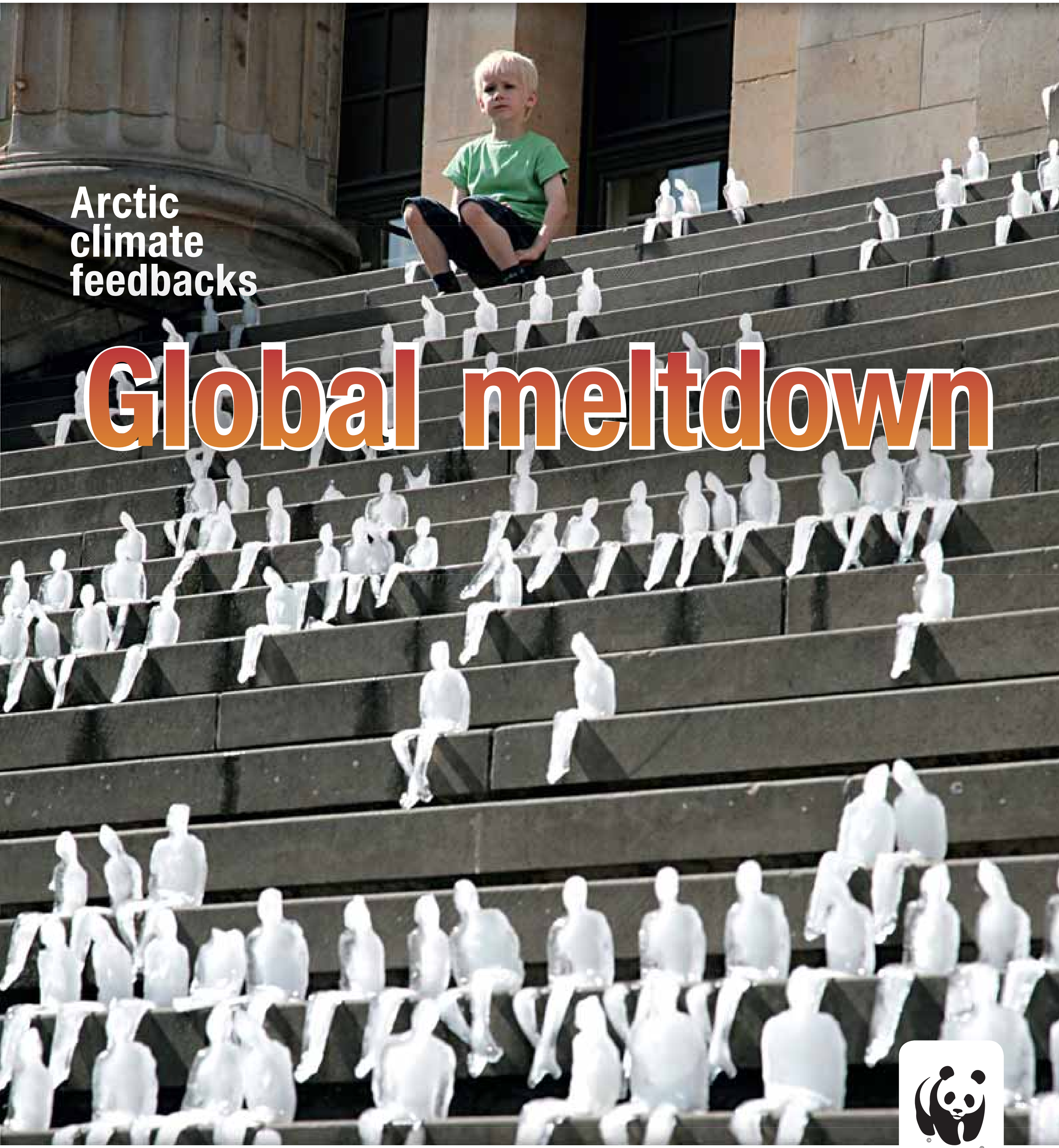
THE CIRCLE

No. 3. 2009



Arctic climate feedbacks

Global meltdown

PUBLISHED BY THE WWF INTERNATIONAL ARCTIC PROGRAMME

WWF

CLIMATE FEEDB

Contents

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Printed at Merkur-Trykk AS

Date of publication: September, 2009.
ISSN 2073-980X = The Circle (Oslo)

Ice sheet, Greenland. PHOTO: Marco Tedesco

Cover: WWF Germany commissioned Brazilian artist Nele Azevedo to create these 1000 ice figures and placed them on steps in Berlin's Gendarmenmarkt square to coincide with the release of the Arctic Climate Feedbacks report. Photo: Andreas Eistert/WWF Germany

The WWF International Arctic Programme gratefully acknowledges the financial support of The W. Garfield Weston Foundation for publication of The Circle.

The shock waves of arctic change

IN A RECENT ARTICLE, Guardian newspaper columnist George Monbiot told his readers to "… forget the sodding polar bears, this is about all of us". Monbiot was writing about the impacts of climate change, and how they are hitting closer to home than most people realize. While we cannot agree with forgetting the polar bears, we can whole-heartedly endorse the rest of the sentiment. It is about all of us, and in ways that are intimately connected to the Arctic.

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 the distribution of frozen soils and vegetation. 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.

> "It is about all of us, and in ways that are intimately connected to the Arctic.

The Arctic is the epicentre of climate change, and the shock waves of that change are radiating out to affect the entire planet and its people, earlier and stronger than expected. 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

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are now being altered in a rapidly warming Arctic. There is emerging evidence that these feedbacks are beginning to accelerate global warming considerably beyond the projections currently being considered by policymakers. There is growing concern that arctic feedbacks may increase regional or global warming significantly enough that it would alter other climate feedbacks. For example, the additional heat absorbed by an increasingly ice-free Arctic Ocean in summer is already accelerating local and regional warming, preventing sea ice from recovering, and is suggested to be responsible for increased emissions of greenhouse gases from permafrost soils.

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 what the United Nations calls '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 (UNFCCC).

The newest message from the Arctic needs to be at the fingertips of those shaping the new global climate deal that will be negotiated in Copenhagen this December. The Intergovernmental Panel on Climate Change 4th Assessment Report from (IPCC 2007), serves as the integrated basis for assessing the sensitivity of our planet to human-induced climate change. It did not cover many of the arctic climate feedbacks to a degree adequately reflecting their global significance. To close this gap, WWF's International Arctic Programme commissioned a report about the global implications of arctic climate feedbacks. The report, published in early September 2009, was authored by senior science experts, most of them lead or contributing authors to IPCC 2007. It assesses the most recent science regarding major arctic feedbacks of global significance for coming decades, providing a comprehensive and up-to-date picture of why and how climate change in the Arctic matters for the rest of the world and its relevance for climate policy decisions.

> **"These growing insights sharpen our awareness of how arctic climate change relates to global average warming, and what level of global warming may constitute what the United Nations calls 'dangerous human interference' with the climate system.**

The WWF report concludes that we are already seeing the first effects of arctic climate feedbacks; they are already upon us considerably earlier than expected, making global climate change more severe than indicated by other recent projections, including those of IPCC 2007. Arctic climate feedbacks are also expected to accelerate earlier than previously projected. If we continue to warm the Earth at the current rate we will see them causing a significant amplification to the consequences of global climate change within this century.

