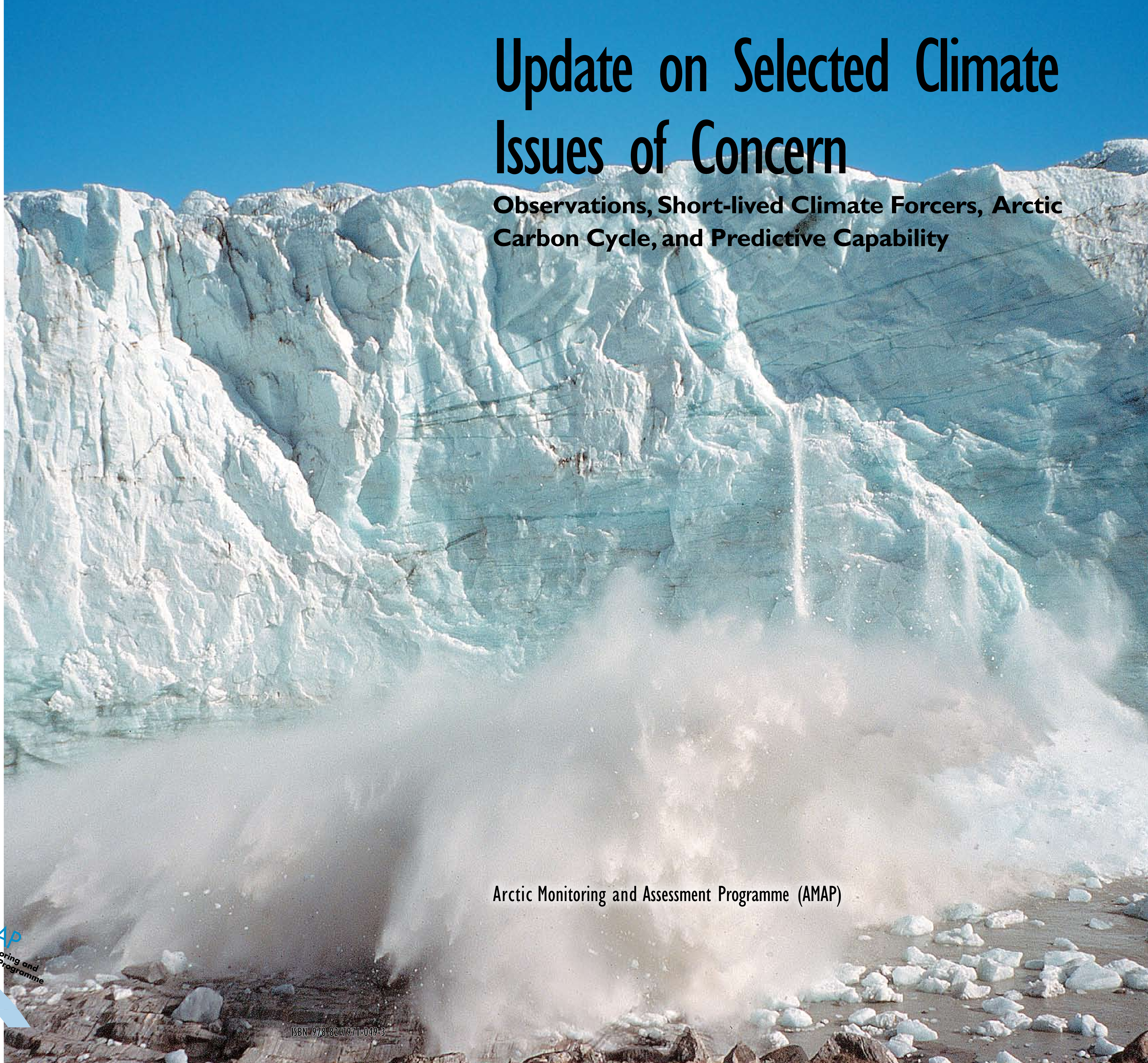

Update on Selected Climate Issues of Concern

Observations, Short-lived Climate Forcers, Arctic Carbon Cycle, and Predictive Capability

Arctic Monitoring and Assessment Programme (AMAP)

AMAP
Arctic Monitoring and Assessment Programme

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Contents

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AMAP Working Group:
John Calder (Chair, USA), Per Døvle (Vice-chair, Norway), Yuri Tsaturov (Vice-chair, Russia), Russel Shearer (Canada), Henrik Larsen (Denmark), Morten Olsen (Denmark), Outi Mähönen (Finland), Helgi Jensson (Iceland), Yngve Brodin (Sweden), Jonas Rodhe (Sweden), Tom Armstrong (USA).

AMAP Secretariat:
Lars-Otto Reiersen, Simon Wilson, Yuri Sychev, Inger Utne.

ACKNOWLEDGEMENTS
Author:
Henry P. Huntington (Huntington Consulting, hph@alaska.net).

Contributing experts:
B. Ådlandsvik
A. Ahlstrøm
O. Alexandrova
M. Ananicheva
L. Anderson
L.G. Anderson
O.A. Anisimov
D. Bancroft
N. Bates
T.S. Bates
I. Bauer
E. Baum
R. Bellerby
R.E. Benstad
T.K. Berntsen
J. Bluestein
S. Bodin
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T. Bond
L.W. Brigham
H.I. Browman
J.F. Burkhart
J. Calder
T.V. Callaghan
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T.R. Christensen
Ø. Christophersen
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C. Vorosmarty
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K. Walter
P. Wassmann
S.J. Wilson
C. Witherspoon
Z. Yang
N. Ye. Chubarova
Q. Zhuang
S. Zimov

Indigenous peoples' organizations, AMAP observing countries, and international organizations:

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Graphical production of *AMAP 2009 Update on Selected Climate Issues of Concern*

Lay-out and technical production:
John Bellamy (johnbellamy@swipnet.se).

Design and production of computer graphics:
Simon Wilson and John Bellamy.

Cover design:
John Bellamy.

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Narayana Press, Gylling, DK-8300 Odder, Denmark (www.narayanapress.dk); a Swan-labelled printing company, 541 562.

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Preface

The Arctic Monitoring and Assessment Programme (AMAP) is a Working Group of the Arctic Council. The Arctic Council Ministers have requested AMAP to:

- produce integrated assessment reports on the status and trends of the conditions of the Arctic ecosystems, including humans;
- identify possible causes for the changing conditions;
- detect emerging problems, their possible causes, and the potential risk to Arctic ecosystems including indigenous peoples and other Arctic residents; and to
- recommend actions required to reduce risks to Arctic ecosystems.

AMAP assessments are generally delivered to Ministers at appropriate intervals in the form of 'State of the Arctic Environment Reports' on pollution and climate related issues. However, on occasion, the AMAP, WG consider it appropriate to inform Ministers about some of the results of ongoing work before it is fully incorporated in a comprehensive assessment report, for example, where such information may be relevant to policy-related discussions that are currently ongoing within the Arctic countries. AMAP convey this information to the Arctic Council Ministers in interim 'Update Reports on Issues of Concern'.

The '*AMAP 2009 Update on Selected Climate Issues of Concern*' is intended to be readable and readily comprehensible report. It summarizes recent observations of changing climate parameters, a review of the significance of short-lived climate forcers and prospects for their mitigation, a new evaluation of the Arctic carbon cycle, and new initiatives to improve understanding of the cryosphere and the ability to model climate changes and impacts at the regional scale. The report does not contain extensive background data or references to the scientific literature. The complete and fully-referenced scientific documentation, including sources for all figures reproduced in the report, is contained in accessible scientific background reports and papers published in the scientific literature.

AMAP '*Update Reports on Issues of Concern*' are based on the same type of rigorous scientific background assessment process, as that which forms the basis for the '*State of the Arctic Environment Reports*'. Therefore, whereas the climate information presented in this report is not the result of a comprehensive assessment of Arctic climate change issues, it does provide an update on some of the work that has been undertaken by AMAP as follow-up of the 2004 '*Arctic Climate Impact Assessment*'. It draws upon peer-reviewed publications as well as workshops conducted under AMAP's auspices. Main source documents are listed on page 15. The report has been reviewed by the authors of the scientific reports, by the members of the AMAP Working Group, and through national review processes in each Arctic country to ensure that the summary is an accurate representation of the scientific background documentation.

A large number of experts from the Arctic countries (Canada, Denmark/Greenland/Faroe Islands, Finland, Iceland, Norway, Russia, Sweden, and the United States), from indigenous peoples organizations, from other organizations, and countries with an interest in Arctic monitoring, have participated in the work presented in this report.

AMAP would like to express its appreciation to all of these experts, who have contributed their time, effort, and data. A list of the main contributors is included in the acknowledgements on the previous page of this report. The list is based on identified individual contributors to the AMAP scientific assessments, and is not comprehensive. Specifically, it does not include the many national institutes, laboratories and organizations, and their staff, which have been involved in the various countries. Apologies, and no lesser thanks, are given to any individuals unintentionally omitted from the list.

Special thanks are due to the lead authors responsible for the preparation of the scientific assessments that provide the basis for this report. Special thanks are also due to the author of this report, Henry Huntington. The author worked in close cooperation with the scientific experts and the AMAP Secretariat to accomplish the difficult task of distilling the essential messages from a wealth of complex scientific information, and communicating this in an easily understandable way.

The support of the Arctic countries is vital to the success of AMAP. AMAP monitoring work is essentially based on ongoing activities within the Arctic countries, and the countries also provide the necessary support for most of the experts involved in the preparation of the assessments, including the participation of indigenous peoples organizations in the work of AMAP. AMAP would in particular like to acknowledge the contributions of Norway and the United States that acted as the (co-)lead countries for several of the work components presented in this report.

The AMAP Working Group, who are responsible for the delivery and content of this 'Update Report on Selected Climate Issues', are pleased to present this report for the consideration by governments of the Arctic countries. This report is prepared in English, which constitutes the official version.

