

An aerial photograph of a snowfield with several blue ice patches. The snow is white and textured, and the ice patches are a vibrant blue color. The patches are scattered across the field, with some being larger and more prominent than others. The overall scene is a mix of white and blue, with the blue patches standing out against the white snow.

Arctic Climate Issues 2011:

Changes in Arctic Snow, Water, Ice and Permafrost

Arctic Monitoring and Assessment Programme (AMAP)

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ARCTIC CLIMATE ISSUES 2011: CHANGES IN ARCTIC SNOW, WATER, ICE AND PERMAFROST

Arctic Climate Issues 2011: Changes in Arctic Snow, Water, Ice and Permafrost

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An aerial view of blue ponds formed in a glacial ice sheet. Glacier Bay National Park, Alaska.

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Preface

This report presents a summary of the findings of the Snow, Water, Ice and Permafrost in the Arctic (SWIPA) assessment. This assessment was performed between 2008 and 2011 by the Arctic Monitoring and Assessment Programme (AMAP) in close cooperation with the International Arctic Science Committee (IASC), the World Climate Research Programme / Climate and Cryosphere (WCRP/CliC) Project and the International Arctic Social Sciences Association (IASSA).

The SWIPA assessment was a follow-up to the *Arctic Climate Impact Assessment (ACIA)*¹ published in 2005. The ACIA represents the benchmark against which this updated assessment of change in the Arctic cryosphere has been developed.

The SWIPA assessment was conducted by an international group of over 200 scientists, experts and knowledgeable members of the Arctic indigenous communities (see Acknowledgments). Lead authors and international experts who independently reviewed the SWIPA assessment report were selected through an open nomination process, and a SWIPA Integration Team was responsible for scientific oversight and coordination of all work related to the preparation of the SWIPA scientific assessment report.

The SWIPA Overview report is produced under the responsibility of the AMAP Working Group. The scientific basis for all information presented in this overview report can be found in the fully-referenced and peer-reviewed SWIPA technical and scientific background report *Snow, Water, Ice and Permafrost in the Arctic (SWIPA): Climate and the Cryosphere*². A notation of which chapters of the full technical report have been principally drawn upon for the overview presented here is indicated in the bottom corner of the first page of the relevant numbered sections.

The Executive Summary of this report, including recommendations for policy-makers was presented to the Arctic Council Ministers at their meeting in Nuuk, Greenland, in May 2011. Since its presentation, the trends documented in the SWIPA assessment have continued, with 2012 seeing record temperatures and loss of sea ice in the Arctic.

Other SWIPA outreach products include films (available with different languages) specifically developed for policy-makers, summarizing the main findings of the SWIPA assessment, and a short summary for educational use. All SWIPA reports and films are available from the AMAP Secretariat and on the AMAP website www.amap.no.

AMAP and its partner organizations would like to express their appreciation to all those experts that have contributed their time, effort and data to the SWIPA assessment; and especially to the lead authors and members of the SWIPA Integration Team. Special thanks are also due to the scientific writers, led by Lynn Dicks for their work in condensing the large amount of scientific material into this readable overview report.

The support of the Arctic countries and non-Arctic countries implementing research and monitoring in the Arctic is vital to the success of AMAP. The AMAP work is essentially based on ongoing activities within these countries, and the countries also provide the necessary support for most of the experts involved in the preparation of the AMAP assessments. In particular, AMAP would like to thank Canada, Denmark, Norway and the Nordic Council of Ministers for their financial support to the SWIPA work, and to sponsors of programs and projects that have delivered data for use in this assessment. Special thanks are given to those experts involved in International Polar Year (IPY) projects who made their results available for the SWIPA assessment.

The AMAP Working Group is pleased to present its assessment to the Arctic Council and the international science community.



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Oslo, October 2012

¹ ACIA, 2005. Arctic Climate Impact Assessment. Cambridge University Press. v + 1042pp.

² AMAP, 2011. Snow, Water, Ice and Permafrost in the Arctic (SWIPA): Climate Change and the Cryosphere. Arctic Monitoring and Assessment Programme (AMAP), Oslo, Norway. xii + 538pp.

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Executive Summary and Key Messages

SWIPA Summary for policymakers

AMAP's new assessment of the impacts of climate change on Snow, Water, Ice and Permafrost in the Arctic (SWIPA) brings together the latest scientific knowledge about the changing state of each component of the Arctic 'cryosphere'. It examines how these changes will impact both the Arctic as a whole and people living within the Arctic and elsewhere in the world.

'Cryosphere' is the scientific term for that part of the Earth's surface that is seasonally or perennially frozen. It includes snow, frozen ground, ice on rivers and lakes, glaciers, ice caps, ice sheets and sea ice. The cryosphere structures the physical environment of the Arctic. It provides services to humans such as freshwater supplies and transport routes. The cryosphere is an integral part of the climate system, and affects climate regionally and globally.

The SWIPA Assessment follows on from the Arctic Climate Impact Assessment (ACIA), published in 2005. It aims to update the findings from ACIA and to provide more in-depth coverage of issues related to the Arctic cryosphere.

The observed changes in sea ice on the Arctic Ocean and in the mass of

the Greenland Ice Sheet and Arctic ice caps and glaciers over the past ten years are dramatic and represent an obvious departure from the long-term patterns.

Some elements of the cryosphere, such as the extent of snow, ice over water, and the dynamics of glaciers and ice streams vary greatly over short timescales (seasonally, or from year to year) and from place to place. Other aspects of the cryosphere, such as the extent of permafrost and large ice sheets, vary and change over decadal time scales and large areas. Distinguishing long-term change from natural variability requires data to be collected at many locations over many years and carefully analyzed. Detecting these cryospheric responses to changing climate presents different challenges and requires long term records as well as high frequency observations.

Why the Arctic cryosphere is changing

The past six years (2005–2010) have been the warmest period ever recorded in the Arctic. Higher surface air temperatures are driving changes in the cryosphere.

Key finding 1

There is evidence that two components of the Arctic cryosphere – snow and sea ice – are interacting with the climate system to accelerate warming.

Key finding 2

The Arctic is warming. Surface air temperatures in the Arctic since 2005 have been higher than for any five-year period since measurements began around 1880. The increase in annual average temperature since 1980 has been twice as high over the Arctic as it has been over the rest of the world. Evidence from lake sediments, tree rings and ice cores indicates that Arctic summer temperatures have been higher in the past few decades than at any time in the past 2000 years. Previously unseen weather patterns and ocean currents have been observed, including higher inflows of warm water entering the Arctic Ocean from the Pacific. These changes are the main drivers of change in the Arctic cryosphere.

In attributing the cause of warming in the Arctic, SWIPA refers to the findings of the Fourth Assessment Report from the Intergovernmental Panel on Climate Change (IPCC). This states that "Most

of the observed increase in global average temperatures since the mid-20th century is very likely [$> 90\%$ probability] due to the observed increase in anthropogenic GHG [greenhouse gas] concentrations".

Climate-cryosphere interactions may now be accelerating warming

The greatest increase in surface air temperature has happened in autumn, in regions where sea ice has disappeared by the end of summer. This suggests that the sea is absorbing more of the sun's energy during the summer because of the loss of ice cover. The extra energy is being released as heat in autumn, further warming the Arctic lower atmosphere. Over land, the number of days with snow cover has changed mostly in spring. Early snow melt is accelerated by earlier and stronger warming of land surfaces that are no longer snow-covered.