The report highlights that Arctic Climate Feedbacks will be felt around the world. Many of them affect the greenhouse gas loading of the atmosphere, so the consequences will be felt worldwide, through further increased global warming. Other feedbacks will materialise as regional consequences. Weather will change as a result of atmospheric feedbacks, ocean currents will change as a result of ocean feedbacks, coasts around the planet will be affected by sea level rise. All these changes will affect many people's access to resources on land and at sea.

A PROMINENT EXAMPLE from the report is how dramatic loss of arctic sea ice amplifies warming in the Arctic and beyond. The additional warming in the Arctic will alter atmospheric circulation, and through it, weather patterns in the Northern Hemisphere. Changes in the Arctic triggered as we speak may soon affect temperatures and precipitation, and through it forestry, agriculture, and water resources, earlier than expected. This arctic amplification — and its consequences for people — will become more pronounced as more ice cover is lost over the coming decades.

Arctic amplification has consequences for the arctic carbon cycle. The report concludes that amplified warming in the Arctic may lead to the disappearance of 90 per cent of near-surface permafrost by the end of this century. This has the potential to release large amounts of carbon into the atmosphere as both carbon dioxide and methane, significantly accelerating global warming. Vast amounts of frozen methane hydrates in the seafloor of the shallow arctic shelf seas could emit increasing amounts of methane to the atmosphere should subsea permafrost destabilise in a warmer Arctic.

“The newest science suggests that to have a probability that can be termed “likely” of staying below two degrees Celsius global average warming since pre-industrial times we cannot emit more than around 1000 gigatonnes of carbon dioxide before 2050. If we continue on the present trajectory of emissions we have one hundred per cent probability of exceeding this dangerous warming threshold.

Scenario projections made in IPCC 2007 do not consider any of the arctic carbon cycle feedbacks; none of the additional carbon dioxide and methane emissions from permafrost soils and seafloor sediments, no waning ocean sink strength.

In a first-of-its kind assessment considering the fate of the increasingly melting ice sheets of Greenland and West Antarctica in a projection of global sea-level-rise, the WWF report concludes that sea level will very plausibly rise by more than 1 metre by 2100, largely due to increased mass loss from the ice sheets. This is more than twice the amount projected in IPCC 2007 that had excluded increasing contributions from ice sheets from their projections. A quarter of the world’s population would be affected by sea-level rise of such magnitude because it will give rise to flooding, shoreline erosion, and saltwater intrusion into surface waters and farmland. The report highlights that ice sheet melt will be the primary contributor to sea-level rise well beyond this century, and issues a stark warning that with ongoing warming, ice sheet melting is projected to continue irreversibly on human timescales.

Probably the most important point of the WWF report is that we have no time to lose. If we allow the Arctic to get much warmer it is really doubtful whether we will be able to keep arctic climate feedbacks under control. People across the world would suffer the consequences. It is in our hands — this update on arctic feedbacks shows how close we are to interfering with the global climate system to a dangerous degree.

There is a limited carbon emission budget that cannot be exceeded if the world wants to escape dangerous climate change and the resulting global upheaval. The newest science suggests that to have a probability that can be termed “likely” of staying below two degrees Celsius global average warming since pre-industrial times we cannot emit more than around 1000 gigatonnes of carbon dioxide before 2050. If we continue on the present trajectory of emissions we have one hundred per cent probability of exceeding this dangerous warming threshold.

So what is needed now is for everybody to listen to these signals from the Arctic and take the necessary action to come to a deal in Copenhagen that reduces emissions as ambitiously and quickly as possible — for the sake of the Arctic — and a living planet. ○

The Arctic in your backyard

THE ARCTIC Climate Feedbacks: Global Implications report that takes up most of this issue marks also a new approach by the WWF Arctic team; a move into the world of multimedia. "While science is the backbone of what we say and what we do, we needed a way to lift the words off the page and reach a wider audience," says Clive Tesar, Head of Communications for the Arctic Programme. "I have seen that Internet-based animated presentations have a great capacity to reach people, so we decided to apply that approach to the feedbacks report."

The result is a presentation that runs just under seven minutes, that blends animation, video and still photographs to tell the story of how climate feedbacks from the Arctic affect people globally. So far, the presentation is online in English and German, and there are plans for it to be also presented in French and Mandarin Chinese.

The presentation can be viewed at http://www.youtube.com/watch?v=1IFCzdvjW_k

Celebrating a Sanctuary for Bowheads

SINCE THE 1980S, WWF has worked with the community of Clyde River (Kangiqtugaapik in Inuktitut, the language of the indigenous Inuit) in northeastern Canada to help document and protect a critical feeding area for bowhead whales. On August 7, 2009, WWF joined Inuit in a great celebration of the creation of this sanctuary — which is now called "Ninginganiq" (or Isabella Bay on English maps).

The sanctuary regulations are being finalized by the Government of Canada, and thereafter a local committee will be completing the management plan for the new sanctuary. It is hoped that this will lead to the creation of a safe gravel airstrip and small accommodation facility, which will allow tourists to witness this spectacular place and the 100 or more bowhead whales that gather here each summer and autumn to feed.

WWF-Canada has supported community-based projects on this special bowhead habitat for 25 years, providing almost $1 million for research, monitoring, and training of local Inuit in recording valuable information on the whales.

Bowheads have no dorsal fin, and can break through ice up to 1 m thick to breathe. But as sea ice melts due to accelerating climate change, bowheads are experiencing major challenges at unprecedented rapid rates. The recent sharp increases in orcas/killer whales — which attack and kill bowheads and narwhal — trouble both Inuit and whale conservationists. On top of threats to its food, and threats from predators, increased commercial shipping, military activities, and hydrocarbon exploration and development (including seismic projects offshore) present further threats to the whales. Sanctuaries such as this one help to manage the threats.

Measuring the success of the Catlin Arctic Survey

THE THREE PERSON team has long been safely back home in the United Kingdom after a gruelling trip across the polar ice, but the journey is not over for the Catlin Arctic Survey (CAS). One of the key goals of the trip was to take measurements of sea ice thickness to help inform future predictions of sea ice in the Arctic.

Despite problems with their technological tools, the team managed many measurements by hand. These measurements are now being analyzed by Dr. Peter Wadhams of the Polar Oceans Physics Group at Cambridge University. Once the analysis is complete, it should give a ground-truthed picture of how much of the ice covered


Photo: Martin Hartley

The Catlin Arctic Survey has maped arctic sea ice thickness.

by the team was thinner first year ice, and how much was multi-year ice. The proportions of each type of ice have an impact on the rate of ice loss for the following year, and could help forecasters predict how soon the Arctic will be entirely free of ice in the summer.

WWF is working with CAS to ensure that the results of Wadham's analysis get to the right audience in advance of the climate negotiations in Copenhagen this December.

Photo: Susan Evans/WWF

Participants in the young leaders meeting beside the Mackenzie River.

Young leaders speak up on climate change

YOUNG LEADERS at a climate summit in the northern Canadian town of Inuvik finished off a meeting in August with a declaration highlighting the north's vulnerability to climate change. The sixty young leaders from across Canada called for strong action on climate change by Canada and the international community.