Tromsø, April 2009

John Calder
AMAP Chair

Lars-Otto Reiersen
AMAP Executive Secretary

Executive Summary

1. The *Arctic Climate Impact Assessment* and the Intergovernmental Panel on Climate Change have established the importance of climate change in the Arctic both regionally and globally. Following those reports, emphasis has been placed on continued observations, a new assessment of the Arctic carbon cycle, the role of short lived climate forcers in the Arctic, and the need for improved predictive capacity at the regional level in the Arctic.
2. The Arctic continues to warm. Since publication of the Arctic Climate Impact Assessment in 2005, several indicators show further and extensive climate change at rates faster than previously anticipated. Air temperatures are increasing in the Arctic. Sea ice extent has decreased sharply, with a record low in 2007 and ice-free conditions in both the Northeast and Northwest sea passages for first time in recorded history in 2008. As ice that persists for several years (multi-year ice) is replaced by newly formed (first-year) ice, the Arctic sea-ice is becoming increasingly vulnerable to melting. Surface waters in the Arctic Ocean are warming. Permafrost is warming and, at its margins, thawing. Snow cover in the Northern Hemisphere is decreasing by 1-2% per year. Glaciers are shrinking and the melt area of the Greenland Ice Cap is increasing. The treeline is moving northwards in some areas up to 3-10 meters per year, and there is increased shrub growth north of the treeline.
3. Reductions in emissions of CO_2 to the atmosphere constitute the backbone of any meaningful effort to mitigate global climate warming. Black carbon, tropospheric ozone, and methane may, however, contribute to Arctic warming to a degree comparable to the impacts of carbon dioxide, though there is still considerable uncertainty regarding the magnitude of their effects. Black carbon and ozone, in particular, have a strong seasonal pattern that makes their impacts particularly important in the Arctic, especially during the spring melt. These climate forcers are also relatively short-lived and have the potential for relatively rapid reductions in emissions and thus in atmospheric levels. There are various options for emissions reductions that can be taken in northern regions and globally. Improving quantitative estimates of the potential benefits of reducing emissions of short-lived climate forcers requires improved climate modelling capability.
4. The Arctic carbon cycle is an important factor in the global climate system. Considerable quantities of carbon, much of it in the form of methane are stored in the Arctic. Should these be released to the atmosphere, they will increase greenhouse gas concentrations and thus drive further climate change (an example of positive feedback). At present, the Arctic appears to be a sink for carbon dioxide and a source for methane. Climate change is likely to result in more carbon dioxide being released to the air but also more being absorbed in the ocean and by growing plants on land and in the ocean. The change in net releases of carbon dioxide and methane is difficult to predict. It appears unlikely, however, that changes in the Arctic carbon cycle will have more than a modest influence on global climate over the next 50-100 years, but large uncertainties exist.
5. Global climate models are limited in their ability to provide reliable, regional-scale projections of various climate parameters. Current and planned projects and programs aim to improve understanding of regional processes, the role of short lived climate forcers, and local impacts of climate change. Improved regional-scale models and projections will help bridge the gap between global studies and models and local impacts and changes in the Arctic, and improve evaluation of adaptive and mitigative actions, particularly concerning local impacts and the likely benefits of reducing emissions of short-lived climate forcers.

Recommendations on monitoring:

- *Sustain and enhance the current level of monitoring of climate change, updating information on key aspects of the Arctic climate system (2)*
- *Enhance and expand networks of monitoring and observation points for short-lived climate forcers, building on existing networks, such as the WMO Global Atmosphere Watch Programme (3)*
- *Initiate and maintain circumpolar measurements of carbon fluxes within the Arctic and imports to and exports from the Arctic (4)*
- *Integrate and expand monitoring efforts to enhance understanding of cause-effect relationships and temporal and spatial variability driving regional scale climate (5)*

Recommendations for studies to address gaps in knowledge:

- *Conduct studies on non-carbon dioxide climate forcers to improve understanding of their role in Arctic climate and develop recommendations for national and international follow up action (3)*
- *Conduct studies on the Arctic carbon cycle to identify key sensitivities and major feedbacks to regional and global climate (4)*
- *Develop reliable regional-scale climate models to support assessment of impacts and evaluation of the effectiveness of adaptive and mitigative actions (5)*

Introduction

This report provides an update on selected topics concerning Arctic climate change, which remains a major issue of concern. In 2004, the Arctic Monitoring and Assessment Programme (AMAP), together with the program for the Conservation of Arctic Flora and Fauna (CAFF), and the International Arctic Science Committee (IASC) produced the *Arctic Climate Impact Assessment*[1] (ACIA). The comprehensive ACIA built on a chapter in the earlier *AMAP Assessment Report: Arctic Pollution Issues*, published in 1998[2], and its accompanying plain-language summary, *Arctic Pollution Issues: A State of the Arctic Environment Report*[3], released the year before. AMAP is currently conducting a more thorough update on certain aspects of Arctic climate change (Changes in the Cryosphere: Snow, Water, Ice, and Permafrost in the Arctic) for delivery in 2011. This new study will incorporate results of the International Polar Year. A preliminary report on the Greenland Ice Sheet component of this study will be presented in the fall of 2009 as an Arctic Council contribution to the UNFCCC COP15.

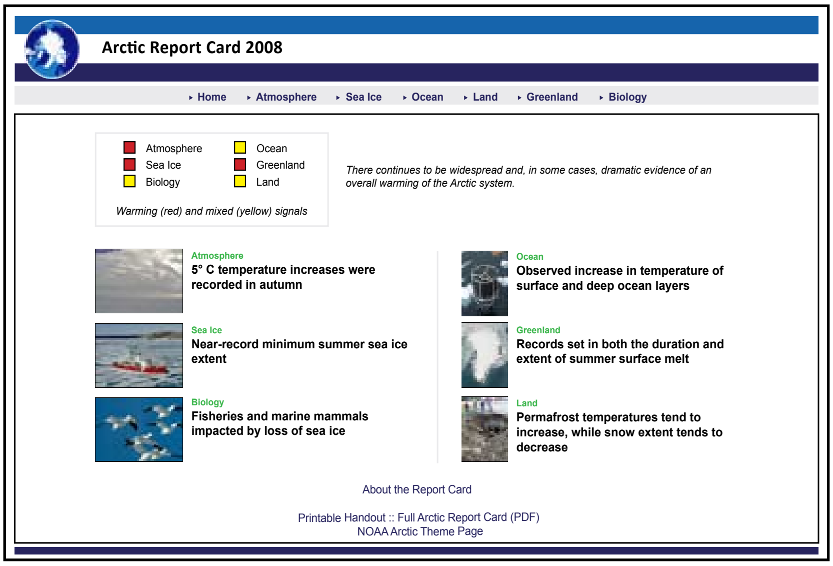
The climate information presented in this report is, therefore not the result of a comprehensive assessment of Arctic climate change issues, but rather is an update on some of the work that has been undertaken by AMAP as follow-up of the *Arctic Climate Impact Assessment*. The report draws upon peer-reviewed publications as well as workshops conducted under AMAP's auspices. From these materials, this plain-language summary has been written to capture the main messages and make them accessible to general readers. The summary has been reviewed by the authors of the scientific reports, by the members of the AMAP Working Group, and through national review processes in each Arctic country. These reviews have ensured that the summary is an accurate representation of the scientific reports.

The *Arctic Climate Impact Assessment* provided a comprehensive view of the topic through the early 2000s. The 2007 report of the Intergovernmental Panel on Climate Change[4] affirmed the findings of the ACIA and acknowledged the importance of the Arctic within the global climate system. The reduction of summer sea ice means more sunlight is absorbed, leading to additional warming. The cycling of water and carbon with, to, and from the Arctic also has the potential for substantial regional and global impacts. Observations since the ACIA was published show that climate-driven changes are occurring even faster than were anticipated in that Assessment. This report summarizes recent observations of changing climate parameters, a review of the significance of short-lived climate forcers and prospects for their mitigation, a new evaluation of the Arctic carbon cycle, and new initiatives to improve understanding of the cryosphere and the ability to model climate changes and impacts at the regional scale.

Arctic Report Cards

To track changes in Arctic environment, the U.S. National Oceanic and Atmospheric Administration (NOAA) produced a report titled *State of the Arctic: October 2006*.[5] Since then, AMAP and CAFF have contributed to subsequent annual "report cards" on the Arctic. This section provides a summary of what has changed, based on the three reports issued as of April 2009.

▼ The Arctic Report Cards website provides an annually-updated summary of the changing state of the Arctic environment.



[1]ACIA, 2004. Impacts of a Warming Arctic. Arctic Climate Impact Assessment. Cambridge University Press. 139 pp.
[2]AMAP, 1998. AMAP Assessment Report: Arctic Pollution Issues. Arctic Monitoring and Assessment Programme, Oslo. xii+859 pp.
[3]AMAP, 1997. Arctic Pollution Issues: A State of the Arctic Environment Report. Arctic Monitoring and Assessment Programme, Oslo. 188 pp.
[4]IPCC, 2007. Climate Change 2007: Synthesis Report. Fourth Assessment Report of the Intergovernmental Panel on Climate Change. IPCC, Geneva, Switzerland, 104 pp.
[5]NOAA, 2006. State of the Arctic: October 2006. NOAA OAR Special Report, NOAA/OAR/PMEL, Seattle, WA. 36 pp. (www.arctic.noaa.gov/reportcard/).

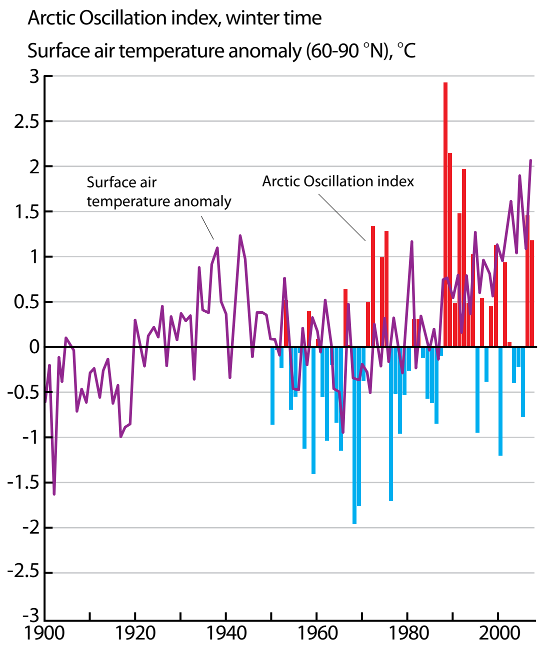
▸ Change in annual average Arctic surface temperature relative to 1961-1990 average, based on land station observations (purple line). The Arctic Oscillation index reflects natural variability that cause conditions to vary on an approximately 10-year cycle; however, recent years appear to diverge from this natural cycle.

Air continues to warm, and atmospheric circulation is highly variable

Surface temperatures around the Arctic have continued to be higher than the 20th century average. The year 2007 was the warmest on record, continuing a trend that began in the 1960s. In contrast to a previous warming phase in the 1930s, the current warming covers the entire Arctic and extends south to the mid-latitudes. A recent exception is the Bering Sea region, which experienced below-average temperatures in the winters of 2006 and 2007. As a result, winter ice extent returned to its long-term average, although summer ice retreated far to the north in 2007 and 2008.