These processes are termed 'feedbacks'. Snow feedbacks are

well known. The sea ice feedback has been anticipated by climate scientists, but clear evidence for it has only been observed in the Arctic in the past five years.

A number of other potential feedback mechanisms at play in the Arctic have been identified. These mechanisms can alter the rate or even direction of climate change and associated changes in the cryosphere. Of those feedbacks expected to have strong effects, seven lead to

further and/or accelerated warming, and just one leads to cooling. The intensity of feedbacks between the cryosphere and climate are not yet well quantified, either within the Arctic or globally. This lends considerable uncertainty to predictions of how much and how fast the cryosphere and the Arctic environment will change.

How the Arctic cryosphere is changing

The extent and duration of snow cover and sea ice have decreased across the Arctic. Temperatures in the permafrost have risen by up to 2°C. The southern limit of permafrost has moved northward in Russia and Canada.

Key finding 3

The largest and most permanent bodies of ice in the Arctic – multi-year sea ice, mountain glaciers, ice caps and the Greenland Ice Sheet – have all been declining faster since 2000 than they did in the previous decade.

Key finding 4

Model projections reported by the Intergovernmental Panel on Climate Change (IPCC) in 2007 underestimated the rates of change now observed in sea ice.

Key finding 5

The extent and duration of snow cover have decreased throughout the Arctic. The Arctic land area covered by snow in early summer has reduced by 18% since 1966. Coastal areas of Alaska and northern Fennoscandia have seen the strongest decreases in the number of days with snow cover. The change is largely caused by snow melting earlier in the spring. Snow depth has decreased in some areas such as the North American Arctic, but has increased in others such as northern Russia.

Permafrost – permanently frozen ground – underlies most of the Arctic land area and extends under parts of the Arctic Ocean. Temperatures in the permafrost have risen by up to 2°C over the past two to three decades, particularly in colder sites (typical permafrost temperatures range from -16°C to just below 0°C, depending on the location). The depth of soil above the permafrost that seasonally thaws each year has increased in Scandinavia, Arctic Russia west of the Urals, and inland Alaska. The southern limit of the permafrost retreated northward by 30 to 80 km in Russia between 1970 and 2005, and by 130 km during the past 50 years in Quebec.

Ice cover on lakes and rivers in the Northern Hemisphere is breaking-up earlier than previously observed. Studies of sediments in High Arctic lakes indicate that the duration of ice cover on some lakes has declined significantly over the past 100 years. The rates of change in lake and river ice conditions vary across the Arctic, although there are few long-term systematic observations.

Large bodies of ice are melting faster

Net loss of mass from the Greenland Ice Sheet has increased from an estimated 50 Gt per year (50 000 000 000 metric tonnes per year) in the period 1995–2000 to ~200 Gt per year in the period 2004–2008. The current loss (~200 Gt per year) represents enough water to supply more than one billion city-dwellers.

Nearly all glaciers and ice caps in the Arctic have shrunk over the past 100 years. The rate of ice loss increased over the past decade in most regions, but especially in Arctic Canada and southern Alaska. Total loss of ice from glaciers and smaller ice caps in the Arctic probably exceeded 150 Gt per year in the past decade, similar to the estimated amount being lost from the Greenland Ice Sheet.

Arctic sea-ice decline has been faster during the past ten years than in the previous 20 years. This decline in sea-ice extent is faster than projected by the models used in the IPCC's Fourth Assessment Report in 2007. The area of sea ice persisting in summer (polar pack ice) has been at or near record low levels every year since 2001. It is now about one third smaller than the average summer sea-ice cover from 1979 to 2000. New observations reveal that average sea-ice thickness is decreasing and the sea-ice cover is now dominated by younger, thinner ice.

More change is expected

Maximum snow depth is expected to increase over many areas by 2050, with greatest increases over Siberia. Despite this, average snow cover duration is projected to decline by up to 20% by 2050.

Key finding 6

The Arctic Ocean is projected to become nearly ice-free in summer within this century, likely within the next thirty to forty years.

Key finding 7

Average Arctic autumn-winter temperatures are projected to increase by between 3 and 6 °C by 2080, even using scenarios in which greenhouse gas emissions are projected to be lower than they have been for the past ten years.

The climate models used for SWIPA do not include possible feedback effects within the cryosphere system that may release additional stores of greenhouse gases from Arctic environments.

Arctic snowfall and rain are projected to increase in all seasons, but mostly in winter. Despite this, Arctic landscapes are generally expected to dry out more during summer. This is because higher air temperatures mean that more water evaporates, snow melt finishes earlier, and water flow regimes are altered.

With increasing snowfall, all projections show maximum snow depth during winter increasing over many areas. The greatest increases (15–30% by 2050) are expected in Siberia. Even so, snow will tend to lie on the ground for

10–20% less time each year over most of the Arctic, due to earlier melting in spring. Models project continued thawing of permafrost.

Projections show that sea-ice thickness and summer sea-ice extent will continue to decline in the coming decades, although considerable variation from year to year will remain. A nearly ice-free summer is now considered likely for the Arctic Ocean by mid-century. This means there will no longer be any thick multi-year ice consistently present.

Climate model projections show a 10–30% reduction in the mass of mountain glaciers and ice caps by the end of the century.

The Greenland Ice Sheet is expected to melt faster than it is melting now, but no current models can predict exactly how this and other land-based ice masses in the Arctic will respond to projected changes in the climate. This is because ice dynamics and complex interactions between ocean, snow, ice and the atmosphere are not fully understood.

How these changes affect Arctic ecosystems and people

Changes in the cryosphere cause fundamental changes to the characteristics of Arctic ecosystems and in some cases loss of entire habitats. This has consequences for people who receive benefits from Arctic ecosystems.

Key finding 8

The observed and expected future changes to the Arctic cryosphere impact Arctic society on many levels. There are challenges, particularly for local communities and traditional ways of life. There are also new opportunities.

Key finding 9

Changes in the cryosphere cause fundamental changes in Arctic ecosystems

Changes in the amount of snow and the structure of the snowpack affect soils, plants and animals. Some species, such as pink-footed goose, benefit from less snow cover in spring. But animals grazing through snow, such as reindeer/caribou, suffer if winter rainfall creates an ice-crust over the snow. This is already happening more often in northern Canada and Scandinavia.

Less snow and faster melting are causing summer drought in forests, wetlands, and lakes supplied by snow melt. Thawing permafrost is also causing wetlands in some areas to drain and dry out, while creating new wetlands elsewhere.

The loss of ice cover over rivers, lakes and seas is changing animal and plant communities in the water.

The loss of large areas of sea ice represents devastating habitat loss for some ice-adapted species, including polar bear, seals, walrus, narwhal and some

microbial communities. Many animals, including bowhead whales, depend on tiny crustaceans that thrive near the sea ice. This food source is changing as the ice edge recedes.

These changes to ecosystems directly affect supplies of water, fish, timber, traditional/local foods and grazing land used by Arctic people. For example, it has been suggested that stocks of some sub-Arctic and Arctic-adapted fish species, including commercially important species, could change as sea ice recedes. Uncertainty about changing supplies of living natural resources makes it difficult to plan for the future.

Forestry may benefit from thawing permafrost in areas where there is enough water for trees to grow, but insect pests are increasingly causing problems. Some hunted animals, such as seals and walruses, are declining in numbers as ice conditions change. Others are moving to new locations, so hunters have to travel further to reach them.

Transport options and access to resources are radically changed by differences in the distribution and seasonal occurrence of snow, water, ice and permafrost in the Arctic. This affects both daily living and commercial activities.

