in affecting sea ice conditions. *Geophysical Research Letters* 34: Art. No. L03711 2007.

4 Wang, M.,Y., and Overland, J.E., 2009. A sea-ice free summer Arctic within 30 years? *Geophysical Research Letters* 36: L07502, April 03, 2009.

5 McGuire, A.D., Chapin, F.S., Walsh, J.E., and Wirth, C., 2006. Integrated regional changes in arctic climate feedbacks: implications for the global climate system. *Annual Rev. Environmental Resources* 31: 61-91.

6 Wu, P.L., Wood, R., and Stott, P., 2005. Human influence on increasing arctic river discharges. *Geophysical Research Letters* 32(2): L02703.

7 Arrigo, K.R., van Dijken, G.L., and Pabi, S., 2008. The impact of a shrinking Arctic ice cover on marine primary production. *Geophysical Research Letters* 35: L19603, doi:10.1029/2008GL035028.

8 Pabi, S., van Dijken, G.L., and Arrigo, K.R., 2008. Primary production in the Arctic Ocean, 1998-2006, *Journal of Geophysical Research*,113: C08005, doi:10.1029/2007JC004578.

9 Anderson, L.G., and Kaltin, S., 2001. Carbon fluxes in the Arctic Ocean - potential impact by climate change. *Polar Research* 20 (2): 225-232.

10 Bates, N.R., Moran, S.B., Hansell, D.A., and Mathis, J.T., 2006. An increasing carbon dioxide sink in the Arctic Ocean due to sea-ice loss? *Geophysical Research Letters* 33: L23609, doi:10.1029/2006GL027028.

11 Bates, N.R., and Mathis, J.T., 2009. The Arctic Ocean marine carbon cycle: Evaluation of air-sea carbon dioxide exchanges, ocean acidification impacts and potential feedbacks. *Biogeosciences Discussion* MS No., bg-2009-159.

12 Orr, J.C., Fabry, V.J., Aumont, O., Bopp, L., Doney, S.C., Feely, R.A., Gnanadesikan, A., Gruber, N., Ishida, A., Joos, F., Key, R.M., Lindsay, K., Maier-Reimer, E., Matear, R., Monfray, P., Mouchet, A., Najjar, R.G., Plattner, G. K., Rodgers, K.B., Sabine, C.L., Sarmiento, J.L., Schlitzer, R., Slater, R D., Totterdell, I.J., Weirig, M.F., Yamanaka, Y., and Yool, A., 2005. Anthropogenic ocean acidification over the twenty-first century and its impacts on calcifying organisms. *Nature* 437: 681–686.

13 Steinacher, M., Joos, F., Frolicher, T.L., Plattner, G.-K., and Doney, S.C., 2009. Imminent ocean acidification of the Arctic projected with the NCAR global coupled carbon-cycle climate model. *Biogeosciences* 6: 515-533.

14 Bates, N.R., Mathis, J.T., and Cooper, L., *in press*. The effect of ocean acidification on biologically induced seasonality of carbonate mineral saturation states in the Western Arctic Ocean. *Journal of Geophysical Research-Oceans* (Paper Number 2008JC004862).

15 Macdonald, R.W. Anderson, L.G., Christensen, J.P., Miller, L.A., Semiletov, I.P., and Stein, R., 2009. The Arctic Ocean. In *Carbon and Nutrient Fluxes in Continental Margins: A Global Synthesis*. Liu, K.K., Atkinson, L., Quinones, R., and Talue-McManus, L., (editors, Springer, New York, 291-303.

16 Jones, E.P., and Anderson, L.G., 1986. On the origin of chemical properties of the Arctic Ocean halocline. *Journal of Geophysical Research* 91: 10,759-10,767.

17 Wallace, D.W.R., Moore, R.M., and Jones, E.P., 1987. Ventilation of the Arctic Ocean cold halocline: rates of diapycnal and isopycnal transport, oxygen utilization and primary production inferred using chlorofluoromethane distributions. *Deep-Sea Research* 34: 1957-1979.

18 Cooper, L.W., McClelland, J.W., Holmes, R.M., Raymond, P.A., Gibson, J.J., Guay, C.K., and Peterson, B.J., 2008. Flow-weighted tracer content (^{18}O, DOC, Ba, alkalinity) of the six largest Arctic rivers. *Geophysical Research Letters* 35: L18606, doi:10.1029/2008GL035007.

19 Carmack, E.C. and Chapman, D., 2003. Wind-driven shelf/basin exchange on an Arctic shelf: The joint roles of ice cover extent and shelf-break bathymetry. *Geophysical Research Letters* 30: 1778, doi: 10.1029/2003GL017526.

20 Maslanik, J.A., Drobo, S., Fowler C., Emery, W., and Barry R., 2007. On the Arctic climate paradox and the continuing role of atmospheric circulation in affecting sea ice conditions. *Geophysical Research Letters* 34: Art. No. L03711 2007.

21 Comiso, J.C., Parkinson, C.L., Gersten, R., and Stock, L., 2008. Accelerated decline in Arctic sea ice cover. *Geophysical Research Letters* 35(1): L01703, doi 10.1029/2007GL031972.

22 Perovich, D.K. Light, B., Eicken, H., Jones, K.F., Runciman, K., and Nghiem. S.V., 2007. Increasing solar heating of the Arctic Ocean and adjacent seas, 1979-2005: Attribution and role in the ice-albedo feedback. *Geophysical Research Letters* 34, L19505.

23 Carmack, E. and Wassman, P., 2006. Food webs and physical-biological coupling on pan-Arctic shelves: Unifying concepts and comprehensive perspectives. *Progress in Oceanography* 71: 446-477.

24 Codispoti, L. Flagg, C., and Kelly, V., 2005. Hydrographic conditions during the 2002 SBI process experiments. *Deep-Sea Research II* 52**:** 3199-3226.

25 Cota, G.F., Pomeroy, L.R., Harrison, W.G., Jones, E.P., Peters, F., Sheldon W.M., and Weingartner T.R., 1996. Nutrients, primary production and microbial heterotrophy in the southeastern Chukchi Sea: Arctic summer nutrient depletion and heterotrophy. *Marine Ecology Progress Series* 135 (1-3): 247-258.

26 Hill, V.J., and Cota, G.F., 2005. Spatial patterns of primary production in the Chukchi Sea in the spring and summer of 2002. *Deep-Sea Research II* 52: 3344-3354.

27 Feder, H.M., Jewett S.C., and Blanchard A., 2005. Southeastern Chukchi Sea (Alaska) epibenthos. *Polar Biology* 28**(**5): 402-421.

28 Anderson, L.G., Jones, E.P., and Swift, J.H., 2003. Export production in the central Arctic Ocean evaluated from phosphate deficits. *Journal of Geophysical Research* 108(C6): 3199, doi:10.1029/2001JC001057.

29 Wanninkhof, R., 1992. Relationship between wind speed and gas exchange over the ocean, *Journal of Geophysical Research, Oceans* 97: 7373-7382.

30 Delille, B., Jourdain, B., Borges, A.V., Tison, J.-L., and Delille, D., 2007. Biogas (CO_2, O_2, dimethylsulfide) dynamics in spring Antarctic fast ice. *Limnology Oceanography* 52: 1367–1379.

31 Takahashi, T., Sutherland, S.C., Wanninkhof, R., Sweeney, C., Feely, R.A., Chipman, D.W., Hales, B., Friederich, G.E., Chavez, F.P., Watson, A.J., Bakker, D.C.E., Schuster, U., Metzl, N., Yoshikawa-Inoue, H., Olafsson, J., Arnarson, T.S., Tilbrook, B., Johannessen, T., Olsen, A., Bellerby, R.J., de Baar, H.J.W., Nojiri, Y., Wong, C.S., Delille, B., and Bates, N.R., 2009. Climatological mean and decadal change in surface ocean pCO_2, and net sea-air carbon dioxide flux over the global oceans. *Deep-Sea Research II* 56: 554-577.

32 Kelley, J.J., 1970. Carbon dioxide in the surface waters of the North Atlantic and the Barents and Kara Sea. *Limnology and Oceanography* 15: 80-87

33 Nitishinsky, M., Anderson, L.G., and Holemann, J.A., 2007. Inorganic carbon and nutrient fluxes on the Arctic Shelf. *Cont. Shelf Res*. 27: 1584–1599, doi:10.1016/j.csr.2007.01.019.

34 Takahashi, T., Sutherland, S.G., Sweeney, C., Poisson, A.P., Metzl, N., Tilbrook, B., Bates, N.R., Wanninkhof, R.H., Feely, R.A., Sabine, C.L., and Olafsson, J., 2002. Biological and temperature effects on seasonal changes of pCO_2 in global ocean surface waters*. Deep-Sea Research II* 49: 1601-1622.

35 Piepenburg, D., 2005. Recent research on Arctic benthos: common notions need to be revised. *Polar Biology* 28(10): 733-755.

36 Bates, N.R., 2007. Interannual variability of the oceanic carbon dioxide sink in the subtropical gyre of the North Atlantic Ocean over the last two decades. *Journal of Geophysical Research (Oceans)* 112: doi:10.1029/2006JC003759.

37 Broecker, W.S., and Takahashi, T., 1966. Calcium carbonate precipitation on the Bahama Banks. *Journal of Geophysical Research* 71,:1575–1602.

38 Solomons, S., Qin, D., Manning, M., Marquis, M., Averyt, K., Tignor, M.M.B., Miller, H.L., and Chen, Z., 2007. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (Cambridge Univ. Press, Cambridge and New York, 2007).

39 Caldeira, K., and Wickett, M.E., 2003. Anthropogenic carbon and ocean *p*H, *Nature* 425 (6956): 365-365.

40 Buddemeier, R.W., Kleypas, J.A., and Aronson, R.B., 2004. *Coral Reefs and Global Climate Change: Potential Contributions of Climate Change to Stresses on Coral Reef Ecosystems*, p. 44, (download report at http://www.pewclimate.org/global-warmingindepth/all_reports /coral_reefs/index.cfm). Pew Center on Climate Change.

41 Fabry, V.J., Seibel, B.A., Feely, R.A., and Orr, J.C. 2008. Impacts of ocean acidification on marine fauna and ecosystem processes. *ICES Journal of Marine Science* 65: 414–432.

42 Feely, R.A., Sabine, C.L, Hernandez-Ayon, J.M., Ianson, D., and Hales, B., 2008. Evidence for upwelling of corrosive “acidified” water onto the continental shelf. *Science* 320: 1490-1492.

43 Jutterström, S., and Anderson, L.G., 2005. The saturation of calcite and aragonite in the Arctic Ocean. *Marine Chemistry* 94: 101-110.

44 Nakaoka, S., Aiki, S., Nakazawa, T., Hashida, G., Morimoto, S., Yamanouchi, T., and Yoshikawa-Inoue, H., 2006. Temporal and spatial variations of oceanic pCO2 and air-sea carbon dioxide flux in the Greenland Sea and the Barents Sea. *Tellus* 58(2): 148-161.

45 Omar, A.M., Johannessen, T., Olsen, A., Kaltin, S., and Rey, F., 2007. Seasonal and interannual variability of the air-sea carbon dioxide flux in the Atlantic sector of the Barents Sea. *Marine Chemistry* 104: 203–213, doi:10.1016/j.marchem.2006.11.002.

46 Fransson, A., Chierici, M., Anderson, L.C., Bussmann, I., Kattner, G., Jones, E.P., and Swift, J.H., 2001. The importance of shelf processes for the modification of chemical constituents in the waters of the Eurasian Arctic Ocean: implications for carbon fluxes. *Continental Shelf Research* 21(3): 225-242.