WWF Canada's Susan Evans co-led a packed session on climate adaptation at the meeting. "The energy and commitment that these young leaders bring to the subject is inspiring," said Evans.

The meeting was organized by a coalition of Indigenous peoples' organizations and NGOs. They are now discussing ways of getting the outcomes of the meeting to the attention of decision-makers before the next round of international climate negotiations.

US assessing walrus status

THE UNITED STATES government has announced that it is considering a listing for pacific walrus under the Endangered Species Act. A statement from the US Fish and Wildlife Service says "… adding the species to the federal list of threatened and endangered species may be warranted. This preliminary finding is based, in part, upon projected changes in sea ice habitats associated with climate change."

The decision to further investigate whether the walrus should be listed was supported by Geoff York, Senior Program Officer with the WWF Arctic Programme. York has just finished sailing though the easternmost stretch of the Northeast Passage above Arctic Russia, and has seen for himself walrus crowded on beaches where they have historically been spread across sea ice at this time of year.

"Given the dramatic and continuing loss of sea ice habitat in the Arctic, WWF supports the decision by the USFWS that Pacific Walrus may merit listing under the Endangered Species Act," says. "Evidence from Chukotka and Alaska show sthat walrus are abandoning the ice in large numbers when it recedes past the shallow, productive waters of the continental shelf. Once on shore, walrus will have less area available for feeding and will be much more vulnerable to disturbance and predation."

The Fish and Wildlife Service is expected to make its determination on the listing status of the walrus by September 10, 2010

Photo: Bill Curtsinger/National Geographic Stock/WWF Canada

Photo: Marco Tedesco

Plumbing the mysteries of Greenland's glacial lakes

RESEARCH HAS established that melting from the massive cap of ice covering Greenland is contributing significantly to global sea level rise (see the article in this edition on page 14). What is not yet firmly established is how this is happening. One theory is that the lakes forming above the Greenland ice sheet are draining down through the ice, lubricating the passage of the ice to the sea. The lakes are also thought to be contributing to melting of the ice as their surface is less reflective than the ice below. This contributes to further melting as the heat absorbed by the lakes melts yet more ice.

Understanding these processes will add more certainty to predictions of how fast the ice sheets could move in the future, leading to better predictions of the rate of sea level rise due to climate change.

This summer a field scientific expedition from the Research Foundation of the City University of New York led by Professor Marco Tedesco, went to Greenland to try to provide some answers to the questions posed by these lakes. The team's tasks included checking satellite measurements of the extent of the lakes, checking their depth, and collecting water samples from the lakes. WWF supported these efforts by helping to support the travel of the team.

"The experiment was successful and we collected all the data we wanted to, and more," says Tedesco. "It was harder than I thought to deploy the boat and prepare it every time for each experiment. However, we made it with a lot of patience, physical strength and keeping up the good mood."

Professor Tedesco and the rest of the team are now analyzing the results of the summer's field work, and will be publishing the results in scientific journals.

The North East Passage: a New Sea?

THIS SUMMER WWF sailed unassisted through the North East Passage, from northern Norway across the north coast of Russia to the Bering Strait, following the wake of the explorer Adolf Erik Nordenskjold. He took two years (1878-79) to become the first man to traverse the passage. Since then very few sailing yachts however have ever been able to complete the trip because of the sea ice.

The expedition, organized by leading Swedish polar expert Ola Skinnarmo, involved three WWF staff: Tom Arnbom from Sweden, Neil Hamilton from Oslo, and Geoff York from Alaska. Over the course of 3 months, the specially designed and reinforced yacht 'Explorer of Sweden' travelled from Stockholm to circumnavigate Svalbard (itself a rare event!), and then began the extraordinary journey from Murmansk to Providenya.

WWF was there primarily to highlight the changes that have occurred to one of the most remote places on Earth, as a result of climate change and to understand the impacts of the changes on the local people so that we can find better ways to work with them in the future.

Changes are already observable in the ecology and the ice-dependent wildlife of the Russian Arctic. We also visited some of the huge conservation areas we helped to establish in the 1990s, like the Great Arctic Reserve.

This voyage proves that in summer it is now possible to easily sail through the North East Passage without any help from ice-breakers. This may bring opportunities for Arctic peoples, but it will also bring disruptions and risks which must be managed before they affect the values we fight to protect. You can view all the blogs from the expedition, including pictures, at www.panda.org/actic.

Melting sea ice and weather changes

One of the most dramatic changes to the globe in recent decades has been the rapid decline of arctic sea ice, say **MARK C. SERREZE** and **JULIENNE STROEVE**. This has major implications for temperature and weather patterns, affecting resources relied upon by society.

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. This heating gradient drives our atmospheric circulation that transports heat from regions of low-latitude warmth to the cooler poles. Changes in the arctic sea-ice cover modify the basic heating gradient 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 its 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 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.

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.

The past two years, 2007 and 2008, saw the lowest and second-lowest ice extent in the satellite record and this summer looks like it will end up as the third lowest. 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.

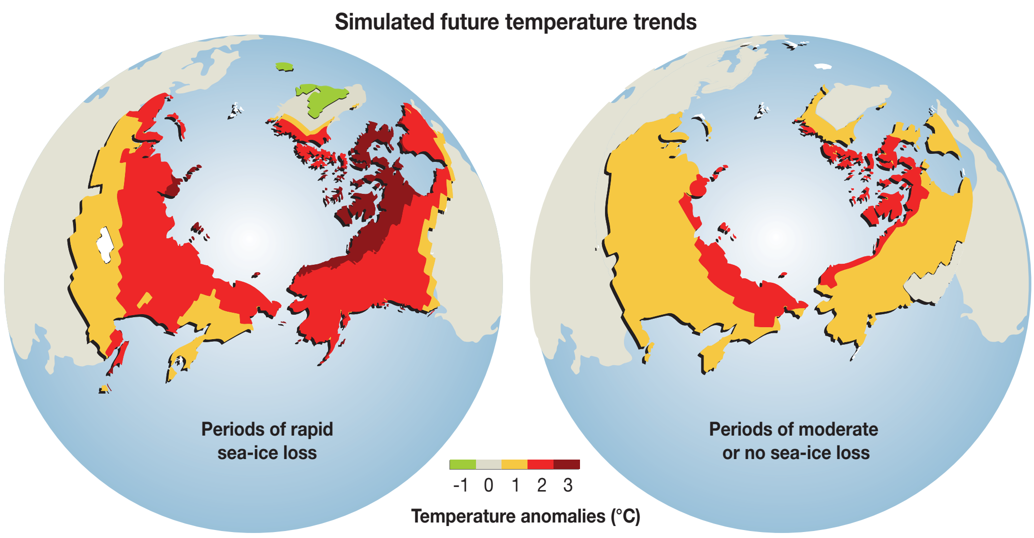
The decreases in sea ice extent are best explained by a combination of natural variability (including changes in atmospheric and oceanic temperature and circulation) and rises in surface air temperatures linked to increasing concentrations of greenhouse gases in the atmosphere. Model simulations mostly 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.