Atmospheric circulation in the Arctic typically oscillates between two general patterns. This phenomenon is known as the Arctic Oscillation (AO), and is similar to (and connected with) the El Niño/La Niña switch in the southern Pacific. The Arctic Oscillation is measured against an index, with positive values indicating one dominant pattern and negative values indicating the other. A negative AO index means weaker winds, lower winter temperatures, and more sea ice. A positive AO means the opposite. The oscillation between positive and negative AO values is the main source of climate variability in the Arctic.

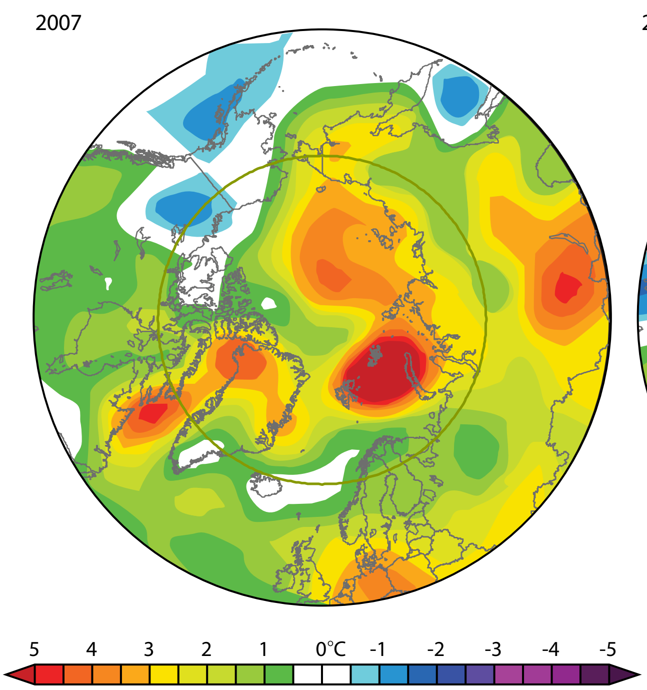
From the mid-1980s to the mid-1990s, the AO was strongly positive, consistent with rising temperatures and reduced sea ice. From the mid-1990s to about 2006, the AO moved between weakly positive and weakly negative values. In 2007 and 2008, the AO was again strongly positive, though not quite as high as it had been in the 1980s and 1990s. Recent patterns in temperatures and barometric pressure, however, differ from the characteristic patterns seen during the 20th century under positive and negative AO values. These changes may reflect alterations in atmospheric circulation patterns in the Arctic.

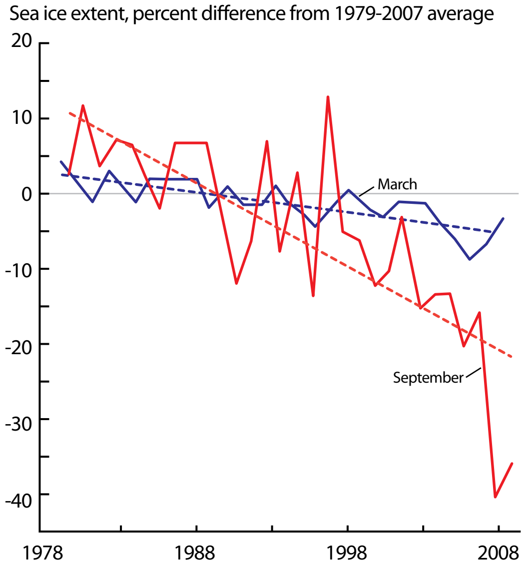


Summer sea ice has decreased dramatically

The most striking change in the Arctic in recent years was the great reduction in summer sea ice extent in 2007. In March of that year, the sea ice had covered nearly all of its long-term average extent. By September, however, sea ice covered only 4.3 million square kilometers, 23% less than the previous record low of 5.6 million square kilometers in 2005 and 39%

▾ Maps of the difference in January-May surface temperature in 2007 and 2008 relative to the long-term average show that although the Arctic as a whole is warming, the pattern of the change is variable over time; some areas exhibit cooling.

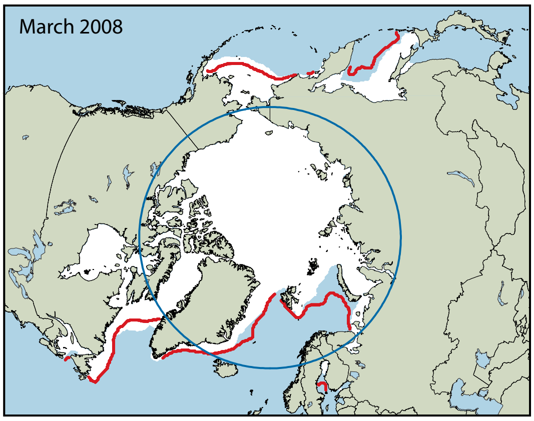




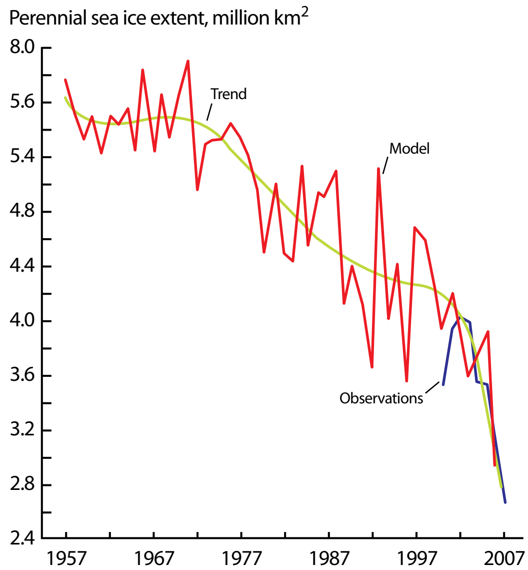
lower than the 1979-2000 average. Most of the loss occurred in the Beaufort, Chukchi, and East Siberian Seas. In 2008, despite cooler weather in spring and summer, the minimum sea ice extent was 4.7 million square kilometers, the second lowest ever recorded. For the first time in existing records, both the Northwest and Northeast Passages were ice free.

Less obvious but still significant is the continued thinning of Arctic sea ice. Recent satellite data support previous observations that sea ice at the end of the melt season is thinner than it used to be, and that the trend is continuing. One cause of this trend is the loss of perennial ice, floes that last through at least one summer. Perennial sea ice extent has been decreasing since at least 1957, and has been dropping even more sharply in recent years. Thinner, younger ice is more susceptible to rapid melting from warmer waters and air, increasing the potential for more dramatic declines in ice extent.

◀◀ Ice cover at the time of minimum ice extent (September) is decreasing more rapidly than that at the time of maximum ice extent (March). September 2007 was the lowest ice extent on record.



◀ Changes in Arctic sea ice extent from September 2007 to March 2008 to September 2008. The red lines indicate the 1979-2000 average minimum (September) and maximum (March) sea-ice extent. Despite the extreme summer minima in 2007 and 2008, the 2008 winter ice extent was near the long-term average.



Bryan and Cherry Alexander

◀ Polar bear falls through thin sea ice, Cape Churchill, Canada

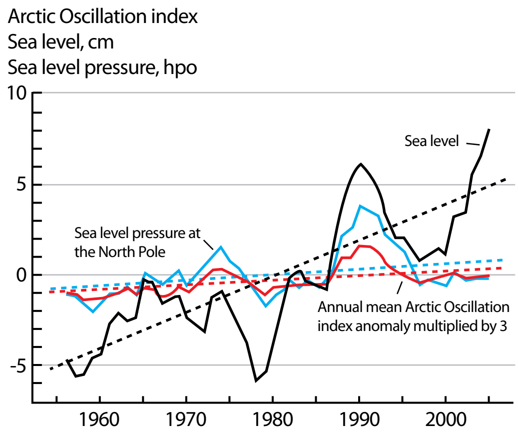
◀◀ In addition to changing ice extent, the thickness of Arctic sea ice is decreasing, as illustrated by time series showing the extent of perennial ice – ice thick enough to survive for more than one Arctic ice season – in March. Even if winter ice extent remains near the long-term average, thinner ice is more susceptible to rapid summer retreat.

Arctic Ocean surface waters are warming

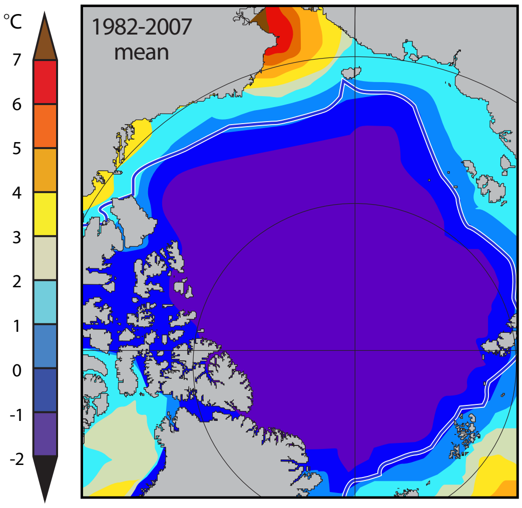
Consistent with the rapid retreat of sea ice in the summer of 2007, the surface waters of the Arctic Ocean have been warming in recent years. In 2007, some ice-free areas were as much as 5° C warmer than the long-term average. Overall, Arctic waters appear to have warmed as a result of the influx of warmer water from the Pacific and the Atlantic. In addition, the loss of sea ice means that more solar radiation is absorbed, heating surface layers further.

The circulation of surface waters in the Arctic Basin is driven by wind. Wind patterns reflect the state of the Arctic Oscillation. In recent years, circulation has been generally anticyclonic, as expected with a weak AO index. One result is that freshwater tends to accumulate in the Arctic Ocean, especially in the Beaufort Gyre. Along the Eurasian coast, freshwater from rivers is a major influence, especially because river discharge has increased over the past century at least. Recently the patterns of ocean circulation have kept river water close to the coast rather than spreading towards the central basin. In 2007, the extensive melt of sea ice put vast quantities of relatively fresh water into the surface layers of the Arctic Ocean.