47 Kaltin, S., Anderson, L.G., Olsson, K., Fransson, A., and Chierici M., 2002. Uptake of atmospheric carbon dioxide in the Barents Sea. *Journal of Marine Systems* 38 (1-2): 31-45.

48 Anderson, L.G., Olsson, K., and Chierici, M., 1998. A carbon budget for the Arctic Ocean. *Global Biogeochemical Cycles* 12 (3): 455-465.

49 Nitishinsky, M., Anderson, L.G., and Holemann, J.A., 2007. Inorganic carbon and nutrient fluxes on the Arctic Shelf. *Cont. Shelf Res.* 27: 1584–1599, doi:10.1016/j.csr.2007.01.019.

50 Semiletov, I.P., Pipko, I.I., Repina, I., and Shakhova, N.E., 2007. Carbonate chemistry dynamics and carbon dioxide fluxes across the atmosphere-ice-water interface in the Arctic Ocean. *Journal of Marine Systems* 66: 204-226.

51 Murata, A., and Takizawa, T., 2003. Summertime carbon dioxide sinks in shelf and slope waters of the western Arctic Ocean. *Continental Shelf Research* 23 (8): 753-776.

52 Bates, N.R., Moran, S.B., Hansell, D.A., and Mathis, J.T., 2006. An increasing carbon dioxide sink in the Arctic Ocean due to sea-ice loss? *Geophysical Research Letters* 33: L23609, doi:10.1029/2006GL027028

53 Anderson, L.G., and Kaltin, S., 2001. Carbon fluxes in the Arctic Ocean - potential impact by climate change. *Polar Research* 20 (2): 225-232.

54 Bates, N.R., and Mathis, J.T., 2009. The Arctic Ocean marine carbon cycle: Evaluation of air-sea carbon dioxide exchanges, ocean acidification impacts and potential feedbacks. *Biogeosciences Discussion*, MS No. bg-2009-159.

55 Anderson, L.G., Dyrssen, D., and Jones, E.P., 1990. An assessment of the transport of atmospheric carbon dioxide into the Arctic Ocean, *J. Geophys. Res*. 95: 1703– 1711.

56 Anderson, L.G., Olsson, K. and Skoog, A., 1994. Distribution of dissolved inorganic and organic carbon in the Eurasian basin of the Arctic Ocean. in Polar Oceans and Their Role in Shaping the Global Environment, American Geophysical Unions, *Geophysical Monograph* 85: 255-262.

57 Lundberg, L., and Haugen, P.M., 1996. A Nordic Seas – Arctic Ocean carbon budget from volume flows and inorganic carbon data. *Global Biogeochemical Cycles* 10: 493–510.

58 Kaltin, S., and Anderson, L.G., 2005. Uptake of atmospheric carbon dioxide in Arctic shelf seas: Evaluation of the relative importance of processes that influence pCO2 in water transported over the Bering-Chukchi Sea shelf. *Marine Chemistry* 94: 67–79.

59 Bates, N.R., 2006. Air-sea carbon dioxide fluxes and the continental shelf pump of carbon in the Chukchi Sea adjacent to the Arctic Ocean. *Journal of Geophysical Research (Oceans)* 111: C10013, doi 10.129/2005JC003083.

5. LAND CARBON CYCLE FEEDBACKS

Josep G. Canadell and Michael R. Raupach

Global Carbon Project, CSIRO Marine and Atmospheric Research, ACT 2601, Australia

THE ARCTIC CONTAINS the largest deposits of organic carbon of any region on Earth. Arctic terrestrial ecosystems play an important role in the global carbon cycle, making large contributions to fluxes of the greenhouse gases carbon dioxide and methane. Both outflows of carbon from and inflows of carbon to Arctic terrestrial ecosystems have been altered as climate has warmed. As warming continues in the future, carbon emissions from Arctic lands are projected to outpace uptake, further adding to global warming.

Key Findings:

- **Arctic lands store large amounts of carbon.** Arctic soils and wetlands store large amounts of carbon. Including all northern circumpolar regions, they have 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.

Arctic terrestrial ecosystems play a significant role in the global carbon cycle, making large contributions to fluxes of the greenhouse gases carbon dioxide and methane. In recent decades, the cycling of these gases in the Arctic has accelerated in response to persistent climate warming. Both outflows from and inflows to arctic terrestrial ecosystems have been altered.

The flux of carbon from terrestrial ecosystems to the atmosphere occurs in the form of carbon dioxide and methane, and into rivers and oceans it occurs in the form of particulate and dissolved organic matter (**Figure 1**). This carbon originates from the decomposition of organic matter deposited thousands of years ago that has been stable as a result of low temperatures in the permafrost (soils frozen for more than two consecutive years) in which it was stored. When permafrost thaws it creates thermokarst, a landscape of collapsed and subsiding ground with new or enlarged lakes, wetlands, and craters on the surface. In this landscape, carbon dioxide is the predominant flux to the atmosphere in upland areas with good drainage and oxygen available for microbial activity. Methane is the dominant flux in waterlogged areas and in lakes where low-oxygen (anaerobic) conditions only allow for methanogens, microbes that decompose organic matter and release methane as a by-product[1]. Disturbances such as fires and insect damage in the forests of southern arctic regions are responsible for additional carbon outflows.

Carbon inflows to arctic terrestrial ecosystems (atmospheric carbon sinks) are increasing as a result of extended plant growth under longer growing seasons and northward migration of woody vegetation due to a warmer climate. Higher levels of atmospheric carbon dioxide also accelerate plant growth. The interplay of these and other processes will determine the net effect of the arctic carbon cycle on greenhouses gases. Warming in the Arctic will lead to a net increase of greenhouse gas emissions, causing the arctic carbon cycle to be an accelerating influence on climate change.

"Warming in the Arctic will lead to a net increase of greenhouse gas emissions, causing the arctic carbon cycle to be an accelerating influence on climate change."

Carbon pools and fluxes

At a global scale, atmospheric carbon dioxide is rising because of an imbalance between inputs of carbon dioxide to the atmosphere (from fossil fuel combustion and land-use change) and removals from the atmosphere by land and ocean carbon dioxide sinks. In 2007, total inputs amounted to 10 gigatonnes of carbon per year (1 gigatonne of carbon equals 1 billion tonnes of carbon) and total removals to about 5.5 gigatonnes of carbon per year (divided roughly equally between land and ocean sinks), leaving 4.5 gigatonnes of carbon per year to accumulate in the atmosphere and raise the atmospheric carbon dioxide concentration by about 2 parts per million (current concentration is 385 parts per million)[2].

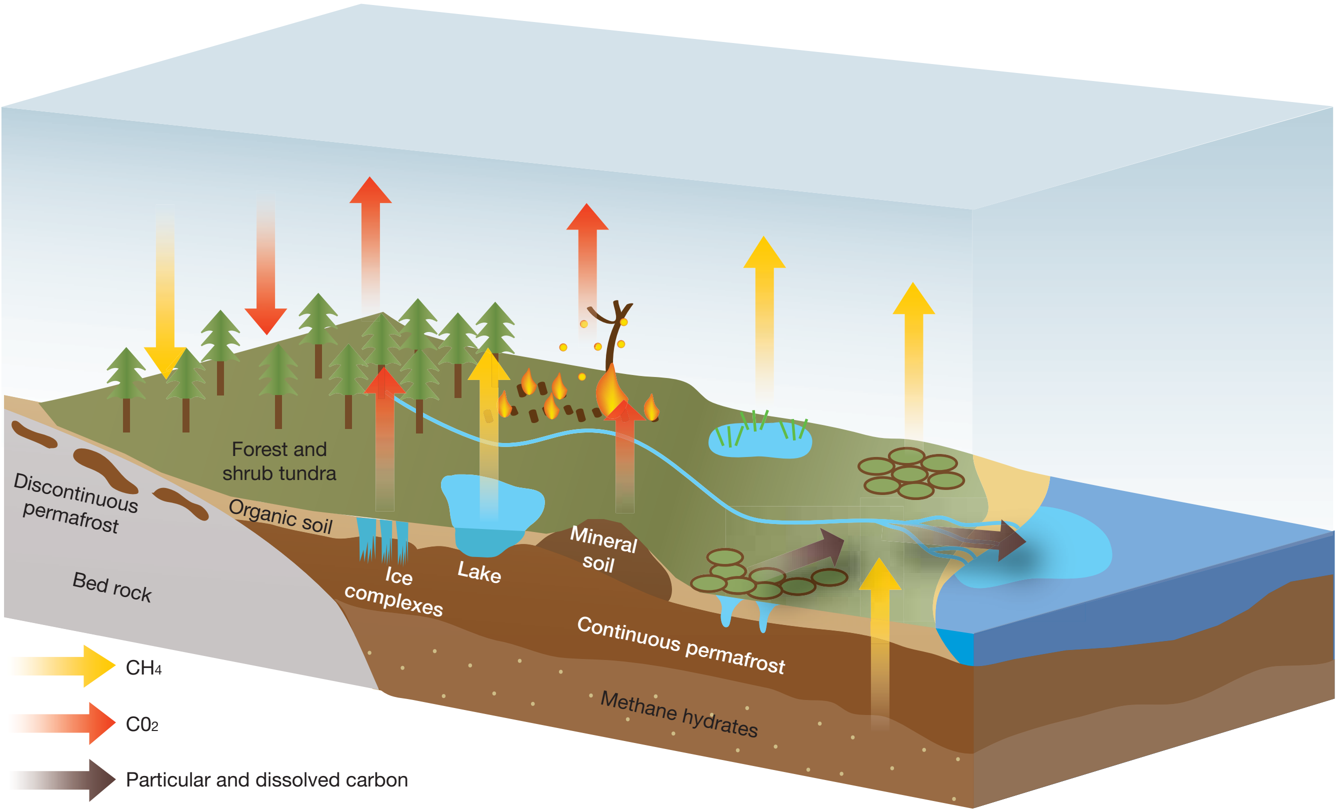


Figure 1. Major carbon outflows (sources) and inflows (sinks) in arctic terrestrial ecosystems. Source: UNEP.

Arctic terrestrial ecosystems make an important contribution to terrestrial carbon fluxes (**Figure 1**). They remove about 0.3 to 0.6 gigatonnes of carbon per year (about 10 to 20 per cent of the total global land carbon dioxide sink), they add about 0.03 to 0.1 gigatonnes of methane to the atmosphere (about 5 to 15 per cent of all methane sources into the atmosphere at present), and they contribute relatively smaller but still significant carbon export as dissolved organic matter into arctic rivers and eventually into the oceans[3]. These quantities represent important natural fluxes that contribute to the global carbon dioxide and methane budgets.

The arctic terrestrial carbon cycle is unique in that it includes the largest deposits of organic carbon of any region on Earth. This carbon was deposited over millennia of slow growth by mosses, grasses and woody plants. As these plants decayed to litter and eventually to soil carbon, there was little release of the stored carbon to the atmosphere as a result of prevalent low temperatures that did not allow microorganisms to break down the organic matter. The result was a slowly growing deposit of carbon that over many millennia became one of the largest deposits on Earth (**Figure 2a**).

Most of these carbon deposits are presently locked away from the atmosphere in frozen ground and so are not contributing significantly to the build up of atmospheric greenhouse gases (**Figure 3**). As the climate continues to heat up, parts of this vast

Figure 3. Frozen soil sediment deposit in Siberia.