MARK C. SERREZE has a PhD in geography and has since 1989 been with the National Snow and Ice Data Center's Cooperative Institute for Research in Environmental Sciences at the University of Colorado as research scientist. His efforts over the past 10 years have increasingly focused on trying to make sense of the rapid environmental changes being observed in the Arctic.

JULIENNE STROEVE has a PhD in geography and is currently a research scientist at the National Snow and Ice Data Center at the University of Colorado. Her 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.

REDUCED SEA ICE AMPLIFIES WARMING

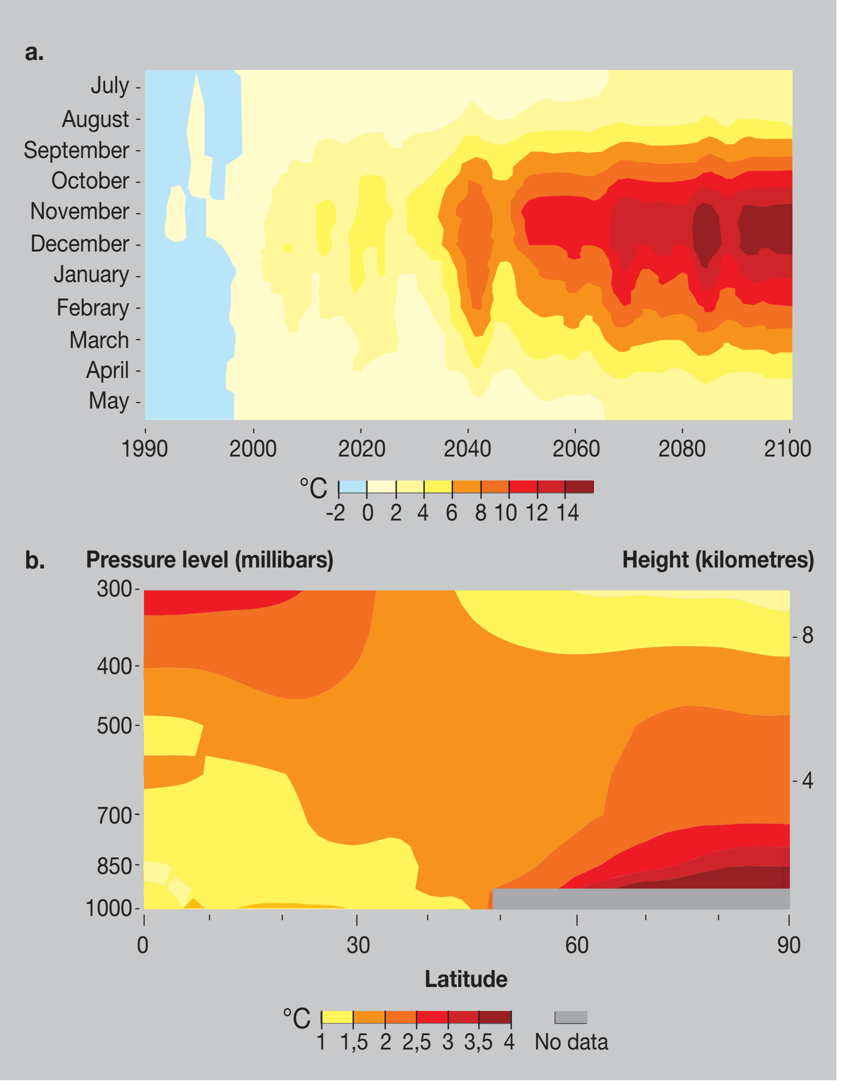
Impacts of sea ice loss on atmospheric circulation can be broadly linked to the antici-



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.

Cartography: Riccardo Pravettoni, GRID Arendal

pated stronger rise in arctic air temperatures compared to warming in middle latitudes, a process termed polar or arctic amplification. 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 ocean to readily absorb the sun's energy, increasing the summer heat content in the top 50 metres of the ocean, which also further accelerates ice loss. Ice formation in autumn and winter, which is important for insulating the warm ocean from the cooling atmosphere, is delayed. This allows for



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

Cartography: Riccardo Pravettoni, GRID Arendal a large upward heat transfer from the ocean to the atmosphere before the ice reforms. 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.

An analysis of atmospheric data sets reveals that anticipated arctic amplification is already occurring. 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 of the atmosphere over the Arctic Ocean through a considerable depth. This 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.

Taken together, these changes will affect the development, tracks and strengths of weather systems, and the precipitation that they generate. Computer simulations indicate that changes could range from drying in the in the American southwest to greater precipitation in parts of Europe.

While there is no universal consensus regarding the spatial patterns of change that will emerge, a common thread between different modelling studies is that changes may be significant and affect areas well beyond the boundaries of the Arctic, impacting transportation, agriculture, forestry and water supplies. ○

Arctic impact on global ocean circulation

We expect significant changes in ocean circulation to occur during this century, in particular a long-term slowdown of the global overturning circulation as well as significant decade-to-decade variations. Changes in ocean circulation are likely to cause societal impacts such as changes in access to important resources, as well as providing an important feedback into Earth's climate system, says **CECILIE MAURITZEN**.

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). As snow and ice melt into the ocean, freshwater is added and the ocean water in those areas becomes less salty. When density changes, ocean circulation is altered.

The Arctic Ocean 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 counterclockwise. The deeper circulation is not directly forced in the Arctic Ocean (it cannot, since it does not 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

CECILIE MAURITZEN is a senior scientist at the Climate Department of the Norwegian Meteorological Institute. 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 ocean circulation using modern automated platforms including profiling floats and gliders, and development of ocean observatories for long-term observations.

and salinity in the Arctic Ocean, the consequences may be felt worldwide. The mechanism involved is the world-encompassing meridional overturning circulation (MOC).

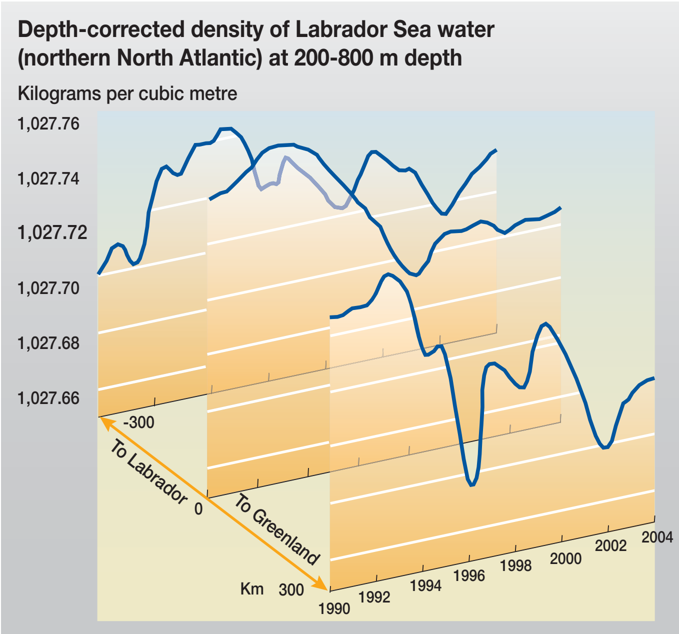
DECREASING CIRCULATION STRENGTH

Since there are no long-term measurements of the MOC, 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 one 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. 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. If the 1965-1995 rate of decrease were to continue for a hundred years, significant changes in ocean circulation would occur.