Key finding 10

Arctic infrastructure faces increased risks of damage due to changes in the cryosphere, particularly the loss of permafrost and land-fast sea ice.

Key finding 11

Cryospheric change affects Arctic livelihoods and living conditions

Access to northern areas via the sea is increasing during the summer as sea ice disappears; allowing increased shipping and industrial activity. Offshore oil and gas activities will benefit from a longer open water season, although threats from icebergs may increase due to increased iceberg production. The International Maritime Organization is devising new mandatory guidelines for ships operating in ice-covered waters. Sea-ice decline creates challenges for local residents who use the ice as a platform for travel and hunting; these challenges may include travelling farther over uncertain ice conditions and increased hazards.

On land, access to many areas is becoming more difficult as ice roads melt earlier and freeze later and as permafrost degrades. Industrial operations reliant on ice roads will need to concentrate heavy load transport into the coldest part of the year. Shorter seasons where ice and snow roads can be used severely impact communities that rely on land transport of goods to maintain reasonable retail costs and ensure economic viability, particularly in northern Canada and Russia. Some land areas become more accessible for mining as glaciers and ice caps recede.

Thawing permafrost is causing increased deformation of buildings, roads, runways and other man-made structures in some areas, although poor design in the past is a contributing factor. New design methods are being developed that consider the likelihood of environmental change. Buildings and other infrastructure are at risk from heavier snow loads and floods caused by the release of ice jams in rivers or sudden emptying of glacial lakes.

Two-thirds of the Arctic coastline is held together and protected by ice. When land-fast sea ice melts earlier and permafrost

thaws, rapid erosion can occur. Along the coasts bordering the Laptev and Beaufort seas, coastal retreat rates of more than two metres per year have been recorded. A number of Inuit villages in Alaska are preparing to relocate in response to the encroaching sea.

In the short term, increased glacier melt creates new opportunities for hydroelectricity generation. This has potential benefits for industry. In the longer term, the volume of meltwater will decrease as glaciers shrink, potentially affecting electricity production.

Melting ice and snow release contaminants that have been stored for many years, allowing the contaminants to re-enter the environment. Exposure of people and top predators to contaminants that accumulate in food chains could further increase.

Increased access to the Arctic creates new economic opportunities. Cruise ship tourism is increasing. More people are coming to witness the effects of climate change on Arctic glaciers, for example at the Ilulissat Icefjord in Greenland. Increased tourism may challenge lifestyles and services in local communities as well as increase the demand for effective infrastructure (e.g., air services, marine navigation aids, and other safety measures). Loss of Arctic wildlife and change of scenery may adversely affect the tourist industry in the long term.

Cryospheric change combined with rapid development creates opportunities and challenges for Arctic residents. Traditional knowledge can help to detect change and adapt to it. While traditional knowledge continues to evolve, it is a challenge to ensure that this knowledge is being passed on to younger generations as lifestyles change. Some aspects of traditional knowledge become less applicable as the cryosphere and other components of the Arctic system change even more rapidly and become less predictable.

Why changes in the Arctic matter globally

Changes in the Arctic cryosphere have impacts on global climate and sea level

When highly reflective snow and ice surfaces melt away, they reveal darker land or ocean surfaces that absorb more of the sun's energy. The result is enhanced

warming of the Earth's surface and the air above it. There is evidence that this is happening over the Arctic Ocean as the sea ice retreats, as well as on land as snow melts earlier.

Overall emissions of methane and carbon dioxide from the Arctic could

Loss of ice and snow in the Arctic enhances climate warming by increasing absorption of the sun's energy at the surface of the planet. It could also dramatically increase emissions of carbon dioxide and methane and change large-scale ocean currents. The combined outcome of these effects is not yet known.

Key finding 12

Arctic glaciers, ice caps and the Greenland Ice Sheet contributed over 40% of the global sea level rise of around 3 mm per year observed between 2003 and 2008. In the future, global sea level is projected to rise by 0.9–1.6 m by 2100 and Arctic ice loss will make a substantial contribution to this.

Key finding 13

increase due to warming of soils and freshwater systems, and thawing of ancient frozen soil beneath the seabed.

The combined outcome of these effects on global climate is not yet known.

All the main sources of freshwater entering the Arctic Ocean are increasing – river discharge, rain/snow, and melting glaciers, ice caps, and the Greenland Ice Sheet. Recent calculations estimate that an extra 7700 km³ of freshwater – equivalent to one metre of water over the entire land surface of Australia – has been added to the Arctic Ocean in recent years. There is a risk that this could alter large-scale ocean currents that affect climate on a continental scale.

Melting glaciers and ice sheets worldwide have become the biggest contributor to global sea level rise. Arctic glaciers, ice caps, and the Greenland Ice Sheet contributed 1.3 mm – over 40% – of the total 3.1 mm global sea level rise observed every year between 2003 and 2008. These contributions from the Arctic to global sea level rise are much greater than previously measured. High uncertainty surrounds estimates of future global sea level. Latest models predict a rise of 0.9 to 1.6 m above the

1990 level by 2100, with Arctic ice making a significant contribution.

Changes in the Arctic cryosphere affect global society

Sea level rise is one of the most serious societal impacts of cryospheric change. Higher average sea level and more damaging storm surges will directly affect millions of people in low-lying coastal flood plains. Sea level rise increases the risk of inundation in coastal cities such as Shanghai and New York.

On the other hand, global economic activity may benefit from cryospheric changes in the Arctic. For example, opening transpolar sea routes across the Arctic Ocean will reduce the distance for ships travelling between Europe and the Pacific by 40% compared to current routes. This could reduce emissions and energy use.

Some unique Arctic species, such as the narwhal, face particular threats as the cryosphere changes. The decline of cryospheric habitats such as sea ice and wetlands over permafrost will impact on migratory species of mammals and birds from elsewhere in the world. These adverse effects on biodiversity are of global concern.

What should be done

Everyone who lives, works or does business in the Arctic will need to adapt to changes in the cryosphere. Adaptation also requires leadership from governments and international bodies, and increased investment in infrastructure.

Key finding 14

Adaptation is urgent and needed at all levels

Cryospheric change affects people at the local level first, and local communities will need to devise strategies to cope with emerging risks.

At national and regional levels, adaptation requires leadership from governments and international bodies to establish new laws and regulations. For example, new fishing regulations will be required as fish stocks change. New standards will need to be developed for construction, particularly in areas affected by thawing permafrost.

Governments will need to invest in transport networks to cope with the shorter ice road season. Search and rescue operations will need to be enhanced to respond to increasing traffic and risks at sea, and accurate forecasts of weather and sea conditions are required to ensure travel safety.

Arctic communities are resilient and will actively respond to cryospheric change. However, rapid rates of change may outpace adaptation capacity. Knowledge and research are needed to foresee how living conditions are likely to change, and to evaluate possible adaptation options. Concerns of indigenous peoples need particular attention in this regard.

Changes in the cryosphere are not the only driver of change in the Arctic. Cryospheric change and climate change occur in the context of societal change, which may be even more challenging. The combined effects of societal, climatic and cryospheric change must be taken into account in adaptation strategies.

Cutting greenhouse gas emissions globally is urgent

Climate change represents an urgent and potentially irreversible threat to human societies. Global climate modeling studies show that deep and immediate

There remains a great deal of uncertainty about how fast the Arctic cryosphere will change in the future and what the ultimate impacts of the changes will be. Interactions (feedbacks) between elements of the cryosphere and climate system are particularly uncertain. Concerted monitoring and research is needed to reduce this uncertainty.