Edward A. G. Schuur

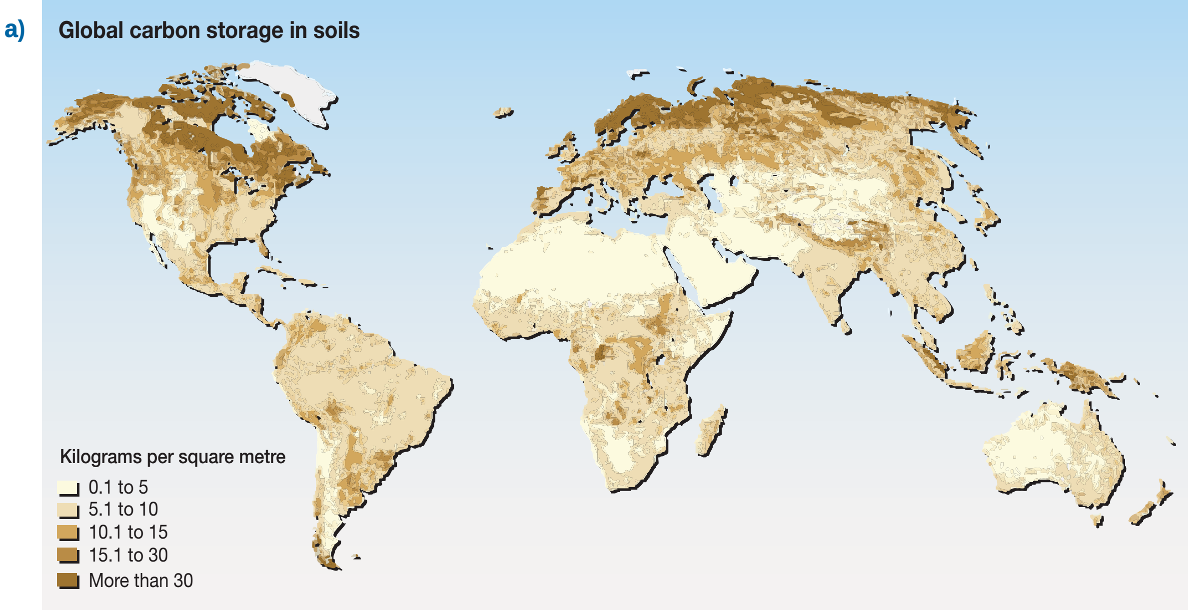


Figure 2. Estimated distribution of soil organic matter in (**a**) global terrestrial ecosystems[27], and (**b**) the circumpolar permafrost region[4].

arctic carbon store are being exposed to conditions favourable to decomposition and, as a result, releasing greenhouse gases to the atmosphere. These emissions will act to accelerate climate change by causing it to feed on itself as more carbon is released to the atmosphere, causing the climate to warm even more rapidly.

Arctic vegetation accounts for about 60 to 70 gigatonnes of carbon[3], but a much larger amount is stored in the soil. A new assessment has estimated that there are 1,650 gigatonnes of carbon stored in the northern circumpolar permafrost region[4], more than twice the amount of carbon in the atmosphere (**Figure 2b**). For comparison with other terrestrial regions, the tropics hold 340 gigatonnes of carbon in vegetation and 692 gigatonnes of carbon in soils, temperate forests hold 139 gigatonnes of carbon in vegetation and 262 gigatonnes of carbon in soil[5]. The new estimate of 1,650 gigatonnes of carbon for arctic soil carbon storage is more than double what has been previously estimated and includes several new pools that were not previously reported, such as such as the carbon content across the region down to 3 metres (1,026 gigatonnes of carbon), yedoma deposits (a carbon- and ice-rich permafrost soil) to an average depth of 25 metres (407 gigatonnes of carbon), and delta deposits (241 gigatonnes of carbon). Deposits located at river deltas are mostly confined to large rivers such as the Mackenzie in Canada, Yukon in

Sergei Zimov

Figure 4. Methane emerging from thermokarst lake in Siberia.

Alaska and Lena in Russia, but yedoma deposits, which are particularly vulnerable to decomposing due to warming, extend more than 1 million square kilometres in the northern plains of Siberia and Central Alaska.

The Arctic also has large stores of methane hydrates (in which methane is chemically trapped in ice) in both marine and land environments. Land-based deep permafrost layers have been estimated to contain 400 gigatonnes of methane hydrates (see *Methane hydrates* chapter).[6]

Vulnerability of arctic carbon

Large carbon pools are not necessarily a threat to climate; this carbon has been stored in frozen ground for many millennia. It is the combination of large soil carbon pools and amplified temperature increases in the Arctic both now and in the future (at least double the global average warming) that makes carbon in the arctic region particularly vulnerable and raises concern about its possible role as an accelerating agent for climate change.

The extent of the vulnerability of carbon in permafrost has been shown by recent measurements of the quantity and age of carbon emissions from thawing soils in Alaska[7]. In areas where thawing has been occurring for decades, up to 80 per cent of all respired carbon came from soil organic matter deposited thousands of years ago (old carbon). Overall, carbon emissions and sinks from plant growth and soil respiration resulted in a net increase in the amount of carbon emitted to the atmosphere. Contrary to earlier claims that old carbon could be quite inert and difficult to decompose, these new results show that carbon accumulated thousands of years ago is highly decomposable and capable of being released to the atmosphere when provided with appropriate conditions through global warming and other climate changes. These results add to earlier findings regarding the high decomposability of organic matter in yedoma sediments in Siberia, where large amounts of plant and animal residues make soil carbon easy to decompose under changed conditions[8].

Even without permafrost thawing, subarctic peatlands also holding large quantities of organic matter are highly sensitive to increased temperatures. Recent experimental work shows that one single degree warming can release as much as 0.1 gigatonnes of carbon per year from this ecosystem worldwide[9].

Vulnerability of carbon pools also comes in the form of disturbances, particularly in boreal forests where fire and insect damage has been on the rise over the last few decades due to longer summers and warmer winters respectively[10, 11,]. In these systems, disturbances play a dominant role in the carbon balance, and it is thought that they will become even more significant under warmer conditions.

In addition to carbon dioxide emissions, methane emissions are an important component of the carbon balance in the arctic region (**Figure 4**). The global warming potential of methane is 25 times higher than carbon dioxide. arctic terrestrial ecosystems currently emit between 0.03 gigatonnes and 0.11 gigatonnes of methane per year, mostly from vast wetlands[3]. In some arctic regions, as much as 20 to 30 per cent of the land area is covered with lakes[12,13].

Methane emissions are tightly coupled to both the water cycle and temperature, with higher emissions in flooded and warmer conditions. As a result of climate change, the Arctic will experience higher precipitation and temperature[14]. Draining waters from permafrost thawing also accelerates the water cycle and promotes the formation and persistence of lakes and wetlands and, as a result, increases methane fluxes. It will be the combination of all these factors with an evolving landscape topography that will determine the ultimate balance between emissions of carbon dioxide and methane. In recent years, methane concentrations in the atmosphere have increased in association with rising global temperatures. After more than a decade of stable concentrations, rapid growth of atmospheric methane was observed in 2007 and 2008, coinciding with two years of unusually high arctic temperatures[15, 16]. The higher temperatures on land were the result of increased absorption of the sun's energy in the arctic region, which was associated with the record high sea ice retreat in the summer of 2007 and the near-record retreat in 2008[17]. Current research suggests that wetlands in the northern polar region are an important cause of the renewed growth of global methane, and isotopic studies (based on small differences between methane molecules from different sources) have ruled out the possibility that the increase is due to emissions from methane hydrates[18] (See *Methane hydrates* chapter). Methane emissions from hydrates on land are largely the result of coastal erosion in the Arctic Ocean, and there is no evidence of an increase in response to human-induced higher temperatures.

"Disturbances driven by warmer and drier conditions have the potential to lead to rapid changes and tipping points."

Future climate effects

In the future, the arctic carbon cycle will undergo one of the biggest transformations of any region. There will be consequences for fluxes of carbon, nutrients, energy and water, for vegetation and biodiversity, and for interactions between the Arctic and global climate.

Many changes will unfold rapidly with immediate effects on the function and structure of the Arctic. For example, disturbances driven by warmer and drier conditions have the potential to lead to rapid changes and tipping points. Increased damage by insect attacks and fires have already tipped the carbon balance in parts of Canada, changing it from a small carbon sink to a net carbon source in just a decade[9, 10]. Likewise, fire in tundra regions overlaying permafrost has the potential to trigger rapid thawing in areas that would not otherwise occur, as darker surfaces absorb more of the sun's energy, which increases soil warming.

Other changes will occur more progressively over the course of decades and possibly extend over hundreds of years, regardless of climate stabilisation pathways chosen by governments. For example, carbon dioxide emissions from soil decomposition, resulting from higher temperatures, will contribute to such long-term fluxes. Current state-of-the-art modelling estimates that as much as 90 per cent of the near-surface permafrost might disappear by the end of this century, with most thawing occurring during the second half of the century[19] (**Figure 5**). This has the potential to release large amounts of carbon into the atmosphere, contributing significantly to warming.

In addition to increased carbon dioxide and methane emissions from decomposition of organic soil carbon, a small but widespread increase in plant productivity has been detected over most northern ecosystems in recent decades[20, 1]. A number of processes are involved, including northward movement of treelines, increased woody vegetation encroachment into the tundra, lengthening of the growing season, and the harder-to-measure carbon dioxide fertilization effect on photosynthesis (a higher atmospheric carbon dioxide concentration that enables increased plant photosynthesis if sufficient water and nutrients are present). These processes have an opposite effect from that of decomposition and disturbances because they remove carbon dioxide from the atmosphere. However, it is likely that carbon dioxide removal by vegetation will be outpaced by the release of carbon dioxide from thawing carbon-rich soils in the long run[1,7].

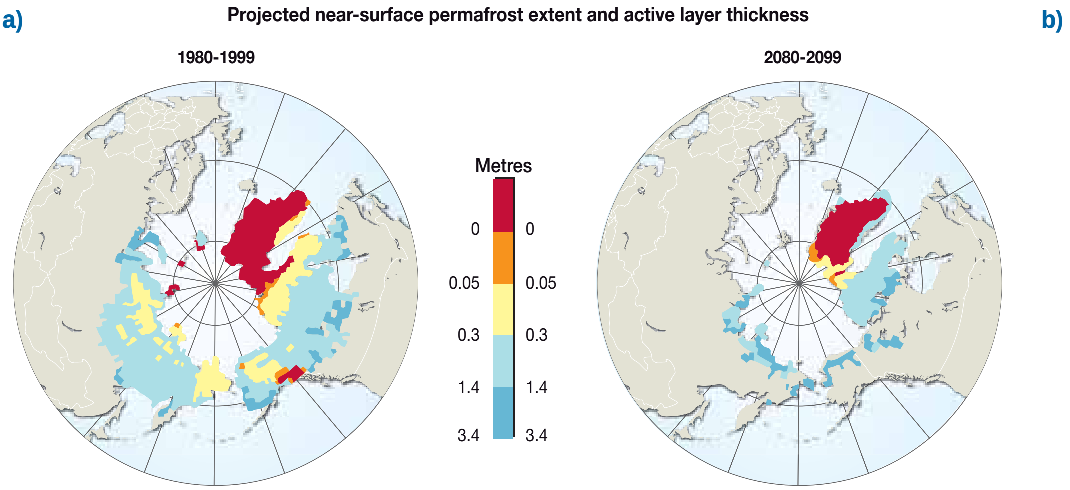
> **"As much as 90 per cent of the near-surface permafrost might disappear by the end of this century. This has the potential to release large amounts of carbon into the atmosphere, contributing significantly to warming."**

Carbon in vegetation can also be released as carbon dioxide to the atmosphere. In fact, carbon in vegetation is more vulnerable than carbon stored in frozen soils because of its exposure to disturbances such as fire and insect damage. Thus, the transfer of carbon locked in frozen ground into living biomass adds an additional long-term factor to those affecting the stability of carbon pools in the arctic region.