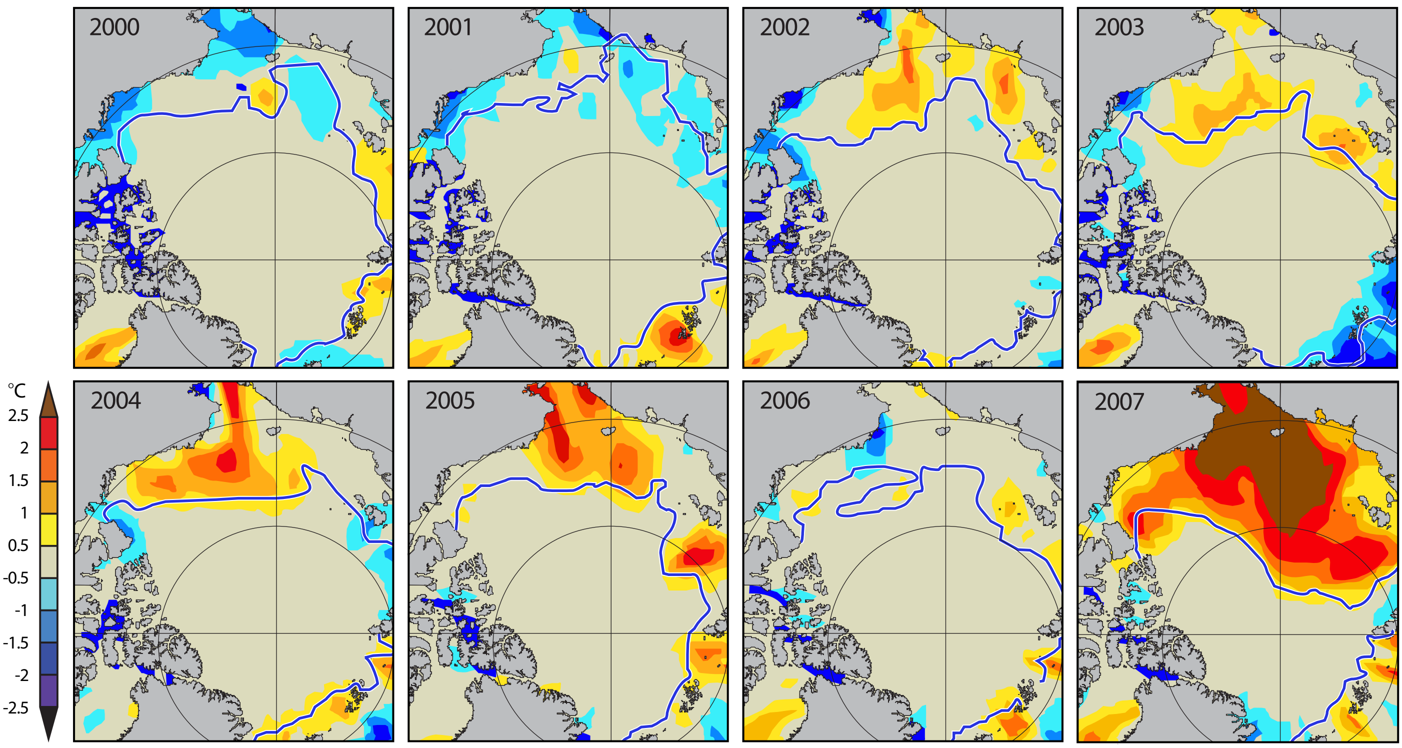
Sea level in the Arctic Ocean followed the Arctic Oscillation until about 1996, influenced primarily by barometric pressure. After that, sea level continued to stay above the long-term average despite the switch of the AO from strongly positive to weak and fluctuating. This suggests that other factors have come into play, such as ocean expansion from heating, increased freshwater content, or the effects of wind.



▸ Arctic sea level at nine stations along the Russian Arctic coastline in relation to the Arctic Oscillation index and sea level pressure and the North Pole. All indices are shown as five-year running averages.



▸ Mean summer surface temperature in the Arctic for the period 1987-2007.



▾ Temperature anomalies in recent years. The blue line indicates minimum sea ice extent. Note the high temperatures in 2007 in the Chukchi Sea and the extreme retreat of sea ice in that sector.

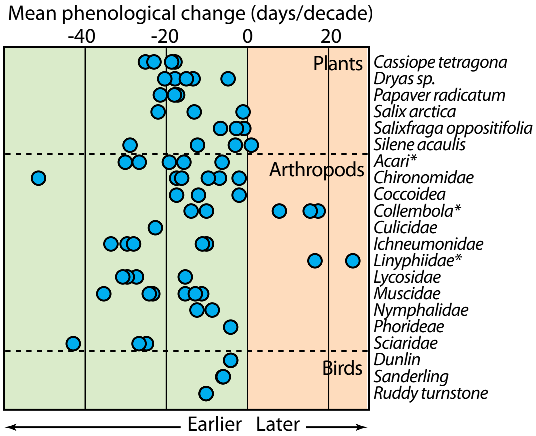
The terrestrial Arctic also shows signs of change

On land, several indicators show continued warming around the region. Permafrost, defined as ground that has remained below the freezing point for at least two consecutive summers, is warming. At its margins, permafrost is thawing. In northern Alaska, temperatures at depths below seasonal influence show a warming trend since at least the 1970s. The trend has not been uniform, and indeed has had a few periods of cooling, but overall the temperatures have risen by 0.5°C to 2°C. In 2007, the trend turned upwards again.

Plants respond more quickly to changes in temperature. They grow more vigorously and densely when the air is warmer. This response can be detected from satellites by measuring the green-ness of the landcover. Most of the Arctic, especially tundra areas, showed increased plant growth over the period from 1981 to 2005. Some areas, especially in the boreal forest, have showed a slight decline. Over longer periods, warming has led to increased shrub growth north of the treeline as well as a slow movement of the treeline itself. In Russia, treeline has displaced tundra patches as quickly as 3-10 meters per year. In Scandinavia and Canada, tree growth near treeline has become denser, with some indication of slow movement into previously exposed areas.

Snow cover in the Northern Hemisphere appears to be declining at about 1-2% per year, depending on the method used to measure it. Because snow reflects sunlight back into space, less snow is a positive feedback to warming trends. In 2007, the average snow cover was 24.0 million square kilometers, which is 1.5 million square kilometers below the 38-year average, and the third-lowest figure on record.

Glaciers can be difficult to use as indicators of change, in part because melt area is not as direct a measure of change as the change in mass of a glacier, but mass is more difficult to measure. Changes in mass correspond to accumulation or loss of ice. Nearly all glaciers studied are decreasing in mass, resulting in rising sea level as the water drains to the ocean. Excluding Antarctica and Greenland, the rate of sea level rise from glacial melt is estimated at 0.58 millimeters per year from 1961 to 2005, with a higher rate of 0.98 millimeters per year between 1993 and 2005. The largest contributors to this rise are glaciers in Alaskaand other parts of the Arctic, and the high mountains of Asia. By 2100, glacial melt may increase sea level by a further 0.1 to 0.25 meters.



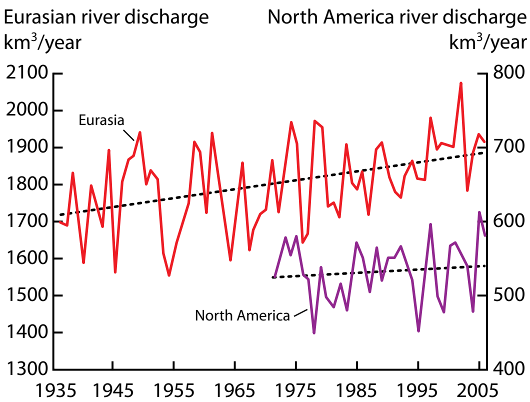
The timing of flowering of plants, emergence of insects, and egg laying of birds have been recorded at different locations In the Zackenberg valley (north-east Greenland) since 1996. On average, the timing of these events has advanced by 2 weeks during the last decade, with the active growing season extended by one month.

Henning Thing

The Zackenberg valley, northeast Greenland.

John Smol

Sampling of Camp Pond (Ellesmere Island, Nunavut, Canada) on the day before it completely dried. Drying out of small ponds on the tundra is one example of ecosystem shift in the terrestrial Arctic.

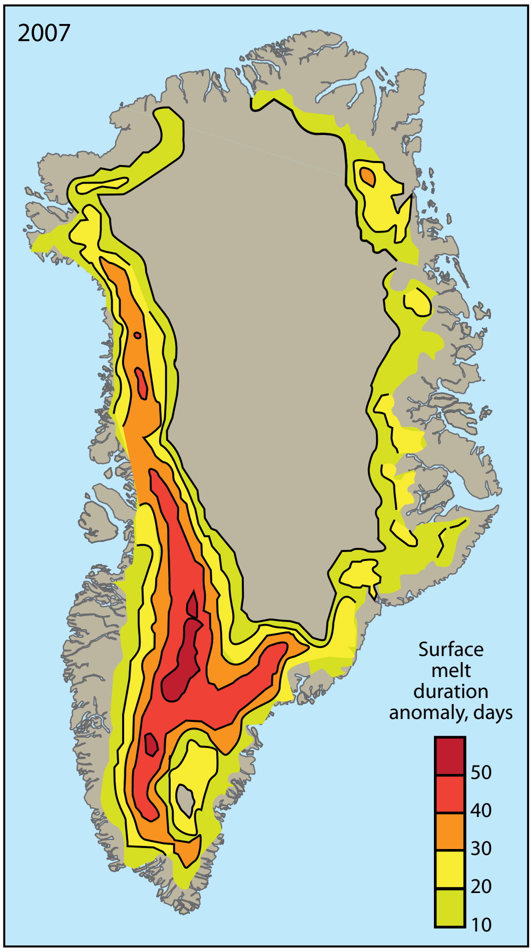


Runoff to the Arctic Ocean from large rivers in Eurasia and North America show that runoff from Eurasian rivers is increasing.

Greenland's ice sheet continues to melt

The Greenland ice sheet is the largest in the northern hemisphere and has been studied extensively. The ice sheet has experienced summer temperatures consistently above the long-term average since at least the mid-1990s. Temperatures along the coast have followed the same pattern, reversing an earlier cooling trend in West Greenland from the 1960s to the 1990s. In 2007, temperatures at various locations were generally above average, though not for every season of the year.

Melting on the ice sheet in 2007 was the most extensive since record-keeping began in 1973. The area experiencing melt was 60% larger than in 1998, the year with the next largest area in the record. Melting lasted on average 20 days longer than usual, up to 53 days longer than usual at elevations between 2000 and 3000 meters between the north and south domes of the ice sheet. The Jakobshavn Isbrae, Greenland's largest glacier, continued the rapid retreat begun in 2001. The Tissarissoq bay on the south side of the fjord became ice free in 2007, probably for the first time in centuries and perhaps longer. Other outlet glaciers in southern Greenland, such as the Kangerlussuaq Glacier and the Helheim Glacier, show the same pattern.