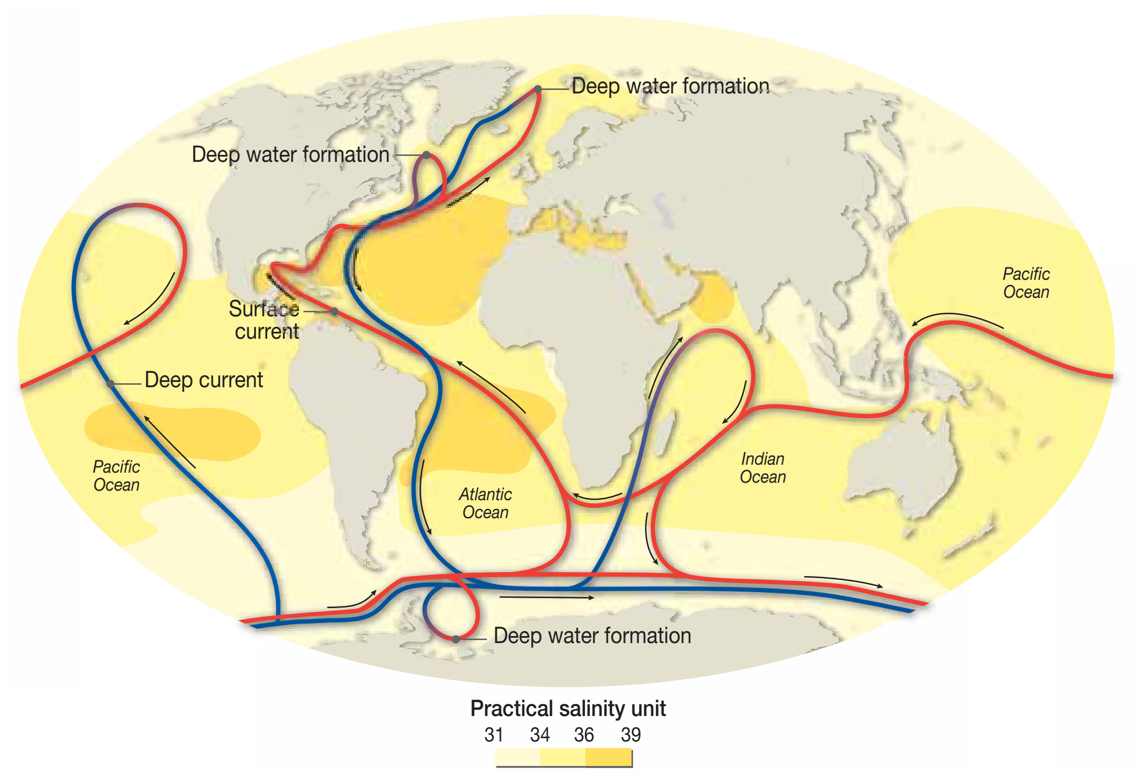
Since the mid-1990s, the salinity has been increasing rather than decreasing in the subpolar North Atlantic. That is because hand-in-hand with the melting ice comes an increase in evaporation at lower latitudes and an increase in precipitation at higher latitudes. In a warmer climate, the water cycle 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, just as it did in



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

Cartography: Riccardo Pravettoni, GRID Arendal



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

In this schematic of the encompassing meridional overturning circulation, 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).

Cartography: Riccardo Pravettoni, GRID Arendal

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 would already be 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 (note that this estimate is controversial) and another estimating a roughly 15 per cent reduction. However, it should be noted that measuring the MOC is notoriously difficult.

FUTURE CONSEQUENCES

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 global climate models consistently project a reduction in the MOC during this century (but not an abrupt collapse). The models indicate, on average, a 25 per cent reduction in MOC strength during this century.

One consequence of the reduced MOC is a delayed warming in the Atlantic sector. This delay is present in all the IPCC 2007 future scenario runs 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 clear 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.

When a nutrient-rich ocean current finds a new path the fish adjust by changing their migration patterns, affecting fisheries.

Photo: Kjell Ove Storvik/Norwegian Seafood Export Council

Finally, society is not only affected by a change in ocean circulation strength, but also by pathway changes. Different ocean currents transport waters with different characteristics, supporting different ecosystems. 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.

Major concern for coastal regions

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, say **ERIC RIGNOT** and **ANNY CAZENAVE**. As the climate heats up air and ocean temperatures rise causing ocean water to expand, melting glaciers and ice sheets, and raising the global sea level.

Sea level is a very sensitive index of climate change and variability. In addition, 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.

While the global average sea level had remained almost stable for the last 3,000 years, tide gauge measurements available since the late 1800s have reported significant sea level rise during the 1900s. Since early 1993, sea level variations have been accurately measured by satellite altimetry. Average global sea level is currently rising at a rate of about 3.3 millimetres per year (plus or minus 0.4 millimetres), roughly twice the average rate recorded by tide gauges over the previous decades.

Analyses of 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 30 per cent of the observed sea level rise since 1993. Highly sensitive to global warming, mountain glaciers and small ice caps have retreated worldwide during the recent decades, with significant acceleration during the 1990s. 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.

As climate heats up, air and ocean

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Photo: Marco Tedesco

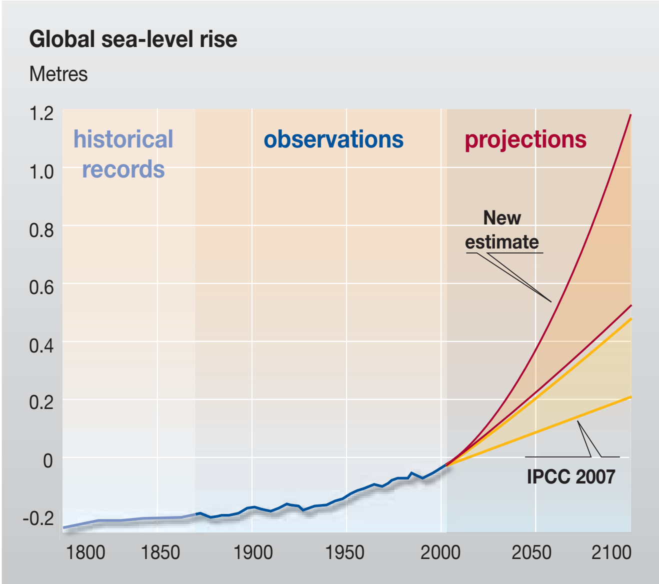
temperatures rise, the melting of ice at the surface of the Greenland Ice Sheet increases, and glaciers flow faster to the ocean and melt faster in the ocean. Even in Antarctica, where air temperatures remain below freezing and melting is limited to the low-lying regions of the Antarctic Peninsula, ocean 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.

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. 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.

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, equivalent to the amount of water required to supply 280 cities like Los Angeles and its 8 million inhabitants 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. The ice sheet loss has increased by about 20 gigatonnes per year every year since the 1970-1980s. 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.