The net effect of the processes described above on the total carbon balance of arctic terrestrial ecosystems is not yet clear. While there are uncertainties about the magnitude of future warming, limitations in knowledge about various processes and how to model them over the large arctic region are the major impediments to projecting future carbon dynamics and their feedbacks with the climate system.

In fact, climate models participating in the last assessment of the Intergovernmental Panel on Climate Change[13] did not take into account the large carbon stocks in the Arctic and the interplay between changes in hydrology and fluxes of carbon dioxide and methane due to permafrost thawing. Other key drivers of carbon fluxes were also ignored by the models including the role of disturbances, the influence of mosses and other organic layers on soil heat and moisture dynamics, the relative sensitivities of different plant types to climate change, and water and

Figure 5. Simulated permafrost area and active layer thickness (**a**) 1980-1999 and (**b**) 2080-2099. (**c**) Observational estimates of permafrost (continuous, discontinuous, sporadic, and isolated). (**d**) Time series of simulated global permafrost area (excluding glacial Greenland and Antarctica)[17].

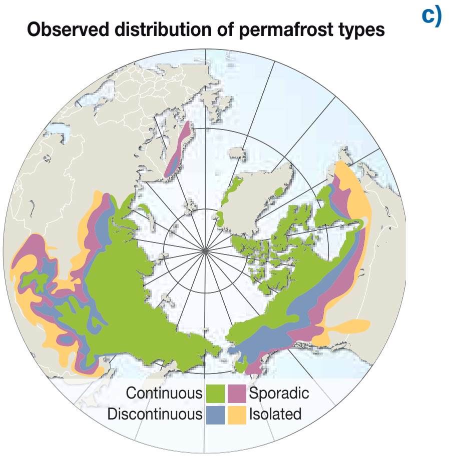


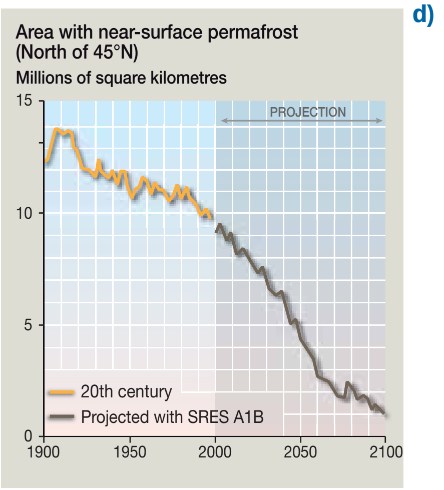
nutrient constraints on the fertilization effect of rising atmospheric carbon dioxide on photosynthesis[3].

While most global climate models with simple representations of the global carbon cycle suggest that the Arctic will be a carbon sink during this century[21], more comprehensive regional carbon models and field experiments dealing with many of the processes listed above indicate that the Arctic will emit significant amounts of carbon. Emission estimates over this century from these studies are between 50 to 110 gigatonnes of carbon — a similar amount of that predicted to be released by some middle- to top-range global deforestation scenarios during the same period[22,7].

Even if carbon emissions from arctic soils could be considered modest relative to the large amounts of fossil fuel emissions, they are significant quantities that add to other land- and marine-based carbon emissions, creating self-reinforcing cycles that further increase warming. There is also the distinct possibility that global warming may trigger a multi-century scale, irreversible process of thawing of permafrost and associated chronic carbon dioxide and methane emissions. It has been suggested that once deep-soil carbon mobilisation begins in warmer parts of the frozen yedoma sediments, the process will become self-sustaining through the heat generated by the activity of microorganisms (similar to the heat generated by the microbial activity in a compost pile). This would lead to an irreversible greenhouse gas emission process, taking place over hundreds of years and independent from the trajectory of human-induced greenhouse gas emissions[23].

Changes in the carbon cycle not only affect emissions and removals of atmospheric carbon dioxide and methane but also lead to changes in the physical landscape[24]. The most important change is a reduction in the reflectivity (albedo) of the surface as permanent and seasonal snow cover is partially replaced by dark,





“Arctic terrestrial ecosystems are sites of key vulnerabilities, which will have an important and accelerating influence on future climate change.”

woody vegetated surfaces, leading to increased absorption of the sun’s energy and more warming. As a result of these physical changes, it has been suggested that reforestation in high latitudes may be a counterproductive climate mitigation option[25]. Recent work in northern Alaska also concludes that decreased albedo due to snowmelt advance under warmer conditions overrides all cooling effects from increased carbon dioxide uptake by plant growth[26].

There is no doubt that the arctic region will undergo massive transformations in its biological and physical systems in response to climate change — in ways no other region will experience. While the size of arctic carbon sinks is increasing (with more carbon stored in living vegetation) leading to a reduced warming influence, emissions of carbon are increasing from the release of carbon dioxide and methane from soils and wetlands, leading to an acceleration of climate change. The increase in dark, dense vegetation in the Arctic, which is absorbing more of the sun’s energy, is also increasing warming. It is becoming more probable that the factors that are increasing climate change will outpace those that are dampening it. Because of this, arctic terrestrial ecosystems are sites of key vulnerabilities, which will have an important and accelerating influence on future climate change.

References

1 Schuur EAG, J Bockheim, JG Canadell, E Euskirchen, CB Field, SV Goryachkin, S Hagemann, P Kuhry, P Lafleur, H Lee, G Mazhitova, F E Nelson, A Rinke, V Romanovsky, N Shiklomanov, C Tarnocai, S Venevsky, JG. Vogel, SA Zimov 2008. Vulnerability of permafrost carbon to climate change: implications for the global carbon cycle. *BioSciences* 58: 701-714.

2 Canadell JG, Le Quéré C, Raupach MR, Field CB, Buitenhuis ET, Ciais P, Conway TJ, Gillett NP, Houghton RA, Marland G 2007. Contributions to accelerating atmospheric CO_2 growth from economic activity, carbon intensity, and efficiency of natural sinks. *Proceedings of the National Academy of Sciences* 104: 18866–18870, doi_10.1073_pnas.0702737104.

3 McGuire AD, Anderson LG, Christensen TR, Dallimore S, Guo L, Hayes DJ, Heimann M, Lorenson TD, Macdonald RW, Roulet N 2009. Sensitivity of the Carbon Cycle in the Arctic to Climate Change. *Ecological Applications* (in press).

4 Tarnocai C, Canadell JG, Mazhitova G, Schuur EAG, P. Kuhry P, Zimov S 2009. Soil organic carbon pools in the northern circumpolar permafrost region. *Global Biogeochemical Cycles* 23: GB2023, doi:10.1029/2008GB003327.

5 Sabine CL, Heimann M, Artaxo P, Bakker DCE, Chen C-TA, Field CB, Gruber N, Le Quere C, Prinn RG, Richey JE, Romero P, Sathaye JA, Valentini R 2004. Current status of past trends of the global carbon cycle. In: Global Carbon Cycle, Integrating Humans, Climate and the Natural World, Field C, Raupach M (eds). Island Press, Washington, D.C, pp. 17-44.

6 Goritz V, Fung I 1994. Potential distribution of methane hydrate in the world’s oceans. *Global Biogeochemical Cycles* 8: 182-195.

7 Schuur EAG, Vogel JG, Crummer KG, Lee H, Sickman JO, Osterkamp TE 2009. The effect of permafrost thaw on old carbon release and net carbon exchange from tundra. *Nature* 459: doi:10.1038/nature08031.

8 Zimov SA, Schuur EAG, Chapin III FS 2006. Permafrost and the Global Carbon Budget. *Science* 312: 1612-1613.

9 Dorrepaal E, Toet S, van Logtestijn RSP, Swart E, van de Weg MJ, Callaghan TV, Aerts R 2009. Carbon respiration from subsurface peat accelerated by climate warming in the subarctic. *Nature* 460: doi:10.1038/nature08216.

10 Kurz WA, Stinson G, Rampley GJ, Dymond CC, Neilson ET 2008a. Risk of natural disturbances makes future contribution of Canada's forests to the global carbon cycle highly uncertain. *PNAS* 105: 1551–1555. doi:10.1073_pnas.0708133105.

11 Kurz WA, Dymond CC, Stinson G, Rampley GJ, Neilson ET, Carroll AL, Ebata T, Safranyik L 2008b. Mountain pine beetle and forest carbon feedback to climate change. *Nature* 452: 987-990. doi:10.1038/nature06777.

12 Smith LC, Sheng YW, MacDonald GM 2007. A first pan=Arctic assessment of the influence of glaciation, permafrost, topography and peatlands on northern hemisphere lake distribution. *Permafrost and Periglacial Processes* 18: 201-208.

13 Riordan B, Verbyla D, McGuire AD 2006. Shrinking ponds in subarctic Alaska based on 1950-2002 remotely sensed images. *Journal of Geophysical Research-Biogeosciences* 111: G04002.

14 IPCC 2007. Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 996 pp.

15 Rigby M, Prinn RG, Fraser PJ, Simmonds PG, Langenfelds RL, Huang J, Cunnold DM, Steele LP, Krummel PB, Weiss RF, O'Doherty S, Salameh PK, Wang HJ, Harth CM, Muehle J, Porter LW 2008. Renewed growth of atmospheric methane. *Geophysical Research Letters* 35: L22805, doi:10.1029/2008GL036037.

16 Zhang J, Lindsay R, Steele M, Schweiger A 2008 What drove the dramatic retreat of arctic sea ice during summer 2007. *Geophysical Research Letters* 60: L11505.

17 Lawrence DM, Slater AG, Romanovsky VE, Nicolsky DJ 2008a. Sensitivity of a model projection of near-surface permafrost degradation to soil column depth and representation of soil organic matter. *Journal of Geophysical Research* 113: F02011, doi:10.1029/2007JF000883.

18 Fisher RE, Lanoisellé M, Sriskantharajah S, Lowry D, Nisbet EG, Westbrook GK, James RH, Green D, Shahkova N, Salyuk A, and the International Siberian Shelf Study (ISSS-08) Team 2009. Methane in Arctic Air during 2008: Monitoring Methane Mixing Ratio and Stable Isotopic Composition. *Geophysical Research Abstracts* 11: EGU2009-0.

19 Lawrence DM, Slater AG, Tomas RA, Holland MM, Deser C 2008b. Accelerated Arctic land warming and permafrost degradation during rapid sea ice loss. *Geophysical Research Letters* 35: L11506, doi:10.1029/2008GL033985.

20 Kimball JS, Zhao M, McGuire AD, Heinsch FA, Clein J, Calef M, Jolly WM, Kang S, Euskirchen SE, McDonald KC, Running SW 2007. Recent climate-driven increases in vegetation productivity for the Western Arctic: Evidence of an acceleration of the Northern terrestrial carbon cycle. *Earth Interactions* 11: 1-30.

21 Friedlingstein P, Cox P, Betts R, Bopp L, Von Bloh W, Brovkin V, Cadule P, Doney S, Eby M, Fung I, Bala G, John J, Jones C, Joos F, Kato T, Kawamiya M, Knorr W, Lindsay K, Matthews HD, Raddatz T, Rayner P, Reick C, Roeckner E, Schnitzler KG, Schnur R, Strassmann K, Weaver AJ, Yoshikawa C, Zeng N 2006. Climate-carbon cycle feedback analysis: Results from the (CMIP)-M-4 model intercomparison, *Journal Climate* 19: 3337-3353.

22 Zhuang Q, Melillo JM, Sarofim MC, Kicklighter DW, McGuire A, Felzer BS, Sokolov A, Prinn RG, Steudler PA, Hu S 2006. CO_2 and CH_4 exchanges between land ecosystems and the atmosphere in northern high latitudes over the 21st century. *Geophysical Research Letters* 33: L17403, doi:10.1029/2006GL026972.