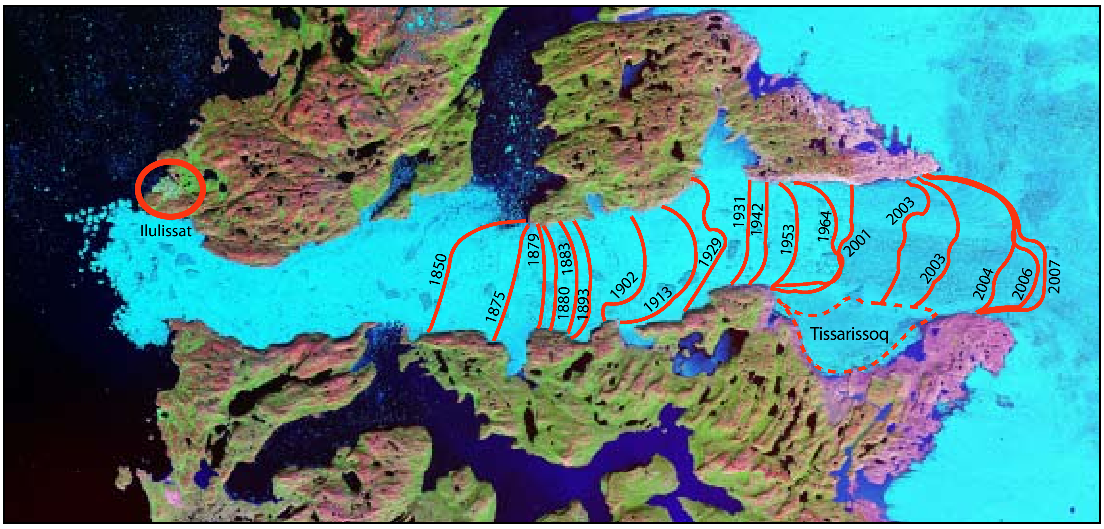
▸ Duration of summer surface melt on Greenland in 2007 relative to 1973-2000 average.

Henning Thing

Henning Thing

▸ Ice breaks off the Russell Glacier east of Kangerlussuaq, Greenland.

▸ ▸ Extensive summer melting at the edge of the Greenland Ice Sheet northeast of Kangerlussuaq, Greenland.



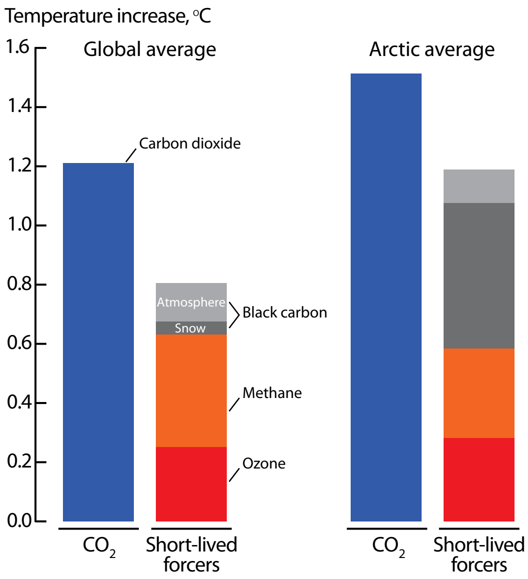
▸ The Ilulissat glacier (Jakobshavn Isbrae) continues to retreat.

Short-lived Climate Forcers

Carbon dioxide (CO_2) is the main driver of global climate change, but black carbon (or soot), ozone, and methane may have a combined effect comparable to those of carbon dioxide, both in the Arctic and globally. While there is still considerable uncertainty regarding the magnitude of effects from these substances, these forcers of climate change do not stay in the atmosphere nearly as long as carbon dioxide, and thus will respond more quickly in the short-term to reductions in emissions. Part of the powerful Arctic impact of these short-lived forcers comes from their seasonal nature, with the strongest impacts coming from late winter to mid-summer. Therefore, while reductions in carbon dioxide emissions remain essential for long-term global (and Arctic) climate stabilization, reducing emissions of short-lived climate forcers has the potential to slow warming in the near-term. By delaying the onset of spring melt, for example, reductions in short-lived climate forcers could slow Arctic warming and ice melt and 'buy time' while the longer-term benefits of carbon dioxide reductions take effect. Each forcer has unique characteristics important to designing appropriate mitigation measures. Reductions would additionally benefit the health of Arctic residents and, indeed, people around the world, providing another reason for prompt action.

Black carbon, methane, and ozone may be substantial contributors to Arctic warming

Black carbon consists of small, dark particles emitted into the atmosphere from inefficient burning, such as wood stoves and diesel engines. It warms the Arctic in two ways. First, a haze layer of dark particles in the atmosphere absorbs sunlight, which contributes to overall global warming including that occurring in the Arctic. Most of the black carbon that reaches the Arctic is emitted from sources in the northern mid-latitudes. Second, some of the airborne black carbon that reaches



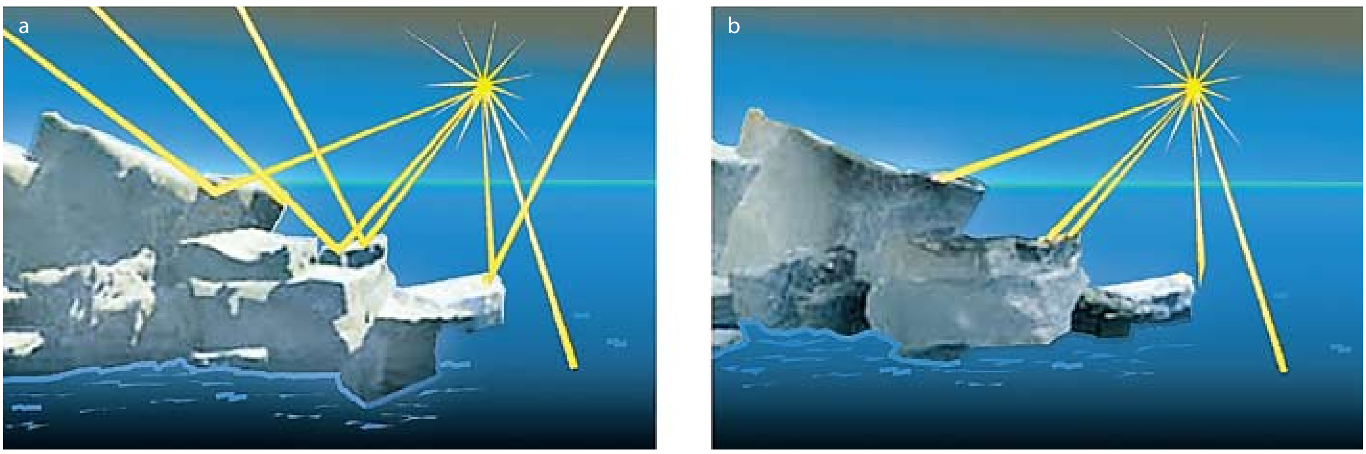
◀ Short-lived climate forcers such as black carbon, methane and ozone may have warming effects similar in magnitude to the long-lived greenhouse gases such as CO_2. Estimates of the warming due to SLCFs are still very uncertain and need to be further refined.

the region is deposited onto ice and snow, resulting in a darkening of the surface. Since dark surfaces absorb more solar radiation, this enhances melting. Recent extensive modeling indicates that the majority of the black carbon deposited in this manner comes from northern latitudes. In Greenland, up to 80% of black carbon is from such sources, divided equally between North America and Europe. On Arctic sea ice, the figure is 70%, with a greater proportion coming from Europe and perhaps northern Asia.

Further sampling of snow and ice in the Arctic will help validate these modeling results. Because deposition in late winter and spring has the greatest impact on the spring melt, seasonal reductions in emissions, such as reductions in springtime burning in agricultural areas, will be particularly important.

Ozone, which is important in the stratosphere for protecting the Earth from ultraviolet light, also occurs in the lower atmosphere or troposphere. It is formed by chemical reactions between various pollutants, including carbon monoxide, nitrogen oxides, and organic compounds such as methane. In the troposphere, ozone is a harmful pollutant and a greenhouse gas.

▼ Polar ice reflects light from the sun back to space (a). Darker, soot-covered ice reflects less light and, thus, enhances warming (b).



Seasonal scenario of radiation, sources, and transport within the Arctic		
Winter/Early Spring	Spring	Late Spring/Summer
● Solar radiation is limited so that the radiation balance is driven primarily by thermal fluxes	● Solar radiation becomes available for photochemical production of ozone and aerosols	● Solar radiation is at a maximum
		● Surface melt begins
● Also the time of the year when transport of pollutants from the mid-latitudes is most efficient (Arctic Haze)	● Transport of pollutants from mid-latitudes still efficient (Arctic Haze)	● Snow-albedo feedback maximizes
	● Agricultural fires begin	● More powerful greenhouse effect due to warmer temperatures
● Build-up of ozone and aerosol precursors		● Boreal forest fire season

Ozone, which is destroyed by sunlight, has a longer lifetime in the atmosphere during the winter, when it can last for months, than during the summer, when it lasts for only few days or weeks. As a result, ozone and the gasses it is formed from are transported efficiently to the Arctic during the winter leading to warming during the spring melt season. Most tropospheric ozone in the Arctic comes from North America.

Methane is a greenhouse gas recognized under the Kyoto Protocol. Its lifetime in the atmosphere, of about nine years, is relatively short when compared with longer-lived greenhouse gasses such as carbon dioxide. As a result, methane is well-mixed throughout the world's atmosphere. Hence, reductions in methane anywhere in the world during any season will benefit the Arctic by decreasing global warming. In addition, reductions in methane emissions will have a more immediate effect on global warming than reductions in longer-lived greenhouse gases.

▼ Gas flaring on the Yamal, western Siberia.

Bryan and Cherry Alexander

Mitigation efforts could provide benefits in the short-term

A global analysis of the potential benefits of reducing emissions of short-lived forcers globally suggests that reductions in black carbon and methane emissions have the most promise. The seasonal impacts of black carbon and ozone may provide an additional opportunity for rapid benefits from seasonal emissions reductions. Improving the quantitative estimates of both the effects of short-lived climate forcers and the potential benefits of reducing their emissions requires improved climate modelling capability.

There are a number of options for reducing emissions of these short-lived climate forcers. Those that appear to have the most potential for early and effective action include emissions controls on diesel engines and oil and gas flaring, improvements in agricultural practices such as reduced burning, and capturing or eliminating methane emissions from major industrial and waste treatment sources. Additional measures could be pursued over a number of years, such as identifying major point sources of black carbon and applying existing pollution-control technology, and using pollution-control measures on vehicle engines to reduce emissions of chemicals that produce ozone.