Key finding 15

cuts in global greenhouse gas emissions are required to hold the increase in global average temperatures below 2°C above pre-industrial levels. Combating human-induced climate change is an urgent common challenge for the international community, requiring immediate global action and international commitment.

Following the ACIA report, published in 2005, Ministers of the Arctic Council acknowledged that “*timely, measured and concerted action is needed to address global emissions.*” They endorsed a number of policy recommendations for reducing greenhouse gas emissions, including to “*Adopt ... strategies ... [to] address net greenhouse gas emissions and limit them in the long term to levels consistent with the ultimate objective of the UNFCCC [United Nations Framework Convention on Climate Change].*”

The key findings of the SWIPA assessment, especially the rapid and accelerated rates of change in Arctic cryosphere conditions, emphasize the need for greater urgency in taking these actions.

Uncertainty can be reduced by further research

Current monitoring, research and model results provide high confidence that significant changes are occurring in the Arctic cryosphere and that these changes will continue in the future. Some of the observed changes align with expectations but one major component of the cryosphere (sea ice) has reacted faster than anticipated just five years ago. Even so, substantial uncertainty remains, particularly concerning the future timing of changes, and the effects of interactions (feedbacks) between components of the cryosphere and climate system.

To reduce the uncertainty in future assessments, more robust observational networks are needed. Satellites and airborne measurements have improved the ability to observe some elements of the Arctic cryosphere such as sea-ice extent and snow cover. Monitoring of other key elements of the cryosphere, notably sea-ice thickness, snow depth, permafrost and glaciers, requires surface-based observations.

Many surface-based snow, freshwater ice, and precipitation gauge networks have diminished or have been completely

lost, and sites for measuring sea ice, land ice, and physical properties of snow are sparse. Observational networks need to be expanded to provide a robust set of cryospheric data for monitoring, model improvement and satellite product validation.

The biggest unanswered questions identified by this report are:

- What will happen to the Arctic Ocean and its ecosystems as freshwater is added by melting ice and increased river flow?
- How quickly could the Greenland Ice Sheet melt?
- How will changes in the Arctic cryosphere affect the global climate?
- How will the changes affect Arctic societies and economies?

Answering some of these questions requires improved monitoring networks. A better understanding of the complex interactions between the physical, chemical and biological environments in the Arctic is needed. There is a lack of systematically collected information on the effects of cryospheric change on human society.

Communicating about cryospheric change and its effects

The SWIPA assessment documents the importance of climate-induced changes in Arctic snow, water and ice conditions and the profound implications for the local, regional, and global society.

Active communication of this new knowledge, to enhance global, national, and local awareness, will help to ensure that the SWIPA assessment generates benefits for people in the Arctic.

A co-ordinated response to cryospheric change

The combined effects of the changing cryosphere, climate change, and rapid development in the Arctic will create political challenges for Arctic societies, as well as the global community. Traditional livelihoods are most vulnerable to changes in the cryosphere. There is a need for co-operation and co-ordinated effort at all levels, to respond to change and increase the resilience of Arctic ecosystems and societies.

Recommendations

Based on the SWIPA key findings, the AMAP Working Group have agreed to the following recommendations:

Adaptation

Members of the Arctic Council and governments at all levels in the Arctic should work to:

- Develop regional-scale assessments of cryospheric change and the associated risks.
- Develop and implement Arctic adaptation strategies appropriate to the scale and character of anticipated changes. Such strategies must take account of other relevant drivers of change.
- Ensure that standards for environmental management are in place, or can be adapted, to take account of cryospheric change. Develop regulations where necessary.
- Upgrade the capacity for search and rescue operations and environmental hazard responses.
- Facilitate measures to increase the accuracy of forecasting for ice, weather, and sea conditions, and make forecasts accessible to all Arctic residents and organizations.

Mitigation

International negotiations to reduce global greenhouse gas emissions should be pursued as a matter of urgency.

Member States of the Arctic Council should increase their leadership role in this process.

Observation

Arctic countries and international organizations should:

- Improve and expand systematic, comprehensive surface-based monitoring of the cryosphere.
- Maintain and support development of remote sensing methods for observing the cryosphere.
- Develop and enhance systems to observe the cascading effects of cryospheric change on ecosystems and human society.
- Expand research into processes that are important for modeling the cryosphere, to reduce uncertainty in predicting cryospheric change. In particular, improvements are needed in modeling permafrost dynamics, snow-vegetation interactions, and mass loss from glaciers, ice caps, and the Greenland Ice Sheet.

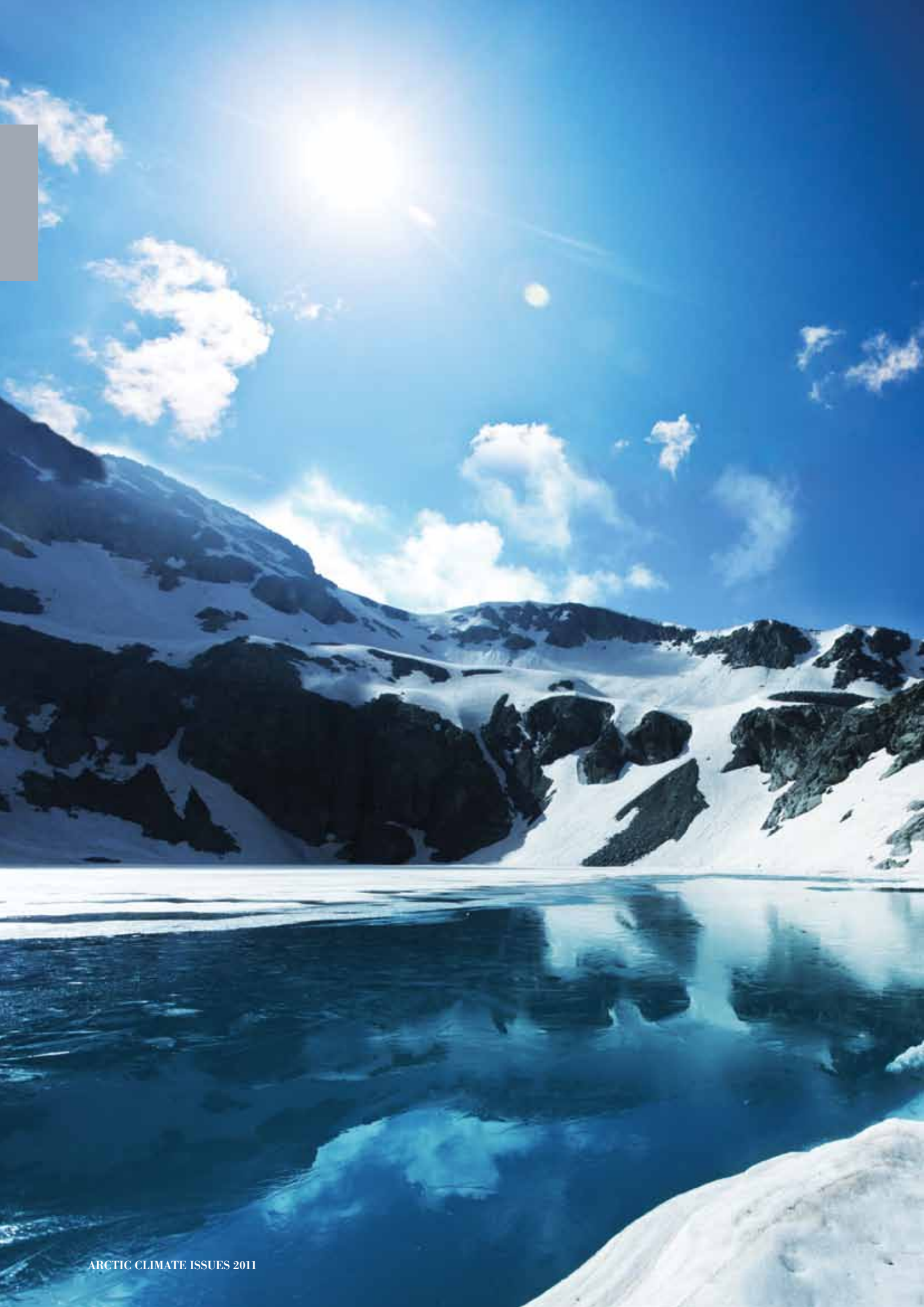
Outreach

The Members and Observers of the Arctic Council should individually and collectively inform and educate Arctic societies and the global society about the changes in the Arctic linked to climate change, and how they affect people locally, regionally and globally.