As climate warming continues, existing models agree that the ice sheet will melt almost completely if local warming exceeds 4 to 5°C.



Future sea-level rise based on simple relationship between rate of sea-level rise and global average temperature.

Cartography: Riccardo Pravettoni, GRID Arendal

In 2008, Antarctica lost nearly as much ice as Greenland, a net loss of about 220 gigatonnes per year. 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.

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.

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.

A certain amount of climate change and associated sea level rise is already locked in for the next several decades based on past emissions 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 have significant impacts.

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. 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.

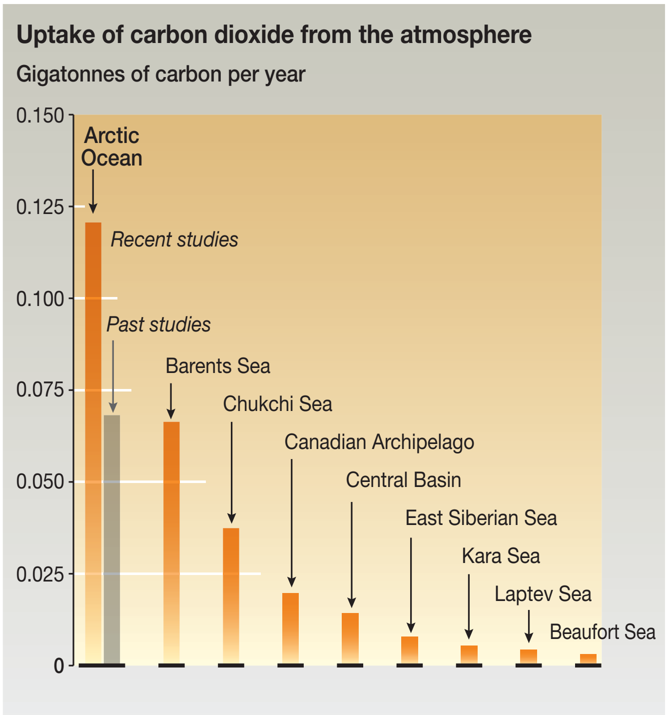
It is very difficult to quantify future sea level rise in specific regions where various factors interact in complex ways. Despite the uncertainties, sea level rise will almost surely cause significant impacts in coastal regions around the world. ○

Sensitive to climate change

Among its other important functions, the Arctic Ocean absorbs carbon dioxide. But absorbing carbon dioxide produced by human activities also has downsides, says **NICHOLAS R. BATES**. 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.

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. 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 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. The arctic landmasses also contain large stores of freshwater (mostly glacial ice and permafrost) and terrestrial carbon compared to the stores of carbon in the Arctic Ocean. As such, arctic rivers contribute disproportionately large amounts of freshwater and other materials, such as carbon, compared to other ocean basins.



Cartography: Riccardo Pravettoni, GRID Arendal

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.

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. Thus, it is important to the feedback between the global carbon cycle and climate.

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, 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.

However, the Arctic Ocean is in rapid transition and over the next few decades, the release of large stores of

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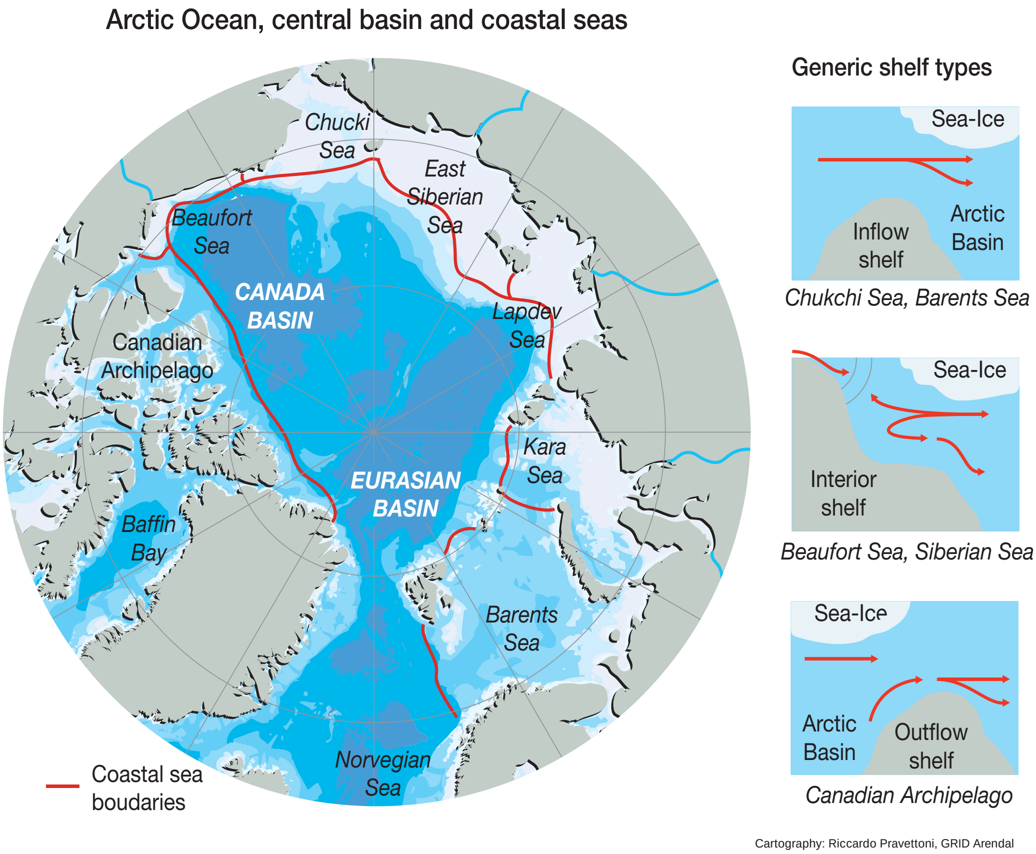

Left panel: *Schematic of the Arctic Ocean, central basin (Canada and Eurasian basins) and arctic continental shelves (with approximate boundaries for each Arctic Ocean coastal sea), and major rivers draining into the region.* **Right panel:** *The three generic types of continental shelves (i.e., inflow,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

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 release of carbon dioxide from the ocean to the atmosphere from this region. Such changes are likely due to changes in the physics, biogeochemistry and ecology of the Arctic Ocean, in ways that are not yet fully understood.

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). This gradual process, termed ocean acidification, has long been recognized by chemical oceanographers, but more recently brought to general attention. The predicted ocean uptake of human-caused carbon dioxide, based on IPCC scenarios, 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, with the Arctic Ocean impacted before other regions as a result of the relatively low *p*H of polar waters compared to other waters

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, reducing the ability of many species to produce calcium carbonate shells or skeletons, with profound implications for arctic marine ecosystems. ○

"Over the next few decades, the release of large stores of carbon from the surrounding arctic landmasses through rivers into the Arctic Ocean may lead to a net release of carbon dioxide from the ocean to the atmosphere from this region.

Future climate effects of the arctic carbon cycle

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, emphasize **J.G. CANADELL** and **M.R. RAUPACH**. As warming continues in the future, carbon emissions from arctic lands are projected to outpace uptake, further adding to global warming.