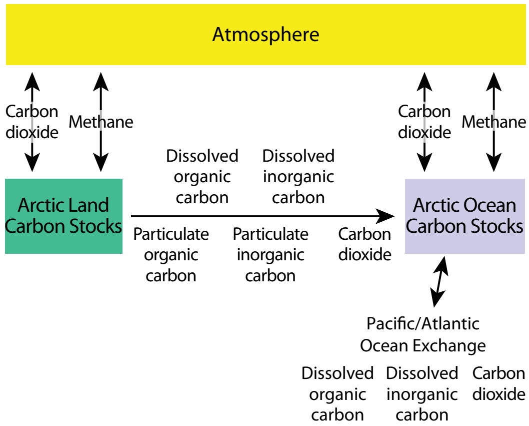
Global Warming Potential

Global Warming Potential is a scale for comparing the warming effects over time of different compounds or substances released into the atmosphere, relative to carbon dioxide and weighted according to the length of time they remain in the air. Reducing emissions of short-lived but powerful forcers such as black carbon and methane will have rapid effects. For example, reducing black carbon emissions by one tonne is the equivalent, over a twenty-year period, of reducing carbon dioxide emissions by 2000 tonnes.

	Emissions in 2000, millions of tonnes	20-year global warming potential, CO_2 equivalents
Black carbon	5	10 000
Methane	287	20 664

The Arctic Carbon Cycle

The Arctic has been warming rapidly in the past few decades. A key question is how that warming will affect the cycling of carbon in the Arctic system. At present, the Arctic is a global sink for carbon. If that changes, and the Arctic becomes a source of carbon, the feedback to global climate has the potential to enhance warming. This section discusses what is known about the sensitivity of carbon cycling in the Arctic and what still needs to be understood.



◀ Overview of carbon transfer between land, sea, and air. A detailed diagram with estimated quantities appears on the following page.

Vast amounts of carbon are stored in the Arctic

For the purposes of this carbon cycle analysis, the Arctic has been defined as the Arctic Ocean plus the lands that drain into the Arctic Ocean and its marginal seas, as well as lands that have permafrost, except for high-elevation areas farther south such as the Tibetan Plateau; see map below.

This area includes about one quarter of the world's land where plants grow. In the low temperatures of the Arctic, much plant matter does not decompose. Instead, it accumulates in thick, carbon-rich soil layers. Thus, the land area considered here contains about one third of the carbon held in the world's terrestrial ecosystems. Furthermore, it holds 40% of the carbon in near-surface soils worldwide. The exchange of carbon dioxide and methane between land and air varies greatly with place and time, as discussed in more detail later.

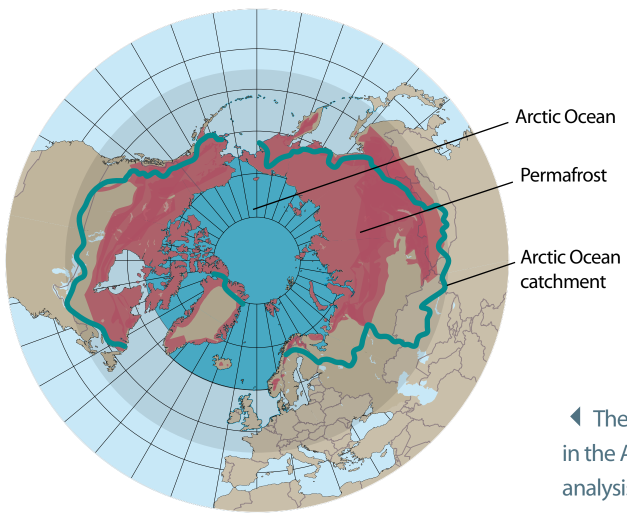
Oceans contain carbon in various forms. Dissolved organic carbon comes from decaying biological material. Dissolved inorganic carbon includes carbon dioxide and other simple molecules and ions containing carbon. Both organic and inorganic carbon are also present in particulates. Of these forms, dissolved inorganic carbon is the most common, and also has the least seasonal variation. The other forms cycle throughout the year in response to biological activity. Sediments also contain carbon, deposited over time as various materials settle to the sea floor.

Rivers are responsible for most of the direct transport of carbon from land to ocean. In the Arctic, this is especially important because rivers contribute a much larger amount of water relative to the size of the ocean than is true elsewhere. The Arctic Ocean holds only one percent of the world's ocean water, but receives about a tenth of the world's river runoff and about a tenth of the dissolved organic carbon carried from land to sea worldwide. Peatlands in the Arctic provide particularly large amounts of carbon into river systems and thus the ocean. Coastal erosion, too, is a major source of carbon to the ocean.

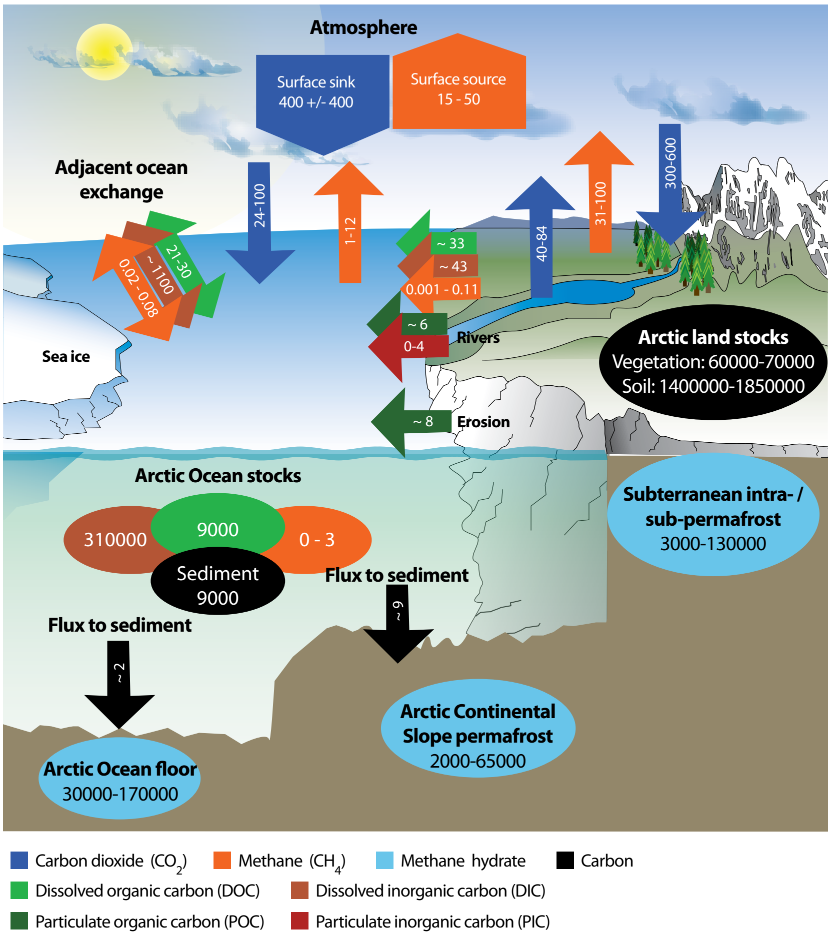
In addition to the usual sources of carbon, primarily from plant matter, the Arctic appears to have huge quantities of methane hydrates. These are ice-like crystals in which water molecules form cages that each holds one methane molecule. Methane hydrates are stable in cold conditions and under high pressure, and thus are found in permafrost on land and continental shelves and also beneath the sediments of the Arctic Basin. As hydrates warm or as pressure is reduced, the methane is released. The amount of methane hydrate present is not well known, but some global estimates suggest it may rival the amounts of all known sources of gas and oil.

Arctic Carbon Stocks

Location	***Amount, billions of tones***
Land	
Soil	1400-1850
Living plants	60-70
Ocean	
Water column	
Dissolved inorganic carbon	310
Dissolved organic carbon	9
Sediments	9.4
Methane Hydrates	
Ocean	30-170
Land	2-65
Total	~1820-2485



◀ The region considered in the Arctic carbon cycle analysis.



▲ Current state of the Arctic Carbon Cycle showing amounts of carbon stored in various environmental reservoirs (units: millions of tonnes C, or millions of tonnes CH_4 for methane and methane hydrate) and the net flux of compounds (units: millions of tonnes C per year, or millions of tonnes CH_4 per year for methane) that determine the movement of carbon between environmental compartments.

At present, the Arctic is a sink for carbon dioxide

Measuring the flow of carbon throughout the entire Arctic is not a simple task. One approach is to measure atmospheric levels of carbon dioxide. Variations over time and space indicate the movement of carbon to or from the atmosphere. This method provides little insight into the reasons for changing carbon concentrations in the atmosphere. Another approach is to measure actual flows of carbon dioxide and methane at local sites. These data can be scaled up for an entire region, based on the particular characteristics of local climate, vegetation, and so on. Although these extrapolations make a number of assumptions, they do provide information on the specific processes that govern carbon flow.

Atmospheric measurements indicate that the Arctic is a modest sink for carbon, with about 400 million tonnes taken from the atmosphere in an average year. This amount can vary greatly from year to year. While different studies generally agree on the size of the sink, they provide different estimates of uncertainty and interannual variation. Changes in weather patterns and variation in forest fire activities are major contributors to the differences among years.

Studies of carbon dioxide flows at specific sites also indicate great variation from year to year. The details of the growing season have great influence on the amount of carbon taken up by plants and also the amount released by decomposition. On the whole, dry tundra systems appear to be sources of carbon, but wet tundra and boreal forest are sinks. Combining various studies and estimates for the terrestrial Arctic, it appears that land areas are a sink for approximately 300-600 million tonnes per year. This amount is 30-60% of the global estimate for the net sink of carbon on land. Growth of trees in the boreal forest appears responsible for most of the sink activity in the Arctic.

Lakes and rivers are a source of carbon to the atmosphere. They also carry carbon to the ocean, as noted earlier. Few measurements of carbon flow have been made in Arctic lakes. In the absence of specific data from the region, global estimates can be scaled down. The Arctic holds 36% of the world's lake surface area and accounts for 10% of global river discharge to the ocean. Taking the same proportions of estimates of global freshwater carbon releases gives an estimate for the Arctic of 25-54 million tonnes of carbon from lakes each year and 15-30 million tonnes from rivers.