Policy Needs

Governments and institutions at all levels should increase co-operation and co-ordinate efforts to respond to the challenges and opportunities associated with cryospheric change.

The Arctic Council should conduct an integrated assessment of the combined impacts of change in the Arctic, focused on how to minimize environmental damage and enhance human well-being.



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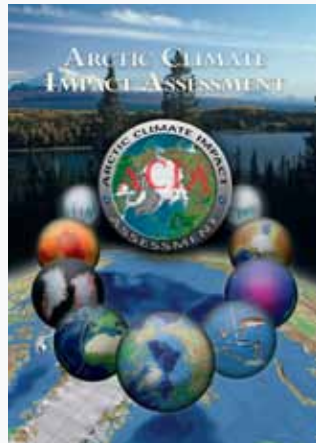
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WHAT HAS CHANGED SINCE THE ARCTIC CLIMATE IMPACT ASSESSMENT IN 2005?

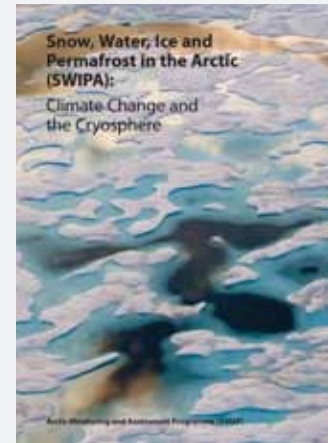
The Arctic Climate Impact Assessment (ACIA) was a thoroughly researched, fully referenced and independently reviewed evaluation of Arctic climate change and its impacts up to 2003. It involved an international team of over 300 scientists, other experts and knowledgeable members of the indigenous communities. The assessment was undertaken by AMAP and the Conservation of Arctic Flora and Fauna (CAFF), along with the International Arctic Science Committee (IASC).

The ACIA represents the benchmark against which this updated assessment of change in the Arctic cryosphere has been developed.

*ACIA
2005*



*SWIPA
2011*



Snow

Snow-cover extent in the Arctic has declined about 10% over the past 30 years.

The Arctic snow-cover extent in May and June shrunk by 18% between 1966 and 2008.

Permafrost

Permafrost has warmed by up to 2 °C in recent decades, and the depth of the layer that thaws each year is increasing in many areas.

Permafrost warming generally continues in the Arctic. Over the past two decades, the depth of the layer that thaws each year has increased in Scandinavia and Arctic Russia. In North America, this has been seen only in the interior of Alaska over the past five years.

Lake and river ice

Later freeze-up and earlier break-up of river and lake ice have combined to reduce the ice-cover season on lakes and rivers by one to three weeks in the past 100 to 150 years.

The rapid reductions in ice-cover duration on high-latitude Canadian lakes, which have become more than four weeks shorter over 19 years, exceed the highest amount of change reported in ACIA.

Mountain glaciers and ice caps

Glaciers throughout the Arctic are melting. The especially rapid retreat of Alaskan glaciers represents about half of the estimated loss of mass by glaciers worldwide, and the largest contribution by glacial melt to rising sea level yet measured.

The rates of loss from glaciers have increased substantially since 1995, and are now similar to estimated rates of mass loss from the Greenland Ice Sheet. Over half of this loss comes from glaciers in the Canadian Arctic and southern Alaska. Melting of Arctic glaciers and the Greenland Ice Sheet is now the dominant contributor to global sea level rise.

Greenland Ice Sheet

The area of the Greenland Ice Sheet that experiences some melting has increased about 16% from 1979 to 2002.

The melt area has been steadily increasing since satellite observations began. The annual mass loss is increasing: the loss of ice has increased four-fold from 1995–2000 to 205 (\pm 50) Gt in 2005–2006.

Sea ice

The average extent of sea ice cover in summer has declined by 15–20% over the past 30 years. This decline is expected to accelerate, with the near total loss of sea ice in summer projected for late this century.

The thickness of sea ice has reduced by 10–15% in recent decades, with reductions of up to 40% in some areas between the 1960s and the 1990s.

The extent of sea-ice cover in September is now about one third smaller than the average extent between 1979 and 2000. An ice-free summer is considered likely for the Arctic Ocean by mid-century.

Average winter sea ice thickness changed from 3.64 m in 1980 to 1.89 m in 2008 – a decrease of around 50%.

Multi-year ice coverage was reduced by 42% between 2005 and 2008.

Climate

Arctic climate is now warming rapidly and much larger changes are projected.

Temperatures have increased sharply in recent decades over most of the region, especially in winter.

Winter temperature increases in Alaska and western Canada have been around 3–4 °C over the past half century.

Arctic precipitation (rain and snow) has increased by about 8% on average over the past century. Greater increases are projected for the next 100 years.

The last six years (2005–2010) have been the warmest period ever recorded in the Arctic.

The recent warming has been strongest in autumn and spring.

Unlike the land-dominated warming described in ACIA, the largest warming since 2005 has been over the Arctic Ocean.

Increases in Arctic precipitation over the land areas north of 55° N show a modest increase of about 5% since 1950. However the five wettest years during that period have all occurred in the past decade.

Projected future change

Increasing global concentrations of carbon dioxide and other greenhouse gases due to human activities, primarily fossil fuel burning, are projected to contribute to additional Arctic warming of about 4–7 °C over the next 100 years.

Average Arctic autumn-winter temperatures are projected to increase by between 3 and 6 °C by 2080.

Sea level rise

Projected contributions to sea level rise from the Greenland Ice Sheet and Arctic ice caps between 2000 and 2020 range from –2 mm to +2 mm per year.

Arctic glaciers, ice caps and the Greenland Ice Sheet contributed 1.3 mm per year to global sea level rise between 2003 and 2008. This was over 50% of the total global sea level rise.

Effects on ecosystems

Reductions in sea ice will drastically shrink marine habitat for polar bears, ice-inhabiting seals, and some seabirds, pushing some species toward extinction.

Permafrost degradation will impact natural ecosystems through collapsing of the ground surface, draining of lakes, wetland development, and toppling of trees in susceptible areas.

Hooded seals, harp seals, ringed seals and Pacific walrus are all showing signs of decline in some areas, related to loss of sea ice.

Thawing of ice-rich permafrost is leading to draining of wetlands, resulting in loss of habitat in some areas. In other areas, thawing permafrost is leading to impeded drainage and a shift in biodiversity to wetland vegetation.