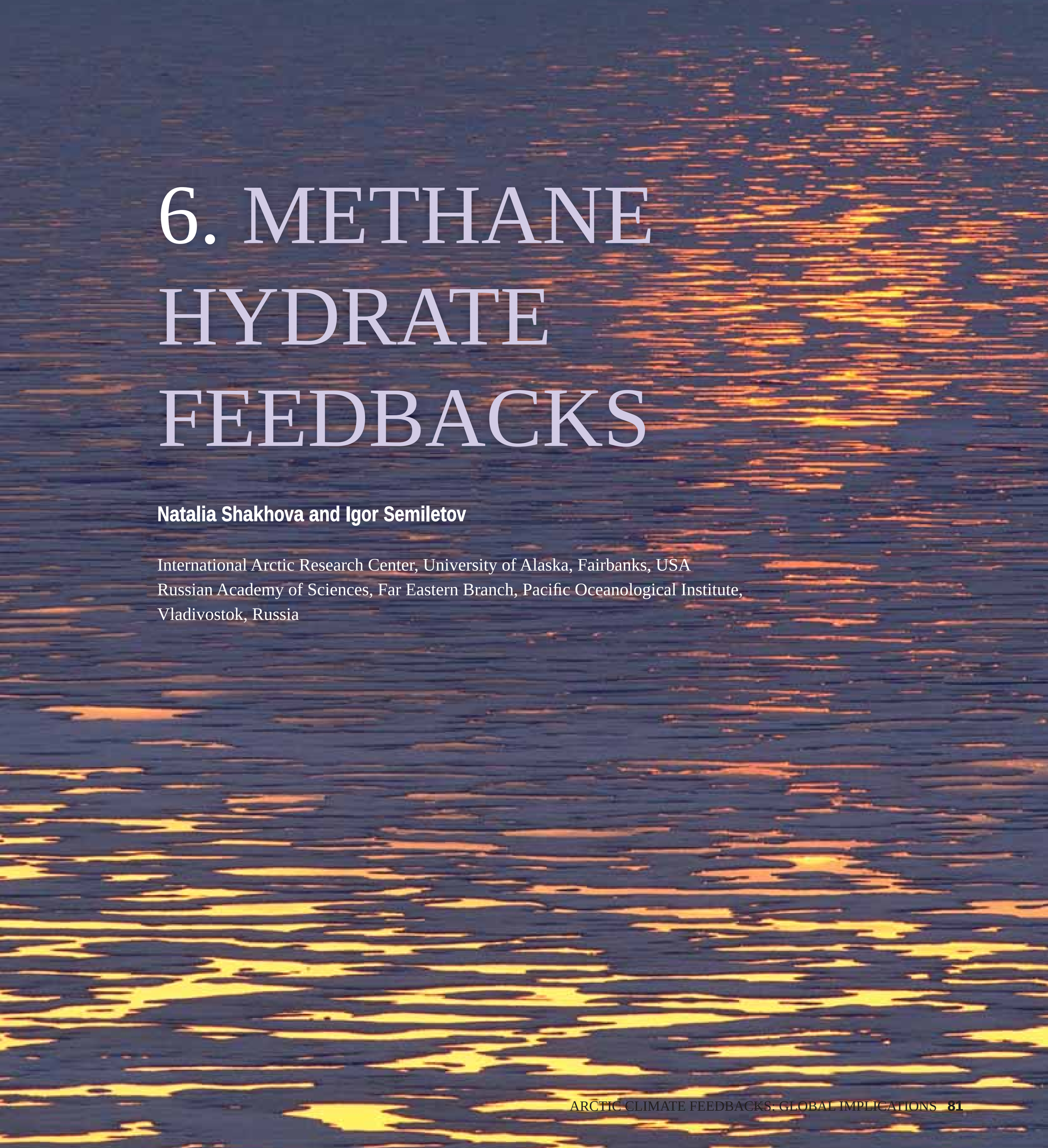
23 Khvorostyanov DV, Ciais P, Krinner G, Zimov SA, Corradis Ch, Guggenberger G 2008. Vulnerability of permafrost carbon to global warming. Part II: sensitivity of permafrost carbon stock to global warming. *Tellus* 60B: 265–275.

24 Jackson RB, Randerson JT, Canadell JG, Anderson R, Avissar R, Baldocchi DD, Bonan GB, Caldeira K, Diffenbaugh NS, Field CB, Hungate BA, Jobbágy EG, Kueppers LM, Nosetto MD, Pataki DE 2008. Protecting Climate with Forests. *Environmental Research Letters* 3: doi:10.1088/1748-9326/3/4/044006.

25 Bala G, Caldeira K, Wickett M, Phillips TJ, Lobell DB, Delire C, Mirin A 2007. Combined climate and carbon-cycle effects of large-scale deforestation. *PNAS* 104: 6550–6555, doi:10.1073.pnas.0608998104.

26 Euskirchen ES, McGuire ADM, Chapin FS III, Thompson CC 2009. Changes in vegetation in northern Alaska under scenarios of climate change, 2003–2100: implications for climate feedbacks. *Ecological Applications* 19: 1022–1043.

27 Bajtes, NH 1996. Total carbon and nitrogen in the soils of the world. *European Journal of Soil Science* 47: 151-163.



6. METHANE HYDRATE FEEDBACKS

Natalia Shakhova and Igor Semiletov

International Arctic Research Center, University of Alaska, Fairbanks, USA
Russian Academy of Sciences, Far Eastern Branch, Pacific Oceanological Institute, Vladivostok, Russia

METHANE IS ABOUT 25 times as potent at trapping heat as carbon dioxide, and there is a huge amount of it stored as methane hydrates in the Arctic. The amount of methane stored in hydrate deposits is more than 13 times greater than the amount of carbon (as methane and carbon dioxide) in the atmosphere. There is more carbon in methane hydrates than in all the fossil fuel deposits in the world. As the climate warms, these deposits can be destabilised, with major climatic repercussions.

Key Findings:

- **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 destabilise when sub-sea permafrost thaws.

- **Thawing sub-sea permafrost is already releasing methane.** Current temperatures in the Arctic are 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 destabilised.** In addition, when methane hydrates destabilise, 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.

Arctic marine ecosystems have not been widely considered to play a significant role in the global carbon cycle or in the methane cycle in particular, for three primary reasons:

1. The Arctic continental shelf represents only 2 per cent of the surface area of the world's oceans; thus, the amount of unfrozen sediments that accumulated during the current warm period (Holocene epoch), along with severe climate conditions, were not thought to be conducive for modern methane generation by microbes in sediments.
2. Organic carbon that accumulated during previous time periods of the Earth's history, before the sea invaded the arctic shelves as the glaciers began to retreat during the current warm period, was thought to be reliably preserved within the sub-sea permafrost and methane that was produced earlier would remain frozen within hydrate deposits.
3. Sub-sea permafrost was considered to be stable, and thus would prevent methane escape from the seabed.

"The amount of methane currently stored in hydrate deposits is more than 13 times greater than the amount of carbon in the atmosphere."

At the same time, it is well-known that because it is enclosed on all sides by land, the arctic shelf has received a huge amount of organic carbon from land, through both coastal erosion and input from arctic rivers. In the Siberian Arctic Shelf alone, where the six great Siberian rivers deliver their waters, the amount of organic carbon that accumulates annually in the bottom sediments approximately equals that accumulated over the entire open-sea area of the World Ocean[1]. That is why sedimentary basins in the arctic continental shelf are the largest and thickest in the world (up to 20 kilometres), and the amount of carbon accumulated within them is called the "arctic super carbon pool"[2]. A large portion of this carbon is stored in methane hydrate deposits. The amount of methane currently stored in hydrate deposits (about 10,400 gigatonnes; 1 gigatonne of carbon equals 1 billion tonnes of carbon)[3] is more than 13 times greater than the amount of carbon (as methane and carbon dioxide) in the atmosphere (about 760 gigatonnes)[4].

The stability of sub-sea permafrost is key to whether methane can escape from seabed hydrates and other deposits[5]. Relict sub-sea permafrost, which underlies the arctic continental shelf, is an overlooked sibling to on-land permafrost. They formed together, but sub-sea permafrost was flooded by the sea in the so-called "Holocene transgression," 7,000 to 15,000 years ago when glaciers melted in a warming climate[6]. This area is now several times larger than that covered by Siberian wetlands. Sub-sea permafrost is potentially much more vulnerable to thawing than land-based permafrost. Prior to the recent rapid climate warming, the temperature of the sub-sea permafrost's environment had already increased by 12 to 17°C when it was flooded[7], because the average temperature of seawater is much higher than the average temperature of the arctic atmosphere. In contrast, when the current, warm Holocene epoch replaced the previous colder glacial epoch, the atmosphere and, thus, terrestrial permafrost, warmed by only about 7°C[8]. This means that sub-sea permafrost is much closer to the temperature at which it thaws than is terrestrial permafrost.

The Arctic is warming more quickly than the rest of the world, and this warming is most pronounced in the arctic shelf[4,9]. The main reason for this is that arctic rivers bring to the arctic shelf continental-scale signals of the terrestrial ecosystems' response to global warming[11]. That is, the degradation of terrestrial permafrost leads to increasing river runoff, which warms the shelf water, which, in turn, transports heat down to shelf sediments and sub-sea permafrost. Shelf water and bottom sediments constitute the sub-sea permafrost environment. Like all physical systems, sub-sea permafrost must reach a thermal equilibrium with its environment, which is significantly warmer than the environment of terrestrial permafrost. The thermal environment of sub-sea permafrost fluctuates from slightly below to slightly above 0°C[11,12]. Since sub-sea permafrost is salty, it thaws even at temperatures slightly below zero[13]. Such temperatures of sub-sea permafrost have been observed recently on the Siberian arctic shelf[14]. When it thaws, sub-sea permafrost loses its ability to seal off the seabed deposits of methane, including hydrates[5,7].

Recent observational data obtained from the largest and shallowest arctic shelf — the East Siberian Arctic Shelf — indicate that methane is already being released from seabed deposits[15,16,17]. This is a worrisome indication that methane emissions from arctic seabed deposits of methane, including methane hydrates, will increase with the warming that has been predicted for the Arctic during this century, with unpredictable consequences for the future climate.

"Recent observational data obtained from the largest and shallowest arctic shelf — the East Siberian Arctic Shelf — indicate that methane is already being released from seabed deposits."

Large amounts of methane are frozen in arctic methane hydrates

Origin and amount of hydrates

Gas hydrates are compounds in which the gas molecules (20 per cent of the volume) are trapped in crystalline cells consisting of water molecules (80 per cent) held together by hydrogen bonds. Gas hydrates can be stable over a wide range of pressures and temperatures. For example, a unit volume of methane hydrate at a pressure of 26 atmospheres and 0°C contains 164 times that volume of gas; thus, 164 cubic metres of gas are contained in a hydrate volume of 0.2 cubic metres. The dissociation of hydrates in response to increasing temperature is accompanied by a substantial increase in pressure[5]. For methane hydrates that formed at 26 atmospheres and 0°C, it is possible to obtain a pressure increase of as much as 1,600 atmospheres upon dissociation. Hydrates are found in the Arctic and in deep water[18]. They can occur in the form of small nodules (5 to 12 centimetres), as small lenses, or even as pure layers that can be tens of metres thick[19]. Hydrates generally form in a sub-sea sediment zone where the combination of pressure and temperature guarantees their stable existence within the so-called hydrate stability zone[5,18]. In the regions where permafrost exists, hydrate-bearing sediment deposits can reach a thickness of 400 to 800 metres[19].