Although the Arctic Ocean is relatively small, its marginal seas in particular are highly productive and thus take up considerable amounts of carbon during the spring bloom. The Arctic is also where much of the world's deep ocean water is formed, as surface waters descend to the depths, carrying carbon with them. Ice cover forms a barrier to ocean-atmosphere exchange, and changes in sea ice will affect the net carbon flow to or from the ocean. There are few direct measurements from the Arctic Ocean, and thus estimates of flow have high uncertainty. Nonetheless, seawater in the Arctic appears to be a sink for 24-100 million tonnes of carbon per year. This accounts for 1-5% of the global estimate for ocean sink activity for carbon.

Carbon is also carried from land to rivers, from rivers to ocean, and from ocean to ocean. Much of this carbon is in the form of dissolved and particulate carbon. This transport is important for determining where carbon may be emitted to the atmosphere or captured in sediments. There is considerable uncertainty involved in most estimates of carbon transport, but river transport, ocean currents, and coastal erosion appear responsible for the largest amounts.

...and a source for methane

Methane is a different story. As with carbon dioxide, the flow of methane involves many factors. Methane also reacts with other molecules in the air. In sum, recent atmospheric studies indicate that the Arctic is a source for 15-50 million tonnes of methane each year, or 3-9% of the global total net emissions from land and sea. Site studies show a higher emission rate, of 31-100 million

Large amounts of carbon are bound up in sub-surface methane hydrates. This 'ice that burns' is now being considered as a possible energy source.

tonnes per year, from land and freshwater sources combined. The role of small lakes in permafrost areas is greater than previously thought. These lakes are surrounded by carbon rich soils laid down in the last ice age, now being released as the water thaws the frozen soil.

Methane hydrates at present do not appear to contribute much to Arctic emissions. Permafrost effectively seals off the ground below, though as permafrost warms it becomes more permeable. Most of the emissions from hydrates come from coastal and continental shelf areas where permafrost is warming, thawing, or eroding. Although no estimates have been made for the Arctic specifically, estimating the Arctic share based on the area of continuous permafrost yields a first-order estimate of less than a million tonnes per year. In other words, the contribution from methane hydrates is at present insignificant compared with emissions from land.

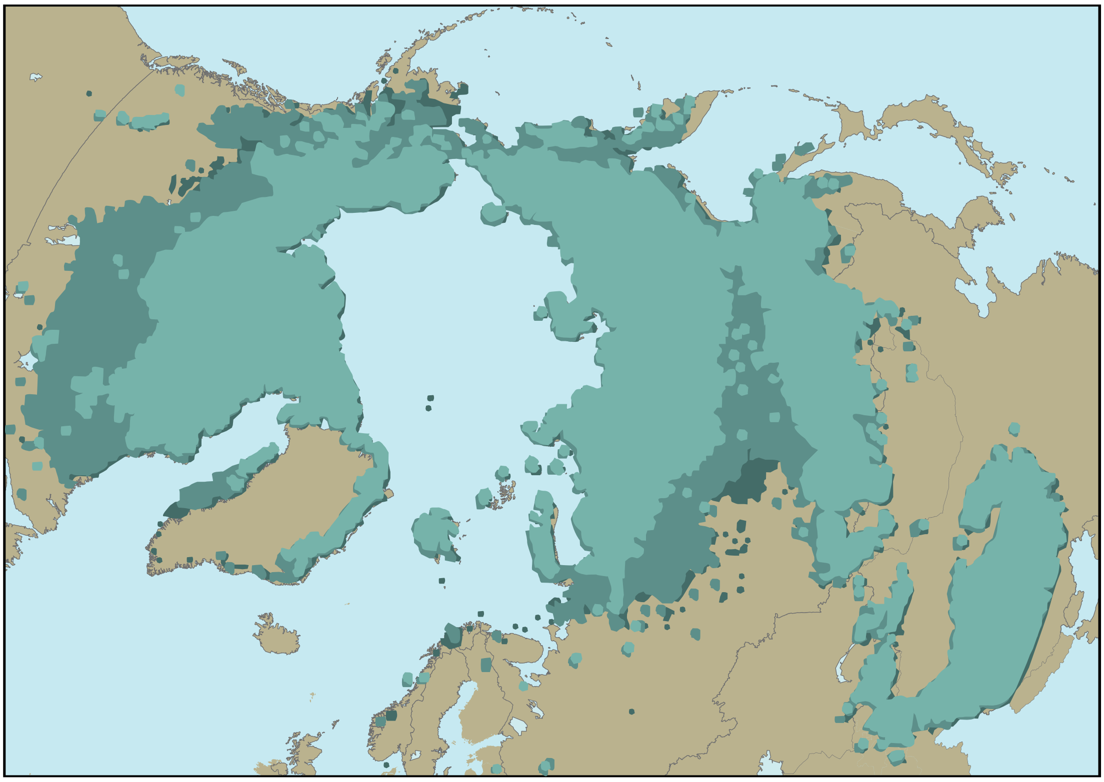
Similarly, little information is available to assess the flow of methane to or from the Arctic Ocean, but what data there are suggest a modest contribution as a source. Much remains to be understood, however, about the transport and reactions of methane in seawater in the Arctic.

The response of the Arctic carbon cycle to global climate change is far from clear

In the next decade or two, the boreal forest may continue to grow, absorbing more carbon as trees become larger and treeline expands. On the other hand, forest fires may increase in frequency and extent and insect outbreaks may kill more trees, both of which would release carbon to the atmosphere. Which trend dominates the other depends in part on precipitation. Dry conditions may reduce plant growth and lead to more fires. It is also unclear whether increased carbon dioxide in the atmosphere will stimulate plant growth.

Over the next half century to a century, the northward movement of deciduous forest types may reduce carbon storage in the boreal forest overall. Broadleaf deciduous forests typically store less carbon than coniferous forests of the type that now dominate the boreal zone. Although shrubs are moving into tundra areas, the movement of the actual treeline is very slow and will likely only have an effect on the carbon cycle of the Arctic over the course of several centuries.

Thawing of near-surface permafrost will mobilize stored carbon. Different studies show different patterns over time, but agree that much carbon will become



Model projections of the loss of permafrost around the Arctic between 2000 and 2050 and between 2050 and 2100.

- Projected loss of permafrost during the period 2000-2050
- Projected loss of permafrost during the period 2050-2100
- Projected permafrost in 2090-2100

available by the end of this century. Furthermore, fire in permafrost landscapes may accelerate thawing, a factor that has not been considered in studies to date. Once permafrost is thawed, the release of carbon depends primarily on the wetness of the soil. Wetter soils will release more methane but relatively less carbon dioxide than dry soils. Recent trends in the Arctic indicate that landscapes are typically drying as a result of climate change.

The impact of Arctic carbon cycle changes on global climate appear likely to be modest. One study projected a potential maximum release of 50 billion (i.e., thousand million) tonnes of carbon from the Arctic terrestrial environment through this century, far lower than the 1500 billion tonnes that are expected to be released by even low-end estimates of fossil fuel burning over the same period. This and other studies also found that the Arctic may continue to be a sink for carbon, depending on responses to increased carbon dioxide in the atmosphere and other factors.

In the marine environment, too, feedbacks from climate to carbon can be both positive and negative. Reduced sea ice will allow more exchange of carbon from sea water to the atmosphere. It will also allow more light to reach the water, stimulating more plankton growth and thus uptake of carbon. Melting of ice will mean more freshwater in upper ocean layers, which can reduce biological activity and result in less carbon being taken up by biota. These effects will act very differently in each season, making projections of the net change even more difficult.

As the ocean warms, it can hold less dissolved carbon dioxide. Furthermore, warmer water may lead to increased production of carbon dioxide and methane through decomposition and other biological activity.

The discharge of water from land to sea increased in the Arctic throughout the 20th century, and is projected to continue to rise and perhaps accelerate during the 21st century. Increased water flow will likely mean increased carbon transport, though the relative proportions of different types of carbon are difficult to predict. One possibility is that carbon carried by rivers ends up stored in coastal sediments. Another possibility is that this carbon decomposes in the water column and is released as carbon dioxide and methane.

The release of methane from gas hydrates currently locked in permafrost is likely to be a very slow process. Most hydrates are at considerable depth and so would not be affected in the short-term by near-surface thawing. Furthermore, methane moving upwards from hundreds of meters underground would most likely be oxidized before reaching the surface and thus reach the atmosphere as carbon dioxide and water rather than as methane. Nonetheless, the fate of gas hydrates remains largely uncertain in both the short- and long-term.

Further research should focus on sensitive elements of the carbon cycle

Current understanding of the Arctic carbon cycle is limited by considerable uncertainties. Even the question of whether the Arctic will be a source or a sink for carbon depends on the extent to which increased carbon dioxide in the atmosphere will stimulate plant growth. The interactions between climate and carbon cycling in many other areas of the Arctic environment are similarly unclear.

Integrated studies of regional carbon dynamics are needed to provide better information on key elements of the Arctic carbon cycle. Such studies should link observations of carbon dynamics to the processes that influence those dynamics. The resulting information should be incorporated into modeling efforts that connect carbon dynamics and climate. The studies should focus on sensitive parts of the system, for example areas experiencing major changes or thresholds such as permafrost loss or increased fire disturbance. Similarly, more research is needed on the relative importance of various processes to determine whether carbon uptake or release will predominate.

A major challenge for carbon modeling is connecting fine-scale observational studies with the larger scales at which models describe the environment. Observational networks should be designed to capture regional variations and also reveal the underlying processes that govern carbon dynamics at various scales. That information can be used to model the interactions among various parts of the carbon cycle. Observational studies should also focus on small- and large-scale processes so that both can be incorporated in models.

For example, uptake of carbon through photosynthesis and release through decomposition depend greatly on local temperature and moisture. Growth or loss of wetlands can be measured at larger scales, as can disturbances such as fires. Since all these factors affect the carbon cycle, studies that ignore one or more of these influences will not provide an accurate picture of carbon dynamics. In turn, models will not be able to capture the major influences on the carbon cycle if they do not reflect all of the major factors that are involved.

The improved understanding of carbon dynamics can be incorporated first in simpler models where the basic ideas can be tested. Then, more complex models that couple air, land, and sea can be developed or revised based on new and better understanding of the fundamental factors involved. This in turn will allow a more confident exploration of the relationships between climate change and carbon cycling in the Arctic.

Improving predictive capacity for the Arctic region

Assessing the future course of climate change in the Arctic requires understanding processes, feedbacks, and impacts at the regional scale. This scale is essential to bridging the gap between global studies and models and local impacts and changes in the Arctic. This section provides an introduction to several initiatives in this area, which will be addressed in more detail in future reports.