Effects on people

Transportation and industry on land, including oil and gas extraction and forestry, will increasingly be disrupted by the shortening of the periods during which ice roads and tundra are frozen sufficiently to permit travel.

As frozen ground thaws, many existing buildings, roads, pipelines, airports and industrial facilities are likely to be destabilized, requiring substantial rebuilding, maintenance, and investment. Future development will require new design elements to account for ongoing warming that will add to construction and maintenance costs.

Seasonal opening of the Northern Sea Route is likely to make trans-Arctic shipping during summer feasible within several decades.

Disruptions are already happening. For example, mild weather during the winter of 2009/10 stranded numerous freight-haulers and local drivers on thawed winter roads in Manitoba, Canada, and led to the closure of a 2200 km section of the ice road network.

New building design methods are being developed that take into account the likelihood of change as well as the consequences of structural failure.

An increasing number of trans-Arctic summer voyages have taken place, mainly for science and tourism. In 2009, two merchant ships passed through the Northern Sea Route (with some support from ice-breakers).



PART 1:

HOW THE ARCTIC CRYOSPHERE IS CHANGING

‘Cryosphere’ is the scientific term for the part of Earth’s surface that is frozen. It comes from the Greek word ‘kryos’, meaning frost or ice. The cryosphere includes snow, permanently frozen ground, ice on rivers and lakes, glaciers, ice caps, ice sheets and sea ice. All these parts of the cryosphere are changing as the climate warms. The most immediate changes are in seasonal patterns of snow cover and ice on water, with earlier melting in spring, later freezing in autumn or less ice during summer. Over longer timescales, permafrost is thawing and glaciers and ice sheets are melting. These changes will have far-reaching effects on nature, people and society, not only in the Arctic but throughout the world.



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Snow cover is decreasing and permafrost is thawing

- The extent and duration of snow cover have decreased throughout the Arctic. The Arctic land area covered by snow in early summer has fallen by 18% since 1966.
- Coastal areas of Alaska and northern Fennoscandia have seen the strongest reduction in the number of days with snow cover.
- Permafrost has warmed by up to 2 °C since the 1980s. The southern limit of permafrost has moved northward in Russia and Canada.
- The depth of soil above the permafrost that thaws each summer has increased in Scandinavia, Arctic Russia west of the Urals and inland Alaska.

Large bodies of ice are melting

- The largest and most permanent bodies of ice in the Arctic – multi-year sea ice, mountain glaciers, ice caps and the Greenland Ice Sheet – have all been declining faster since 2000 than they did in the 1990s.
- Ice cover on lakes and rivers in the northern hemisphere is now breaking up earlier.
- The loss of mass from the Greenland Ice Sheet has increased from an estimated 50 (\pm 50) Gt/y from 1995–2000 to 205 (\pm 50) Gt/y in 2005–2006.
- Nearly all mountain glaciers and ice caps in the Arctic have retreated over the past 100 years. The total loss of ice from them probably exceeded \sim 150 Gt/y in the last decade.
- The loss of summer sea ice is happening faster than projected in the Intergovernmental Panel on Climate Change (IPCC)'s Fourth Assessment Report in 2007.
- Arctic sea-ice cover is thinning. Older, thicker ice types are being lost and Arctic Ocean sea ice is now dominated by thinner, younger ice.



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1.1 THE ARCTIC CRYOSPHERE

The cryosphere is the part of the Earth's surface that is frozen for some part of the year. It includes snow, permanently frozen ground, ice on rivers and lakes, glaciers, ice caps, ice sheets and sea ice.

For all of human history the cryosphere has defined the Arctic – a wintry world, temporarily or permanently covered with snow or ice. Much of the soil is frozen to the bedrock. During the year, some ice and snow melt or thaw, and water moves between different components of the cryosphere. But the Arctic cryosphere is changing. The rate of some of these changes is accelerating and the effects on Arctic landscapes will be profound.

Interactions between cryosphere elements can accelerate change

The elements of the cryosphere are not isolated from one another, but form part of a dynamic system. There are some important interactions, which could alter the rate of change.

- With less sea ice, the ocean surface can warm up more in summer. This may increase the rate of ice loss from outlet glaciers in Greenland by warming them from beneath.
- Snow is an insulating layer, whether it lies over solid ground or ice. Deeper snow reduces surface freezing during winter, while a thin snow cover and/or earlier snowmelt in spring could lead to earlier ice break-up on rivers and lakes.

It is difficult to measure or predict the specific effects of these interactions across the whole Arctic.

The Arctic as the world's refrigerator

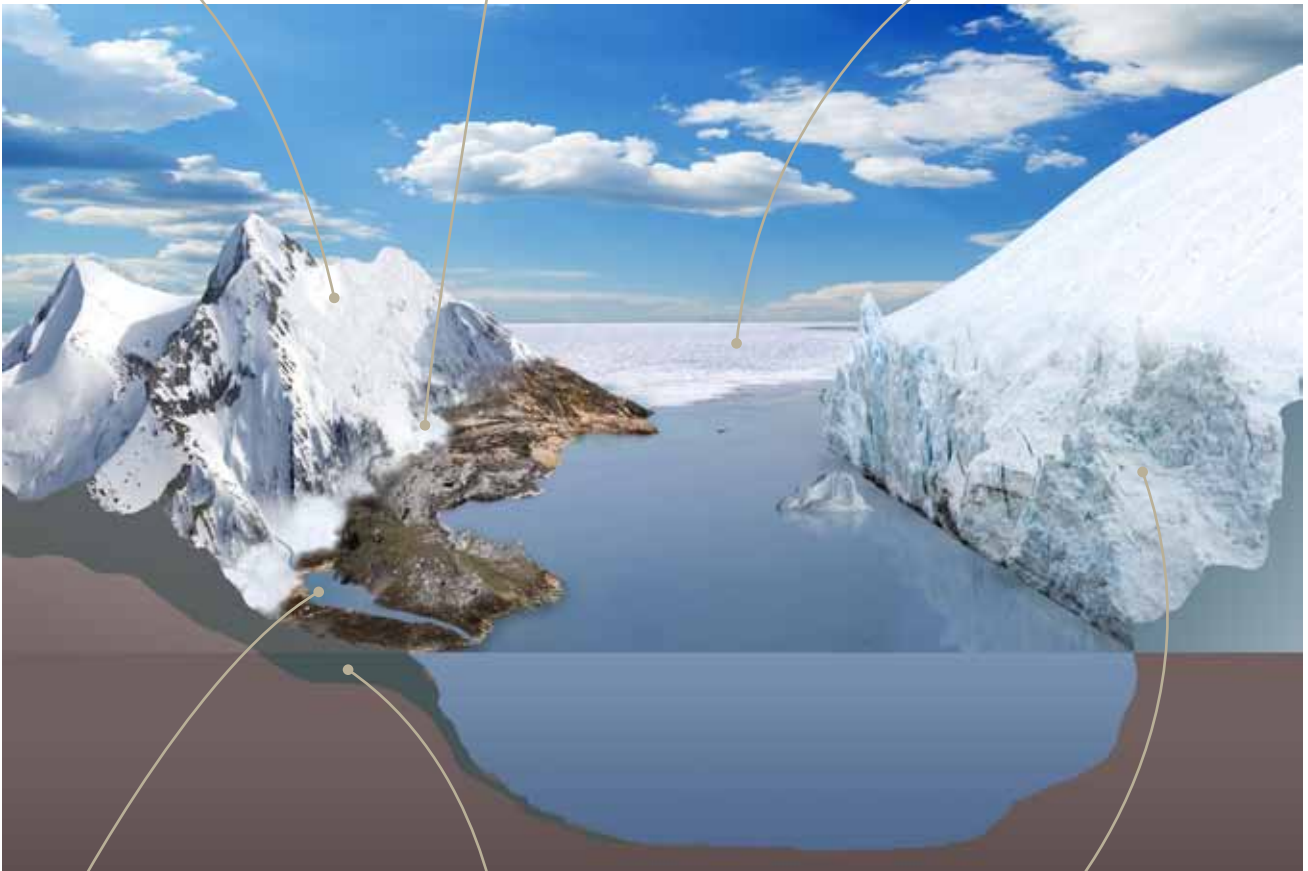
In its current state, the Arctic has a cooling effect on world climate. It does this in four ways:

1. By strongly reflecting away the sun's energy from its largely white (icy or snowy) surfaces.
2. By storing large amounts of carbon in frozen soils, thus reducing the levels of greenhouse gases in the atmosphere.
3. By acting as a heat sink, cooling down bodies of warmer water and air that arrive from further south.
4. By exporting sea ice, cold water and Arctic air to southern latitudes.