Photo: Sergei Zimov

Methane emerging from thermokarst lake in Siberia.

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.

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. As the climate continues to heat up, parts of this vast 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, 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, more than twice the amount of carbon in the atmosphere. 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. The new estimate of 1,650 gigatonnes of carbon for arctic soil carbon storage is more than double what had been previously estimated and includes several new pools that were not previously reported.

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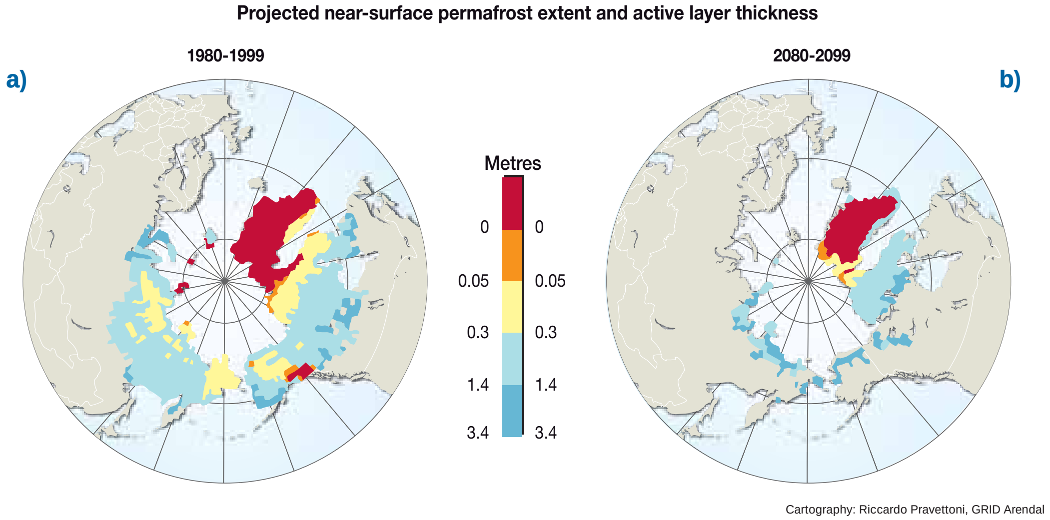
VULNERABILITY OF ARCTIC CARBON

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



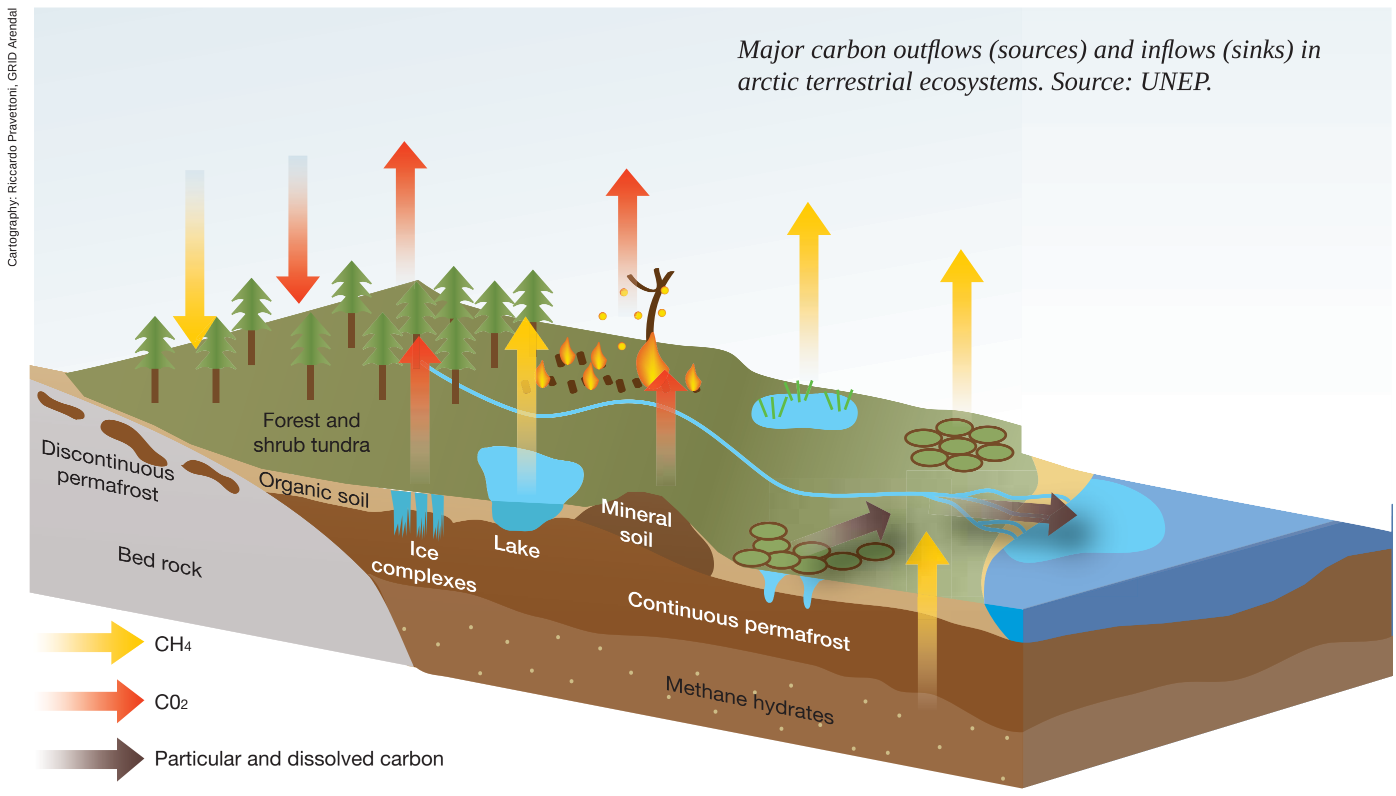
*Simulated permafrost area and active layer thickness (**a**) 1980-1999 and (**b**) 2080-2099.*

shown by recent measurements of the quantity and age of carbon emissions from thawing soils in Alaska. Contrary to earlier claims that old carbon could be quite inert and difficult to decompose, these measurements 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.

Even without permafrost thawing, subarctic peatlands are also holding large quantities of organic matter and are highly sensitive to increased temperatures.

Vulnerability of carbon pools also comes in the form of disturbances, particularly in boreal forests where fire and insect damage have been on the rise over the last few decades due to longer summers and warmer winters respectively.

In addition to carbon dioxide emissions, methane emissions are an important component of the carbon balance in the arctic region. The global warming potential of methane is 25 times higher than carbon dioxide.