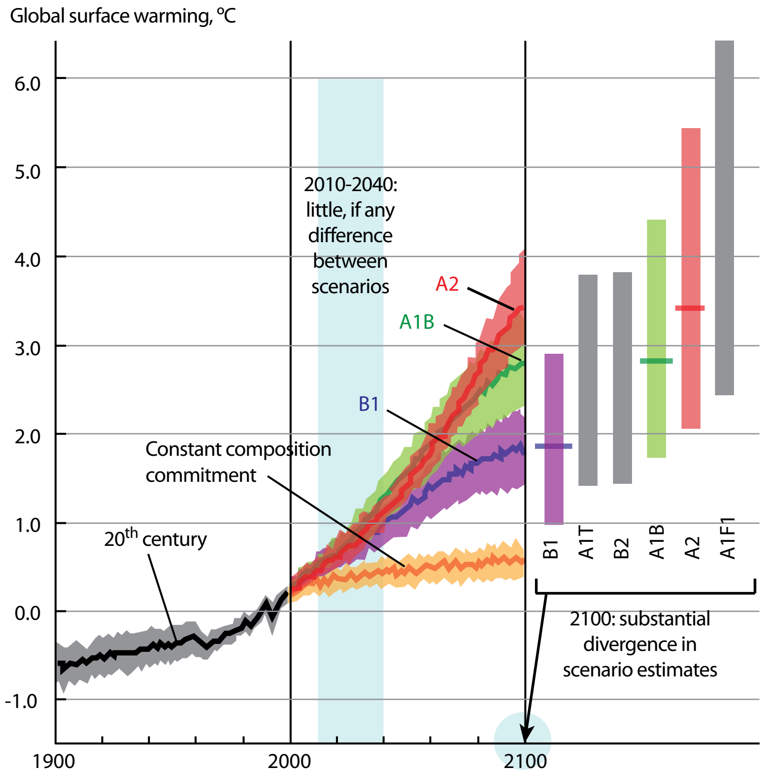
Reliable regional-scale modeling is needed to support Arctic process and impact studies

A recent evaluation of global climate models was conducted in preparation for the Climate Change and the Cryosphere: Snow, Water, Ice, and Permafrost in the Arctic (SWIPA) study. 25 models were evaluated for their ability to simulate 20th century climate parameters such as surface air temperature, sea level atmospheric pressure, and summer sea ice extent. The models varied greatly in their abilities, with some models performing well for some criteria but not for others. Simply put, there is no single best model for all purposes. For the short-term, model selection must be done carefully and documented well to maintain the integrity of the overall projections of changes in the Arctic. In the longer term, Arctic climate studies require reliable regional-scale models that can capture the various parameters of interest for different process and impact studies.

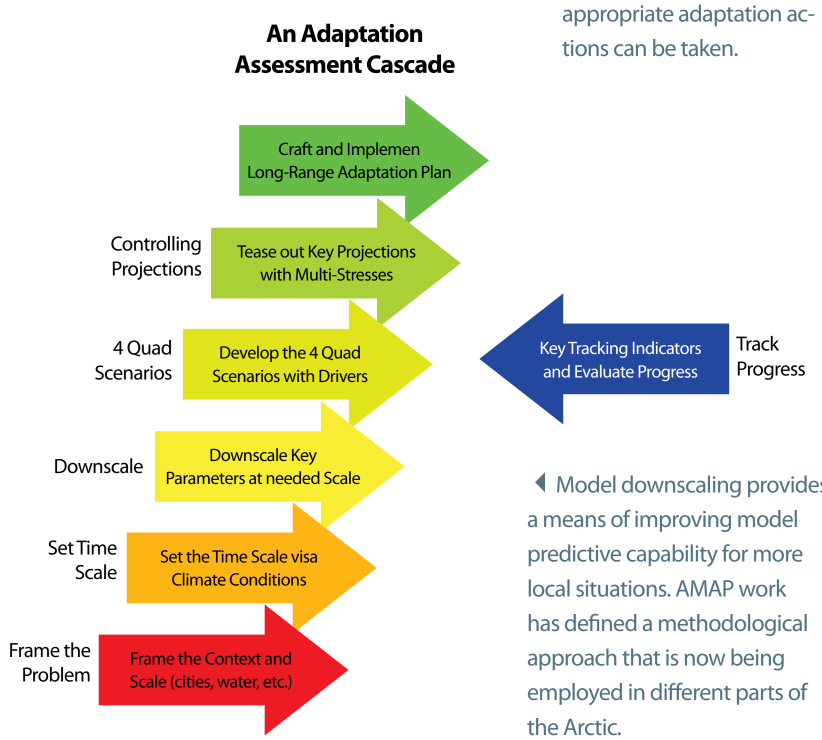
The SWIPA project itself is intended to develop more detailed and thorough knowledge about ongoing processes, supporting more accurate projections about the Arctic cryosphere and allowing better assessment of impacts on local, regional, and global scales. The project builds on work done through the International Polar Year (IPY), the Intergovernmental Panel on Climate Change, and the Arctic Council, as well as other national and international programs. Specifically, SWIPA will integrate scientific information on the impacts of climate change on ice, snow, and permafrost in the Arctic, considering impacts within the Arctic and beyond. It will update existing scientific information with results of relevant new research and monitoring.

The effects of short-lived climate forcers also require further study. Improving the quantitative estimates of these effects and the potential benefits of reducing emissions of non-carbon dioxide forcers requires improved climate modeling capability.

Finally, assessing social and economic impacts of climate change typically requires detailed information at local scales. Global climate models, though powerful and complex, must operate on a coarse geographical scale to keep their computation requirements within reason. This means, however, that their outputs do not have sufficient resolution for many impact studies. Until sufficiently detailed regional models are developed, downscaling of climate model outputs offers additional tools to support local-scale impact assessments. Projects using this approach are underway in the Arctic and will provide additional insight into the reliability and utility of various downscaling methods.



▲ Model projections of global warming under different IPPC scenarios are fairly consistent for the period up until around 2040, but beyond that the projected temperatures vary widely. The predictive capacity of the models needs to be improved for possible impacts by the end of the century so that appropriate adaptation actions can be taken.



◄ Model downscaling provides a means of improving model predictive capability for more local situations. AMAP work has defined a methodological approach that is now being employed in different parts of the Arctic.

Summary

The Arctic continues to warm. Since publication of the *Arctic Climate Impact Assessment* in 2005, several indicators show further and extensive climate change. Air temperatures are increasing in the Arctic. Sea ice has decreased sharply, reaching a record low in 2007. Surface waters in the Arctic Ocean are warming. Permafrost is warming and, at its margins, thawing. Plants are growing more rapidly, with trees and shrubs appearing farther north. Snow cover in the Northern Hemisphere is decreasing by 1-2% per year. Glaciers are shrinking and the Greenland Ice Cap is melting. Most of the significant outlet glaciers of the Greenland Ice Cap have accelerated, retreated, and thinned, leading to increased loss of ice from Greenland, especially since 2003.

Even if there is still considerable uncertainty regarding the magnitude of their effects, black carbon, tropospheric ozone, and methane may contribute to global and Arctic warming to a degree comparable to the impacts of carbon dioxide. Black carbon and ozone, in particular, have a strong seasonal pattern that makes their impacts particularly important in the Arctic, especially during the spring melt. These climate forcers are relatively short-lived and have the potential for relatively rapid reductions in emissions and thus in atmospheric levels. There are various options for emissions reductions that can be enacted in northern regions and globally.

The Arctic carbon cycle is an important factor in the global climate system. Considerable quantities of carbon and methane are stored in the Arctic. If released to the atmosphere, they could increase greenhouse gas concentrations and thus drive further climate change. At present, the Arctic appears to be a sink for carbon dioxide and a source for methane. Climate change is likely to result in more carbon dioxide being released to the air but also more being absorbed by growing plants on land and in the ocean. The balance between these two responses is not clear, but it appears unlikely that changes in the Arctic carbon cycle will have more than a modest influence on global climate in the next 50-100 years. There is, however, considerable uncertainty involved, especially over longer time periods.

Global climate models are limited in their ability to provide reliable, regional-scale projections of various climate parameters. Current and planned projects and programs aim to improve understanding of regional processes, the role of short lived climate forcers, and local impacts of climate change. Improved regional-scale models and projections will help improve evaluation of adaptive and mitigative actions, particularly concerning local impacts and reducing emissions of short lived climate forcers, which may be of comparable importance to carbon dioxide in driving temperature increases.

Henning Thing

▸ The Greenland Ice Sheet meets land at Russell Glacier, 20 km east of Kangerlussuaq, Greenland.

Background scientific documentation for this report

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Improving predictive capacity for the Arctic region: Model down-scaling

Final Report of the Workshop on Adaptation of Climate Scenarios to Arctic Climate Impact Assessments, Oslo, May 14-16, 2007. AMAP Report 2007:4

Benestad, R.E., I. Hanssen-Bauer and D. Chen, Empirical-Statistical Downscaling. World Scientific Publishing, 2008. 300 pp

Sources of photography in this report

Photographers and suppliers of photographic material:

Bryan and Cherry Alexander (www.arcticphoto.com) – pages 3 and 8

page 3: Polar Bear falls through thin Autumn sea ice. Cape Churchill, Canada.

page 8: Gas flares in the Vingoyarhinsky oil fields. Purovsky Region, Yamal, Western Siberia.

Henning Thing (het@fi.dk) – cover, pages 5, 6 and 14

page 5: The Zackenberg valley, with the Zackenberg research station and Zackenberg mountain in the background.

page 6 (left): Russell Glacier at the edge of the Greenland Ice Sheet, 20 km east of Kangerlussuaq airport (June 24, 2007).

page 6 (right): Extensive summer melting at the edge of the Greenland Ice Sheet, 25 km northeast of Kangerlussuaq airport (August 2, 2007).

page 14: Where the Greenland Ice Sheet meets land at Russell Glacier, 20 km east of Kangerlussuaq airport (July 6, 2007).

John Smol (Queen's University, Kingston, Ontario Canada, smolj@queensu.ca) – page 5

Detailed caption:

Marianne Douglas (University of Alberta) conducts a final sampling of Camp Pond (Cape Herschel, Ellesmere Island, Nunavut, Canada) on July 15, 2007, the day before the pond desiccated totally. Paleolimnological data showed that these were previously permanent water bodies that have existed for millennia, but limnological monitoring data (which began in 1983) indicated increased evaporation that eventually resulted in total desiccation of many Cape Herschel ponds beginning in 2005.