Glaciers and ice caps hold frozen freshwater from snowfall, stored on land through millennia. These bodies of ice have diminished throughout the Arctic. This creates faster meltwater flows into rivers and lakes, and more freshwater entering the ocean, leading to global sea-level rise.

Snow accumulates on the surface, mainly during winter, as a snowpack. It stores water temporarily and so affects lake levels and patterns of river flow. The duration of snow cover is decreasing all over the Arctic, with snow melt occurring faster and earlier in the spring.

Sea ice is the ice that forms on the surface of the ocean when the temperature drops well below freezing. Sea-ice extent in the Arctic Ocean at the end of summer has been at or near record low levels nearly every year since 2001. The decline in summer sea-ice extent has accelerated during the past ten years. Reduced ice cover significantly changes the environment of the Arctic Ocean.



Lakes and rivers form a complex network of freshwater flows and stores, interwoven into the Arctic landscape. The length of time they are ice-covered has decreased. This change affects the dynamics of water flow and the conditions in the waterbodies themselves. The amount of rain and snowfall has increased slightly, and so has the amount of water flowing out of large Arctic rivers into the northern seas.

Permafrost is soil, rock, sediment or other earth material that stays frozen for two years or more. It forms an impermeable layer below the surface, preventing water from draining away and leading to high water levels and wet conditions in many areas. Permafrost has warmed, and in some areas has begun to thaw.

The Greenland Ice Sheet is a massive ice body up to 3050 metres thick. It is the largest bulk of freshwater ice in the northern hemisphere and holds close to 3 million km³ of ice. The rate of ice loss at the edges of the ice sheet has increased since 2000 and the ice sheet is now shrinking.



1.2 MONITORING CHANGE IN THE ARCTIC CRYOSPHERE

Change in the cryosphere takes place on different timescales, from seasonal changes in snow cover or river and lake ice, to change over centuries, such as the diminishing Greenland Ice Sheet, or thawing permafrost.

Some observed changes affect a large area all at once, such as changes

in Arctic sea ice. Others are smaller scale, like changes to ice cover over lakes and rivers.

These different scales of change mean that a range of different techniques is required to observe, monitor and project cryospheric change for the whole Arctic.

How the cryosphere interacts with other systems

The cryosphere is an integral part of the **climate system**. The **ecosystem** and **human society** are both intimately linked to the cryosphere and affected by changes to it.

Changing climate, described by average temperatures, rain and snowfall and wind patterns, is the main driver of cryospheric change. These aspects of climate are also affected by changes in the cryosphere. Reduced sea-ice cover can lead to higher temperatures over the Arctic Ocean, for example.

Arctic ecosystems – forests, tundra, lakes, rivers, wetlands and oceans – contain species found nowhere else on

Earth. They also provide rich feeding and breeding grounds for migratory animals from further south. Changes in the cryosphere, such as thawing permafrost and shrinking sea ice, alter fundamental properties of ecosystems. Changes in physical surfaces, light levels, water flows and nutrient availability are already having impacts on many Arctic species, from trees to walrus.

Human society, with its complex social and economic interactions, is dependent upon the cryosphere in many ways. Society will have to adapt locally, regionally and globally as ice and snow patterns change, and global climate and sea level are affected.

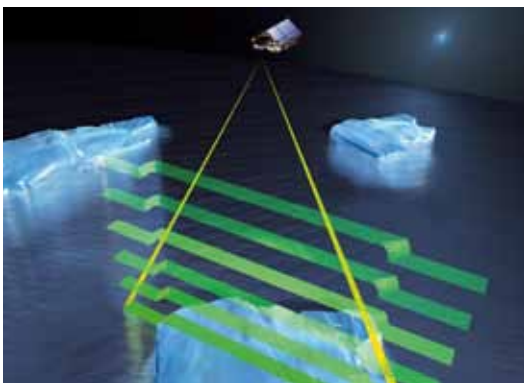
Discerning change from natural variability

Some parts of the cryosphere vary greatly over short timescales (seasonally, or from year to year) and from place to place. Actual temperatures, snowfall, wind patterns and consequently the behavior of snow and ice are influenced by a very large number of factors. Scientists expect these complex natural systems to show wide ranges of values, and not to adhere to easily discernible patterns every year. Distinguishing long-term change from this natural variability requires data to be collected over many years. A single year when the cryosphere does not behave the same as in the previous five or ten years, or temperatures are unexpectedly low or high, will not be representative.

In this context, the changes in Arctic sea ice over the last ten years are dramatic and represent an obvious departure from the long-term pattern.



The various types of observation system (satellite, aircraft, and *in situ*) and scales of operation



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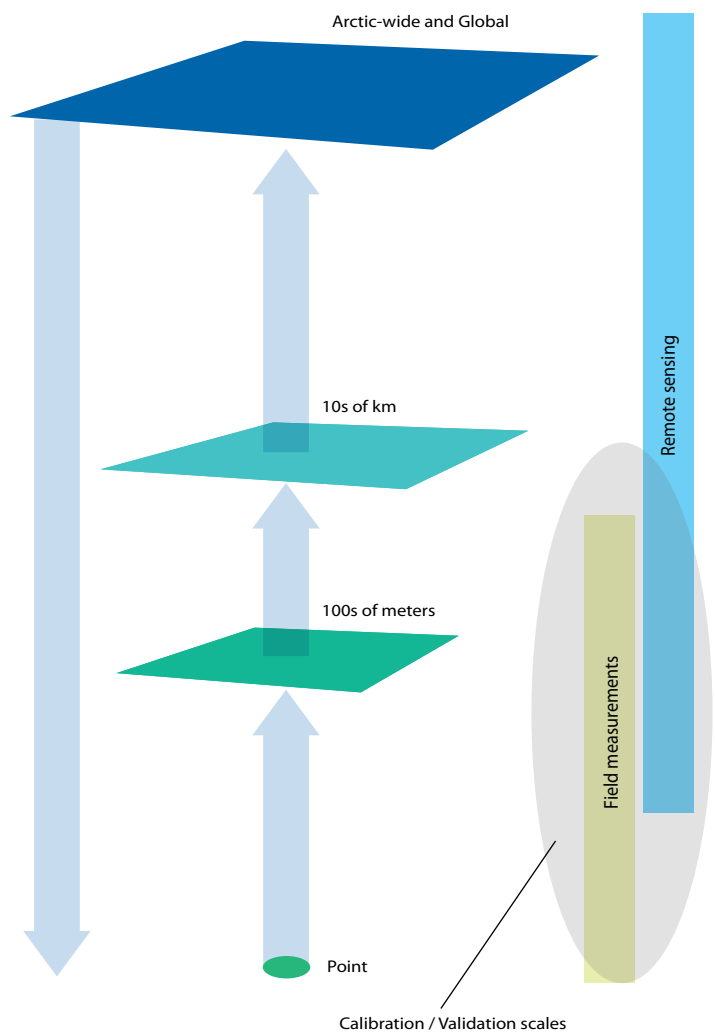
© Patrick Black / NASA



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© Roland Kallenborn



1.3 SNOW COVER IS DECREASING

Snow is a dominant feature of the High Arctic terrestrial landscape for eight to ten months of the year. It has substantial impacts on plants, animals and humans that live in the Arctic, as well affecting the climate itself.