There are three types of hydrate deposits:

1. **Primary deposits** are formed from gases dissolved in reservoir water under conditions of low bottom temperature and high pressure exerted by the overlying water. They form where the water column is more than 700 to 1,000 metres deep (primarily non-arctic deposits) or more than 200 metres deep (primarily arctic deposits). These deposits can be stratigraphic, meaning that they do not depend on geological structures, have no seals, and occur in a widely dispersed (not localised) state or in the form of nodules. They can also be structural. In contrast to stratigraphic type hydrates, structural hydrates are usually massive, consisting of lumps of nearly pure hydrate. Alteration of the climate cycle affects the stability of these hydrates by changing the position and thickness of the hydrate stability zone[5], leading to release of some free gas to the water column, where it is usually altered by the presence of oxygen and does not reach the atmosphere[19].
2. **Secondary deposits** usually originate under extremely low temperatures and high pressure exerted by the overlying rock on arctic lands. They consist of gas frozen within the hydrate stability zone and free gas located above and beneath it[5,11], at depths as shallow as 70 metres beneath the seafloor and in layers up to 110 metres thick[19]. Permafrost seals off and controls the release of gas from these deposits.
3. **Relic deposits** are found within permafrost as shallow as 20 metres, and are thought to be formed when shallow fields of natural gas froze during the ice ages, when the arctic shelves were above sea level[20, 21].

The Arctic Ocean contains all three types of hydrate deposits: primary arctic deposits, and secondary and relic hydrate deposits that formed when the arctic shelves were above sea level. Specific features of arctic hydrates include:

1. very high spatial concentration[11, 19] (**Figure 2a**);
2. extremely high pore saturation, from 20 to 100 per cent of pore space. In contrast, primary oceanic (non-arctic) hydrates occupy only 1 to 2 per cent of pore space[19];
3. extreme sensitivity to warming. Destabilising hydrates that formed at temperatures below 0˚C (primary arctic hydrates, secondary and relic) requires only one-third the energy required to destabilise hydrates that formed at temperatures above 0˚C[5] (primary non-arctic hydrates);
4. very thick layers (up to 110 metres)[19]; and
5. offshore occurrence, more than three times more frequent than onshore occurrence[20].

Continental shelves hold most of the methane hydrate

Terrestrial permafrost is estimated to contain 400 gigatonnes of methane hydrates, while sub-sea continental shelf reservoirs are estimated to contain 10,000 gigatonnes of methane hydrates[3]. For comparison, all recovered and non-recovered fossil fuels (coals, oil and natural gas) are estimated to contain about 5,000 gigatonnes of carbon[3]. Since the arctic continental shelf makes up 25 per cent of the entire area of the world's oceanic continental shelves (7 million square kilometres of the ocean's area, 28.8 million square kilometres), it is estimated to contain 2,500 gigatonnes of carbon in the form of methane hydrates, which is more than 3 times greater than the amount of carbon currently stored in the atmosphere and more than 600 times greater than the current atmospheric content of methane[4]. Release to the atmosphere of only 0.5 per cent of the methane stored within arctic shelf hydrates could cause abrupt climate change[22].

> **"Release to the atmosphere of only 0.5 per cent of the methane stored within arctic shelf hydrates could cause abrupt climate change."**

Vulnerability of hydrates and the role of permafrost

Since most hydrate deposits in the Arctic are permafrost-controlled, permafrost stability is key to hydrate stability. Permafrost is defined as soils (on-land permafrost) or sediments (sub-sea permafrost) that are frozen year-round. Anything that is frozen can thaw, and permafrost is no exception. Permafrost can degrade in two ways. It can thaw from the top downward, in which the active layer expands downward, creating taliks (bodies of thawed permafrost)[23]. The active layer is the upper layer of permafrost soils or sediments that thaws in summer, and is usually not more than 1 metre thick. However, beneath water more than 2 metres deep it can be thicker, because the water insulates the permafrost and prevents it from completely re-freezing during winter. Permafrost also can degrade from the bottom up as a result of geothermal heat flux, when heat from the interior of the Earth radiates upward, causing the frozen sediment to thaw from below[24]. Permafrost can be degraded from the top down and from the bottom up at the same time.

The temperature regime of sub-sea permafrost is determined by the annual temperature of the surrounding seawater (**Figure 1**), just like the thermal regime of terrestrial permafrost is determined by the arctic surface temperature. Annual average arctic shelf water temperature is more than 10°C higher than terrestrial arctic surface temperature. An increase in surrounding temperature changes the thermal regime of permafrost, and the permafrost temperature will slowly adjust to achieve a new equilibrium with its thermal environment. This process may take thousands of years.

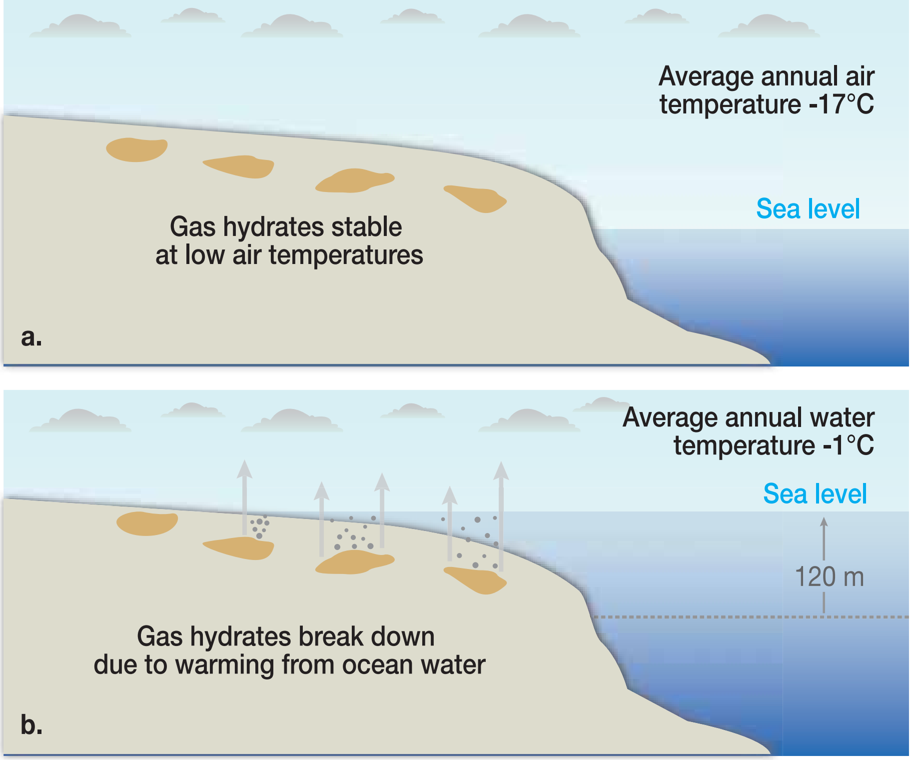


Figure 1. Illustration of how changes in sea level affect the stability of arctic hydrates: **a**) cold epochs: sea level is low, the arctic shelf is exposed above the water surface, average annual temperature is -17˚C; **b**) warm epochs: sea level is high, the arctic shelf is submerged, average annual temperature of sea water is -1˚C.

In the case of arctic sub-sea permafrost, this process began long ago, when the sea flooded the arctic shelves 7,000 to 15,000 years ago, increasing the temperature of the environment of the newly submerged permafrost by 12°C or more[24]. As the sub-sea permafrost moved toward thermal equilibrium, its temperature increased to near its thawing point[11], which for salt-containing permafrost occurs at temperatures slightly below 0°C[13]. Any further increase in temperature, resulting from, for example, continued global warming, will lead to thawing.

Thawing sub-sea permafrost is already releasing methane

Insufficient attention has been paid to using numerical models to project changes that might occur in sub-sea permafrost as a result of global warming. Modelling results have suggested that sub-sea permafrost should be stable across most of the arctic shelf. For example, permafrost on the East Siberian Arctic Shelf was predicted to be stable from the coast to a water depth of 70 metres[24], which encompasses more than 90 per cent of the shelf area. However, recent observational data obtained in the East Siberian Arctic Shelf showed that extensive methane release from the seafloor is occurring at depths ranging from 6 to 70 metres[16, 17], emerging as huge clouds

East Siberian Arctic Shelf
contains the shallowest hydrate deposits,
most vulnerable to release

Predicted hydrate deposits

Water depth less than 50 metres

Figure 2. **a)** Map of predicted hydrate deposits (blue)[30], and **b**), map showing the sea floor topography of the Arctic Ocean [31]; red color refers to depths less than 50 metres. The largest, shallowest, and thus the most vulnerable fraction of the arctic shelf is the East Siberian Arctic Shelf, is enclosed by the square.

of bubbles rising through the water column. This bubbling release of gas is called ebullition. Oxidation in the water column usually prevents methane released from oceanic hydrates in deep ocean waters from reaching the atmosphere. However, because the East Siberian Arctic Shelf is extremely shallow (more than 75 per cent of its entire area of 2.1 million square kilometres is shallower than 40 meters; **Figure 2b**), the majority of the methane gas released from the East Siberian Arctic Shelf seafloor avoids oxidation in the water column and is released to the atmosphere. Atmospheric concentrations of methane above the sea surface were found to be as much as 4 times greater than normal atmospheric levels[18] (**Figure 3**). Such outburst-like emissions have also been observed from shallow hydrate deposits at lower latitudes, where no permafrost seals exist to prevent methane release from hydrate deposits[25].

It has been widely assumed that no methane could be emitted from the arctic shelf during the winter ice-covered period. However, new observational data suggest that methane ebullition and other emissions occur throughout the year. Flaw leads (openings between sea ice) and polynyas (winter ice-free areas) compose 1 to 2 per cent of the winter shelf area. Methane fluxes from European arctic polynyas were found to be 20 to 200 times higher than the ocean average and, where concentrations of dissolved methane in the bottom water do not exceed 50 nanomoles (1 nanomole of methane = 16 billionths of a gram of methane per litre of water), can reach 20,000 tonnes of methane a year[26]. Where ice seals the water surface, methane accumulates beneath the ice. In some areas of the East Siberian Arctic Shelf, for example, concentrations of dissolved methane measured in winter beneath the ice were as high as 20,000 nanomoles[27]; when this ice melts in spring, methane is released to the atmosphere. A similar phenomenon has been observed in lakes on land. The isotopic signature of methane bubbles in seawater over the East Siberian Arctic Shelf indicates a mixture of a few possible sources, including hydrates[16]. This is true for summer as well as winter methane emissions. (Isotopic signatures are determined by small differences in the weight of molecules that make up gases such as methane.)

It is suggested that the natural degradation of sub-sea permafrost that occurs as a result of the combined effect of bottom-up geothermal and top-down seawater heat fluxes, possibly accelerated by amplified arctic warming, is leading to the partial destabilisation of sub-sea permafrost. As a result, methane is already being released from widespread seabed deposits, and vents extensively to the arctic atmosphere. In the East Siberian Arctic Shelf, which constitutes about 30 per cent of the entire arctic shelf area, more than 50 per cent of the area studied is currently releasing methane to the atmosphere.

Climate change and future methane release from arctic hydrates

The potential of climate change to destabilise arctic hydrates has significant implications both for the global climate and for arctic ecosystems. Previous results, based on studying less than 1 per cent of the total area of the arctic shelf and extrapolated to the entire area of the arctic shelf, implied that annual methane emissions to the atmosphere from decaying hydrate deposits could be equal to about 100,000 tonnes of methane[28]. However, more recent estimates suggest the amount of methane that could be released from the arctic continental shelf, which covers an area of 7 million square kilometres, could be two orders of magnitude greater. Indeed, methane release measured from the East Siberian Arctic Shelf alone (30 per cent of the arctic shelf seas) suggested total emissions as high as 5 million tonnes of methane[15]. If ebullition from arctic continental shelves is similar in proportion to that from northern lakes, then current annual emissions of methane from the arctic shelves could vary from 10 million to 50 million tonnes of methane. This estimate is based on findings from the East Siberian Arctic Shelf alone and does not include non-gradual releases of methane associated with hydrate deposit decay, because the time scale and spatial distribution of such episodes are still unknown. Therefore, the contribution of the arctic shelves to methane release is currently underestimated.