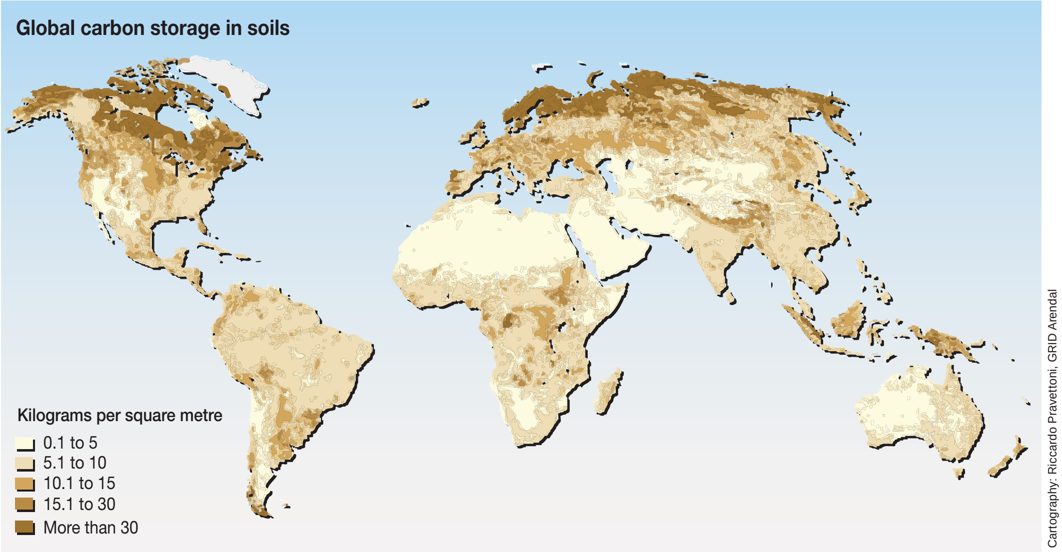


Major carbon outflows (sources) and inflows (sinks) in arctic terrestrial ecosystems. Source: UNEP.

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. 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.



Estimated distribution of soil organic matter in global terrestrial ecosystems.

Other changes will occur more progressively over the course of decades and possibly extend over hundreds of years, regardless of climate stabilization 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. 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.

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, 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.

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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. 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. ○

Climate threats from thawing permafrost

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, emphasize **NATALIA SHAKHOVA** and **IGOR SEMILETOV**. 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 destabilized, with major climatic repercussions.

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. 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".

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) is more than 13 times greater than the amount of carbon (as methane and carbon dioxide) in the atmosphere (about 760 gigatonnes). Release to the atmosphere of only 0.5 per cent of the methane stored within arctic shelf hydrates could cause abrupt climate change.

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VULNERABLE PERMAFROST

The stability of sub-sea permafrost is key to whether methane can escape from seabed hydrates and other deposits. Relict sub-sea permafrost, which underlies the arctic continental shelf, is an overlooked sibling to on-land permafrost. Sub-sea permafrost is potentially much more vulnerable to thawing than land-based permafrost as it 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. 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. 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

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

Predicted hydrate deposits

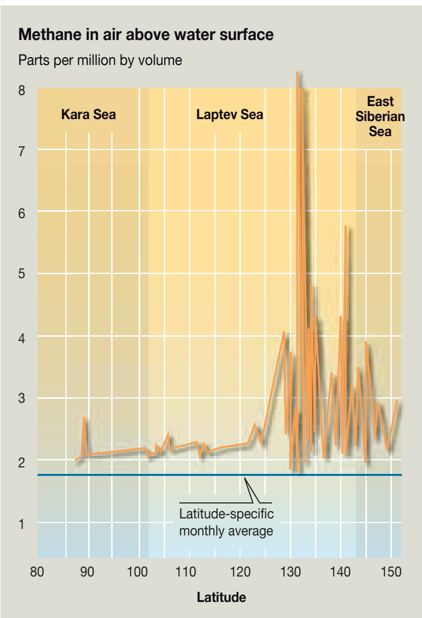
Water depth less than 50 metres

Map of predicted hydrate deposits (blue), and map showing the sea floor topography of the Arctic Ocean; 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.

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. Since sub-sea permafrost is salty, it thaws even at temperatures slightly below zero. Such temperatures of sub-sea permafrost have been observed recently on the Siberian arctic shelf. When it thaws, sub-sea permafrost loses its ability to seal off the seabed deposits of methane, including hydrates.

EXTENSIVE METHANE RELEASE

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. Extensive methane release from the seafloor is occurring at depths ranging from 6 to 70 metres, emerging as huge clouds of bubbles rising through the water column. 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), 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 four times greater than normal atmospheric levels.



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.

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.

ENORMOUS AMOUNTS

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, 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. 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. ○

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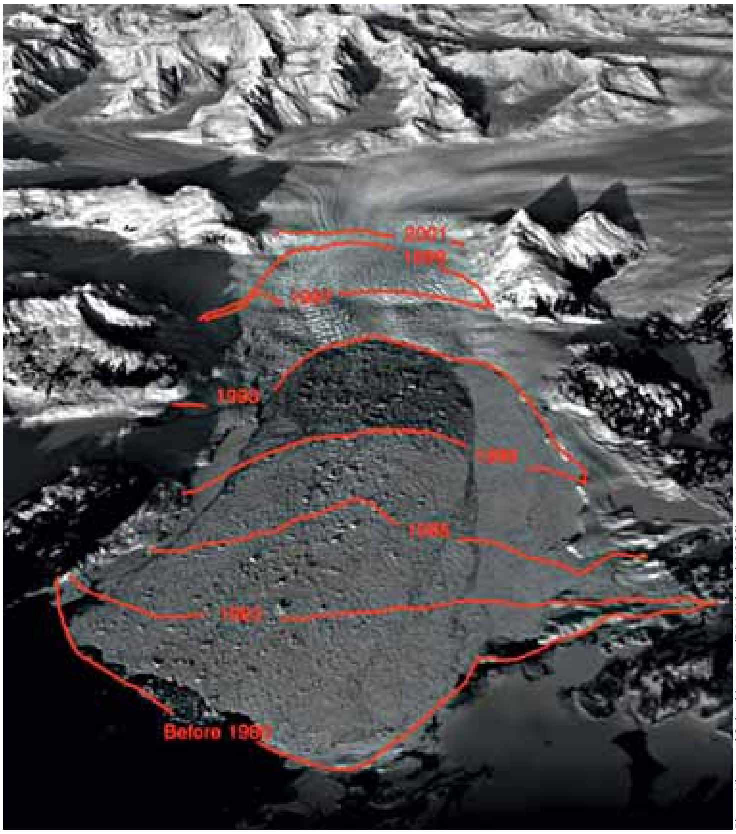

Photo: History of Columbia retreat (R.M. Krimmel, USGS)

Glacier on disintegration course

Alaska's Columbia Glacier in Prince William Sound on the south coast of Alaska continues on its disintegration course. The glacier was named after the Columbia University by the Harriman Alaska Expedition in 1899. It is one of the fastest moving glaciers in the world, and has been retreating since the early 1980s.

The glacier is a tidewater glacier, which means its terminus rests on bedrock about a thousand feet below sea level. The terminus has retreated a total of 16 kilometers at an average rate of approximately .6 kilometers per year since 1982. Retreat has been accompanied by nearly 500 meters of thinning at the present position of the terminus. In the next few decades it is expected to retreat another 15 kilometers, to a point where the bed of the glacier rises above sea level.

It is predicted that the retreat of the Columbia Glacier will create a new fjord, possibly to be named "Port Columbia", within the next few decades.