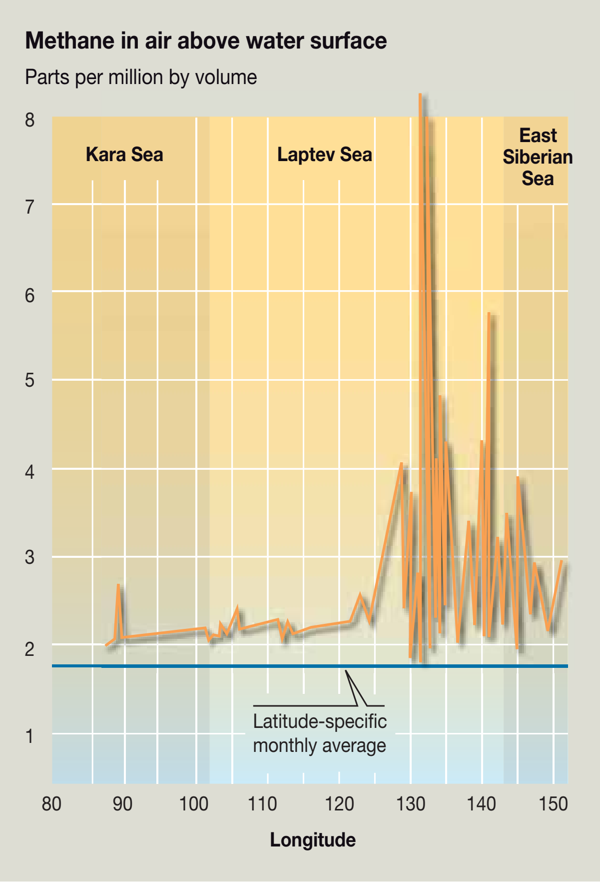


Figure 3. Mixing ratio of methane in the air above the water surface measured along a ship's route in September 2005. The dotted line shows the Latitude-specific monthly average of 1.85 parts per million by volume established for the Barrow, Alaska, USA, monitoring station at 71° 19' N, 156° 35' W (http://www.cmdl.noaa.gov/ccgg/insitu.html); this is the normal level of methane in the atmosphere at this latitude.

The most vulnerable hydrates are on the East Siberian Shelf

The amount of methane that could theoretically be released from decaying hydrate deposits in future episodic events could be enormous. As the East Siberian Arctic Shelf is the largest and the shallowest part of the arctic shelf, methane emissions from the East Siberian Arctic Shelf would contribute the most significantly. Given that this shelf comprises about 30 per cent of the arctic shelf, the amount of methane stored within its seabed could be as much as 750 gigatonnes. It is currently suggested that about two-thirds of the methane preserved in hydrates is stored as free gas[11], which would add about an additional 500 gigatonnes. Because sub-sea permafrost is similar to its terrestrial counterpart, the carbon pool held within it is comparable to that within terrestrial permafrost; about 500 gigatonnes of carbon is contained within a 25-metre thick permafrost body, which is available for methane or carbon dioxide production when the permafrost thaws[29]. Thus, the entire amount of carbon stored in the East Siberian Arctic Shelf (1,750 gigatonnes) is equal to that held in the entire remaining area of the Arctic continental shelf as hydrate deposits' carbon. Recent studies have examined two possible cases of how surface air temperature could respond to release of only 2 per cent (50 gigatonnes) of the total amount of methane preserved in arctic continental shelf hydrate deposits if this amount is released in either of two ways: slowly over 50 to 100 years, or quickly over approximately 5 to 10 years. When methane is released quickly over the brief 5 to 10 year time period, the maximum temperature increase is higher by about a factor of three compared to the "slow" case. This greater temperature response is more likely to produce irreversible consequences.

Conservative modelling shows that about 5 to 10 per cent of the East Siberian Arctic Shelf area may be underlain by open taliks[24], which provide a pathway for methane to escape from deeper parts of the sediments to the water column. The amount of methane that could potentially be released from disturbed hydrates might reach 37.5 to 75 gigatonnes, and the shallow waters of the East Siberian Arctic Shelf would allow a large fraction of this methane to reach the atmosphere. Multi-year observational data obtained in the East Siberian Arctic Shelf suggest that, contrary to modelling results, more than 80 per cent of bottom water and 50 per cent of surface water in the study area is supersaturated with methane by a factor of 10 to 1,000 relative to the background level of 3.5 nanomoles[18]. That means that very likely more than 5 to 10 per cent of the East Siberian Arctic Shelf area is already affected by sub-sea permafrost destabilisation. Nevertheless, it is still very uncertain whether this methane enters the water column after slowly diffusing through the sediments, allowing part of it to be oxidized within the upper sediment layers, or if it could burst out suddenly from time to time in a violent episodic event that would allow no time for oxidation before the methane is released to the atmosphere.

References

1 Vetrov, A.A., and E.A. Romankevich 2004. Carbon Cycle in the Russian Arctic Seas. Springer-Verlag Berlin Heidelberg, 330pp.

2 Gramberg, I.S., Kulakov Yu. N., Pogrebitsky Yu.E., and D.S. Sorokov 1983. Arctic oil and gas super basin, X World Petroleum Congress. London, p 93-99.

3 Dickens, G.R. 2003. Rethinking the global carbon cycle with large, dynamic and microbially mediated gas hydrate capacitor, Earth and Planetary Science Letters 213 (3-4): 169-183.

4 IPCC (2007) Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 996 pp.

5 Makogon, Y.F., Holditch, S.A., Makogon T.Y. 2007. Natural-gas hydrates - A potential energy source for the 21st Century, Journal of Petroleum Science and Engineering 56: 14–31.

6 Fleming, K., Johnston, P., Zwartz, D., Yokoyama, Y., Lamneck, K. and J. Chappell 1998. Refining the eustatic sea-level curve since the last glacial maximum using far- and intermediate-field sites, Earth and Planetary Science Letters 163: 327-342.

7 Romanovskii, N.N., H.-W. Hubberten, A.V. Gavrilov, V.E. Tumskoy, G.S. Tipenko, M.N. Grigoriev and Ch. Siegert 2000. Thermokarst and land-ocean interaction, Laptev Sea region, Russia, Permafrost and Periglacial Processes 11(2): 137-152.

8 Houghton, J. 1997. Global warming: the complete briefing. Cambridge University Press, Cambridge, UK, 251 pp.

9 http://www.eoearth.org/article/State_of_the_Arctic_Report

10 Savelieva, N.I., Semiletov, I.P., Vasilevskaya, L.N., Pugach, S.P. 2000. A climate shift in seasonal values of meteorological and hydrological parameters for Northeastern Asia, Progress in Oceanograpgy, 47 (2-4): 279-297.

11 Soloviev, V.A., G.D. Ginzburg, E.V. Telepnev, and Yu.N. Mikhaluk 1987. Cryothermia and gas hydrates in the Arctic Ocean, Sevmorgeologiaß, Leningrad, 150pp.

12 Osterkamp T.E., and W.D. Harrison 1985. Sub-sea permafrost: Probing, thermal regime, and data analyses, 1975-1981. Summary report. Geophysical Institute, University of Alaska Fairbanks, 108pp.

13 Himenkov, A.N., and A.V. Brushkov 2006. Introduction into the structural cryology, Science Press, Moscow 279 pp.

14 Rachold V., Bolshiyanov D.Y., Grigoriev M.N., Hubberten H.-W., Junker R., Kunitsky V.V., Merker F., Overduin P., and W. Schneider 2007. Eos 88 (13): 149-156.

15 Shakhova, N. E., Sergienko, V. I. and I. P. Semiletov. 2009. The Contribution of the East Siberian Shelf to the Modern Methane Cycle. Herald of the Russian Academy of Sciences, 2009, Vol. 79, No. 3, pp. 237–246 (translated by Pleiades Publishing, Ltd., 2009, ISSN 1019-3316).

16 Shakhova N. , C. Sapart, I. Semiletov, D. Kosmach, and T. Roeckmann 2009. First isotopic data on methane from the East Siberian Arctic Shelf, Geophysical Research Abstracts 11: EGU2009-3333.

17 Shakhova, N., Semiletov, I., Salyuk, A. N., Belcheva, N.A. 2007. Anomalies of methane in the atmosphere above the East Siberian Arctic Shelf, Transaction of Russian Academy of Science, 414 (6): 819-823.

18 Kvenvolden, K.A. 2002. Methane hydrates in the global carbon cycle, Terra Nova 14 (5): 302-306.

19 Hyndman R.D., and S.R. Dallimore 2001. Natural gas hydrates studies in Canada. Recorder 26: 11-20.

20 Chuvilin, E.M., Yakushev, V.S., and Petrova, E.V. 2000. Gas and possible gas hydrates in the permafrost of Bovanenkovo Gas Field, Yamal Peninsula, west Siberia. Polarforschung 68: 215-219.

21 Yakushev, V.S. 1989. Gas hydrates in the cryolithozone. Geology and Geophysics 11 (in Russian).

22 Archer, D.E., and Buffett, B. 2005. Time-dependent response of the global ocean clathrate reservoir to climatic and anthropogenic forcing, Geochem., Geophys., Geosy. 6(3): doi: 10.1029/2004GC000854.

23 Romanovskii, N.N., and H.-W. Hubberten 2001. Results of permafrost modeling of the lowlands and shelf of the Laptev Sea Region, Russia. Permafrost and Periglacial Processes 12 (2): 191-202.

24 Romanovskii, N.N., H.-W. Hubberten, A.V. Gavrilov, A.A. Eliseeva, and G.S. Tipenko 2005. Offshore permafrost and gas hydrate stability zone on the shelf of East Siberian Seas. Geo-mar. Lett. 25: 167-182

25 Leifer, I., Luyendyk, B.P., Boles, J., and J.F. Clark 2006. Natural marine seepage blowout: Contribution to atmospheric methane. Global Biogeochemical Cycles 20: GB3008, doi:10.1029/2005GB002668.

26 Damm, E., Schauer, U., Rudels, B., Haas, C. 2007. Excess of bottom-released methane in an Arctic shelf sea polynya in winter, Continental Shelf Research 7: 12-18.

27 Semiletov I.P. 1999. On aquatic sources and sinks of CO2 and CH4 in the Polar regions. J.Atmosph. Sci. 56: 286-306.

28 Kvenvolden, K.A., Lilley M.D., Lorenson T.D., Barnes P.W., McLaughlin E. 1993. The Beaufort Sea continental shelf as a seasonal source of atmospheric methane. Geophys. Res. Lett. 20 (220): 2459-2462.

29 Zimov, S.A., E.A.G. Schuur, and F.S. Chapin III. 2006. Permafrost in the global carbon budget. Science 312: 1612-1613, DOI: 10.1126/science.1128908.

30 Soloviev, V.A. 2002. Gas-hydrate-prone areas of the ocean and gas-hydrate accumulations. Journal of the Conference Abstracts, 6(1), 158 (abstract/poster).

31 Jakobsson, M., Macnab, R., Cherkis, N., Schenke, H-W., et al., 2004. The International Bathymetric Chart of the Arctic Ocean, map scale 1:6,000,000, World Data Center for Marine Geology & Geophysics, Boulder, Research Publication RP-2.

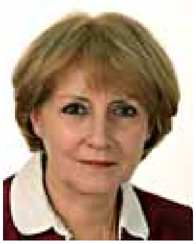
Author Team

NICHOLAS R. BATES

Nick Bates is a senior research scientist and associate director of research at the Bermuda Institute of Ocean Sciences. He earned a Ph.D. in Oceanography from the University of Southampton (U.K.) in 1995. His research interests focus on carbon dynamics and processes in the ocean, including ocean biogeochemical cycling of carbon, nitrogen and dissolved organic matter, and physical and biological processes influencing ocean-atmosphere gas exchange of carbon dioxide. Bates contributed to the Intergovernmental Panel on Climate Change Fourth Assessment report and to the Surface Ocean-Lower Atmosphere Study-Integrated Marine Biochemistry and Ecosystem Research (SOLAS-IMBER) joint carbon implementation plan. He was also a recent member of the Intergovernmental Oceanographic Commission-Scientific Committee on Oceanic Research International Ocean Carbon Coordination Project scientific steering group and the SOLAS-IMBER working group on surface observations. He is a member of the U.S. Carbon Cycle Scientific Steering Group for the federal Carbon Cycle Interagency Working Group.

JOSEP G. CANADELL

Josep G. Canadell is a research scientist at the Commonwealth Scientific and Industrial Research Organization, Division of Marine and Atmospheric Research, and the executive director of the Global Carbon Project, a joint project of the Earth System Science Partnership. His work involves internationally coordinated research on global and regional carbon budgets; vulnerable carbon stores and sinks including permafrost and peatlands; human-induced carbon trends; and climate mitigation strategies to stabilize atmospheric carbon dioxide. He also works with policymakers and governments on climate change science and policies. Canadell was an author of the Intergovernmental Panel on Climate Change Fourth Assessment report that received the Nobel Peace Prize in 2007.



ANNY CAZENAVE

Anny Cazenave is a senior scientist at the Laboratoire d'Etudes en Géophysique et Océanographie Spatiale, Centre National d'Etudes Spatiales, Toulouse, France. Her research interests include satellite geodesy and space research and she has led several space missions. She has published more than 165 papers in international journals and was the lead author of the Intergovernmental Panel on Climate Change Fourth Assessment chapter "Oceanic Climate Change and Sea Level". She has also served as the international secretary of the American Geophysical Union (2002-2006) and president of the Geodesy section of the European Geosiences Union (1999-2004). Cazenave is a fellow of the American Geophysical Union, a member of the French Academy of sciences and is a foreign member of the U.S. National Academy of Sciences and the Indian Academy of Sciences.

CECILIE MAURITZEN

Cecilie Mauritzen is a senior scientist at the Climate Department of the Norwegian Meteorological Institute. She is a physical oceanographer, specialising in large-scale ocean circulation and its role in the Earth's climate system. She obtained her Ph.D. from the Massachusetts Institute of Technology/Woods Hole Oceanographic Institution Joint Program in 1994, where her studies focused on mapping the northernmost overturning of the global thermohaline circulation as it extends into the Nordic Seas and the Arctic Ocean. She has worked as an oceanographer in the United States, France and Norway. She was a lead author of the Intergovernmental Panel on Climate Change Fourth Assessment report, which was published in 2007. Her current research is concerned with observations of ocean circulation using modern automated platforms including profiling floats and gliders, and development of ocean observatories for long-term observations. She led or was involved in four international Arctic projects during the International Polar Year.

MICHAEL R. RAUPACH

Michael R. Raupach is a research scientist in Commonwealth Scientific and Industrial Research Organization, Division of Marine and Atmospheric Research. He is a Fellow of the Australian Academy of Science and a Fellow of the Australian Academy of Technological Sciences and Engineering. From 2000 to 2008, he was an inaugural co-chair of the Global Carbon Project of the Earth System Science Partnership. His research encompasses global and continental carbon and water cycles, carbon-climate-human interactions, land-air interactions, fluid mechanics and particle transport, and is a frequent contributor to the policy and public debate on climate change. He contributed to the Intergovernmental Panel on Climate Change Fourth Assessment report that received the Nobel Peace Prize in 2007.

ERIC RIGNOT

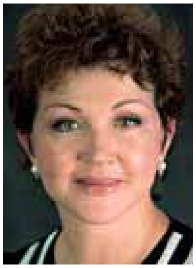
Eric Rignot a Professor of Earth System Science at University of California Irvine, USA, and a Joint Faculty Appointee at NASA's Jet Propulsion Laboratory in Pasadena, California, USA. He received a Ph.D. in electrical engineering from the University of Southern California. He is a principal investigator on several NASA-funded projects, including studies of the mass balance of the Greenland and Antarctic ice sheets using radar interferometry combined with other methods; the interactions of ice shelves with the ocean; and the development of high-order, high-resolution numerical models of ice sheet flow constrained by satellite observations. He was a contributing author to the Intergovernmental Panel on Climate Change Fourth Assessment report.

IGOR SEMILETOV

Research Associate Professor Igor Semiletov leads the Russia-U.S. Marine Carbon Group at the International Arctic Research Center, at the University Alaska Fairbanks and the Pacific Oceanological Institute, Far Eastern Branch of the Russian Academy of Sciences, where he founded the Laboratory of Arctic Studies. He also has been the head of the International Arctic Science Committee's Bering Sea Impact Study project in Vladivostok, Russia, and has served on the steering committee of the Russian-American Initiative on Shelf-Land Environments in the Arctic. Since early 1990s, Semiletov has studied the Siberian Arctic seas extensively and has published more than 80 papers and chapters on the area, including projects with the Russian Foundation for Basic Research, the National Atmospheric and Oceanic Administration and the U.S. National Science Foundation.

MARK C. SERREZE

Mark C. Serreze received a Ph.D. in geography from the University of Colorado, Boulder, in 1989, where he studied Arctic sea ice variability. Subsequently, he has been a research scientist at the National Snow and Ice Data Center's Cooperative Institute for Research in Environmental Sciences at the University of Colorado. His Arctic research interests are wide-ranging and include atmosphere-sea ice interactions, synoptic climatology, boundary layer problems, numerical weather prediction and climate change. He has conducted fieldwork in the Canadian Arctic on sea ice and icecaps and on the Alaskan tundra. Efforts over the past 10 years have increasingly focused on trying to make sense of the rapid environmental changes being observed in the Arctic.



NATALIA SHAKHOVA

Senior Research Scientist Natalia Shakhova leads the Russia-U.S. Methane Study at the International Arctic Research Center, at the University Alaska Fairbanks and the Pacific Oceanological Institute, Far Eastern Branch of the Russian Academy of Sciences. She is also a leading research scientist at the Laboratory of Arctic Studies at Pacific Oceanological Institute. Since 2004, she has been a leader in methane studies on the East Siberian Arctic Shelf, with a focus on climate-driven feedbacks. Over the last five years, she has published more than 20 papers and chapters, including projects funded by the Russian Foundation for Basic Research, National Oceanic and Atmospheric Administration and U.S. National Science Foundation.

Shakhova is also an author of the Intergovernmental Panel on Climate Change Fifth Assessment report.

JULIENNE STROEVE

Julienne Stroeve received a Ph.D. in geography from the University of Colorado, Boulder, where she studied the surface energy balance of the Greenland Ice Sheet using satellite imagery and has extensive experience in remote sensing of polar regions using satellite imagery. Currently, she is a research scientist at the National Snow and Ice Data Center at the University of Colorado. Stroeve has participated in several field campaigns in Greenland and the Arctic in order to confirm data obtained from spacecraft, including sea ice concentration, surface temperature and surface reflectivity. Current research projects include monitoring the rapid decline of the Arctic sea ice cover and investigating how the transition toward a seasonally ice-free Arctic will affect climate in the Northern Hemisphere.

Editors

MARTIN SOMMERKORN

Martin Sommerkorn is Senior Climate Change Advisor to WWF's International Arctic Programme. His current main focus is on communicating both the impacts and the global relevance of arctic climate change to the public and to policy-makers, particularly targeting the international process for the mitigation of atmospheric greenhouse gases. In 2008, Martin joined WWF after more than 15 years of carrying out research in the circumpolar Arctic, and an even longer time of travelling and working there. An ecologist by training his own research is in the field of ecosystem ecology, where he focuses on how climate change affects the flows of carbon in arctic tundra.

SUSAN J. HASSOL

Susan Joy Hassol is a climate change communicator, analyst, and author known for her ability to translate science into English, making complex issues accessible to policymakers and the public for two decades. In 2009, Susan worked with a team of scientists to write Global Climate Change Impacts in the United States, an authoritative yet accessible report from the U.S. Global Change Research Program. Susan was lead author of Impacts of A Warming Arctic, the synthesis report of the Arctic Climate Impact Assessment published in 2004. In 2006, Susan was honored by the Climate Institute with its first ever award for excellence in climate science communication.

The information contained in the *Arctic Climate Change* section of the *Executive Summary* was compiled from:

Sommerkorn M., Hamilton N. (eds.) 2008. Arctic Climate Impact Science – an update since ACIA. http://assets.panda.org/downloads/arctic_climate_impact_science_1.pdf

J. Richter-Menge, J. Overland, M. Svoboda, J. Box, M.J.J.E. Loonen, A. Proshutinsky, V. Romanovsky, D. Russell, C.D. Sawatzky, M. Simpkins, R. Armstrong, I. Ashik, L.-S. Bai, D. Bromwich, J. Cappelen, E. Carmack, J. Comiso, B. Ebbinge, I. Frolov, J.C. Gascard, M. Itoh, G.J. Jia, R. Krishfield, F. McLaughlin, W. Meier, N. Mikkelsen, J. Morison, T. Mote, S. Nghiem, D. Perovich, I. Polyakov, J.D. Reist, B. Rudels, U. Schauer, A. Shiklomanov, K . Shimada, V. Sokolov, M. Steele, M.-L. Timmermans, J. Toole, B. Veenhuis, D. Walker, J. Walsh, M. Wang, A. Weidick, C. Zöckler. 2008. Arctic Report Card 2008, http://www.arctic.noaa.gov/reportcard <http://www.arctic.noaa.gov/reportcard>.

All figures in this report have been redrawn from the original sources referenced in the figure caption.

ARCTIC CLIMATE FEEDBACKS:
GLOBAL IMPLICATIONS

Martin Sommerkorn & Susan Joy Hassol, editors

With contributions from:
  Mark C. Serreze & Julienne Stroeve
  Cecilie Mauritzen
  Anny Cazenave & Eric Rignot
  Nicholas R. Bates
  Josep G. Canadell & Michael R. Raupach
  Natalia Shakhova & Igor Semiletov

Reviewed by:
  David Carlson
  Robert Corell

First published by
WWF International Arctic Programme
August, 2009

2nd edition November, 2009

ISBN: 978-2-940443-00-0
Recommended citation:
Sommerkorn, M. and Hassol, S.J. (eds.) Arctic Climate Feedbacks: Global Implications.
WWF International Arctic Programme, Oslo, 2009. 97pp.

Cartography: GRID Arendal,
Riccardo Pravettoni in collaboration with
Laura Margueritte.
Editorial assistance: Marta Darby
Photos: Staffan Widstrand page 5, 17, 28, 39, 54, 69, 81
Cover: Ketill Berger, http://www.chamberlinproductions.org, NASA
Design: Ketill Berger, Film & Form

WWF IS ONE OF THE LARGEST and most experienced independent conservation organizations, with almost 5 million supporters and a global network active in
more than 100 countries.
WWF's mission is to stop the degradation of the planet's natural environment and to build a future in which humans live in harmony with nature, by:

- conserving the world's biological diversity
- ensuring that the use of renewable natural resources is sustainable
- promoting the reduction of pollution and wasteful consumption.

WWF International Arctic Programme
P.O.Box 6784, St Olavs Plass
0130 Oslo
Norway

Tel: +47 22 03 65 00
arctic@wwf.no

www.panda.org/arctic

for a living planet