The amount of snow in the Arctic is measured in several different ways. Three important measures are:

- the number of days with snow on the ground (snow-cover duration)
- the area of land covered by snow at a given time (snow-cover extent)
- the actual amount of snow (often measured as snow depth).

Snow-cover duration and snow-cover extent, which can both be measured from satellites, have decreased.

There is less certainty about changes in snow depth because this has to be measured on the ground, so the observations are less extensive.

The maps on the facing page show how the number of days with snow cover has changed between 1972 and 2008, as measured every week from images taken by satellites.

Decreases in snow-cover duration are much more widespread and marked in spring than in autumn. The greatest reductions in the duration of snow cover (dark orange/red) are seen in coastal regions, particularly coastal Alaska, northern Scandinavia and northern Canada.

On average across the entire Arctic, the period of winter snow cover has become four days shorter every decade between 1972/73 and 2008/09. Since 1978, the duration of snow cover has decreased by between 4 and 9 days per decade in all Arctic coastal areas except for the Kara Sea and the Chukchi Sea coasts.

The area covered by snow is decreasing too. Satellite images show that the Arctic land area covered by snow in May and June shrank by 18% between 1966 and 2008.

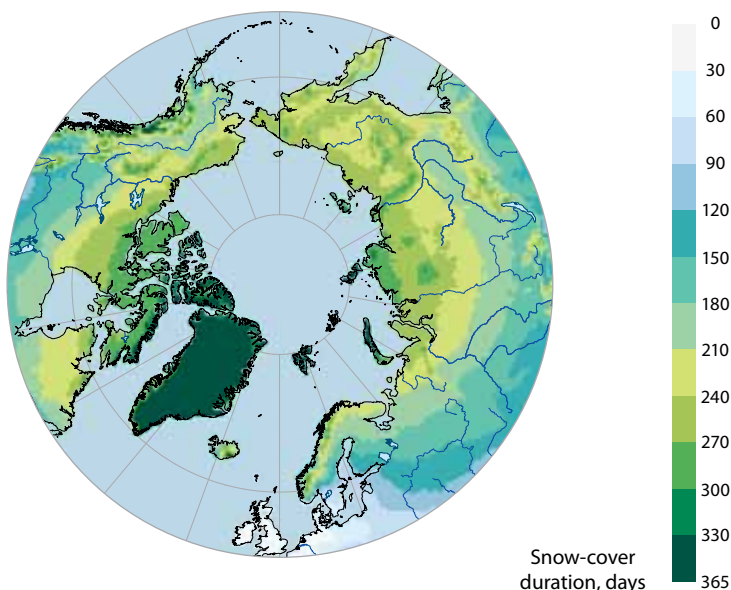
How do we know how much snow there is?

Arctic-wide measurements such as snow-cover duration and snow-cover extent can be measured using images from satellites. The National Oceanic and Atmospheric Administration (NOAA) has weekly records of snow-cover extent almost continuously from 1966; the longest satellite-derived environmental dataset in existence.

Features of snow that are important locally are its depth, its density and the total amount of snow (measured as the depth of liquid water if the snow melted). These cannot easily be measured from satellites, so they must be measured on the ground. They vary greatly from place to place and time to time, depending on weather conditions, wind patterns and the shape of the land.

The best surface observations come from daily measurements of snow depth, from a network of monitoring stations across the Arctic. For some stations, measurements go back as far as 1937. The network is sparse in some areas such as Siberia, and in the Canadian High Arctic and Greenland most stations are on the coast rather than inland.

Average snow-cover duration, 1998 – 2007



TECHNICAL TERMS EXPLAINED

Snow-cover duration

Number of days in which at least 50% of the visible land surface is continuously covered with snow.

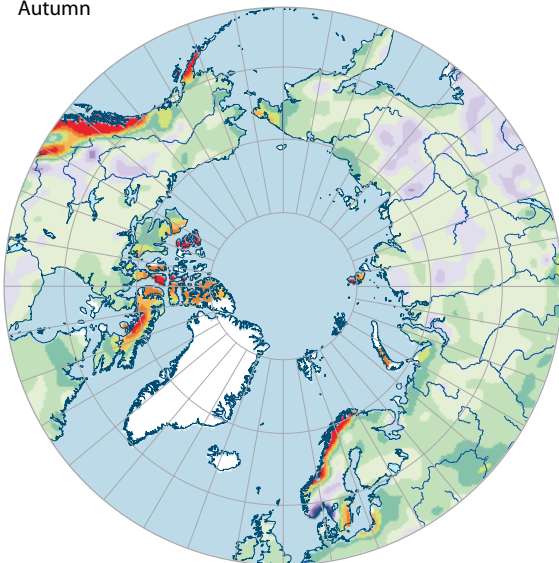


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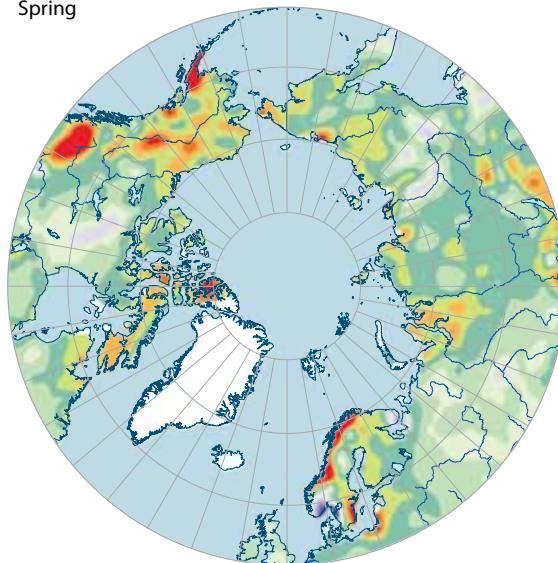
The largest and most consistent change in snow cover is earlier disappearance of snow in the spring.

Change in snow-cover duration for autumn (snow-cover onset period) and spring (snow-cover melt period) between 1972/73 and 2008/09

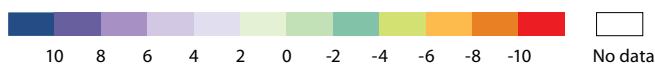
Autumn



Spring



Change in snow-cover duration, days



© nansen_CAM1_2008



Not the same everywhere

The changes in snow cover have not been the same everywhere. Over the North American Arctic, the duration of snow cover and snow depth have decreased consistently since around 1950. Over northern Europe and Siberia, snow-cover duration has been decreasing since around 1980, but snow depth is not consistently decreasing.

In northern Russia, snow is actually settling earlier, rather than later in autumn. This has lengthened the period of snow cover by two to four days since 1972.

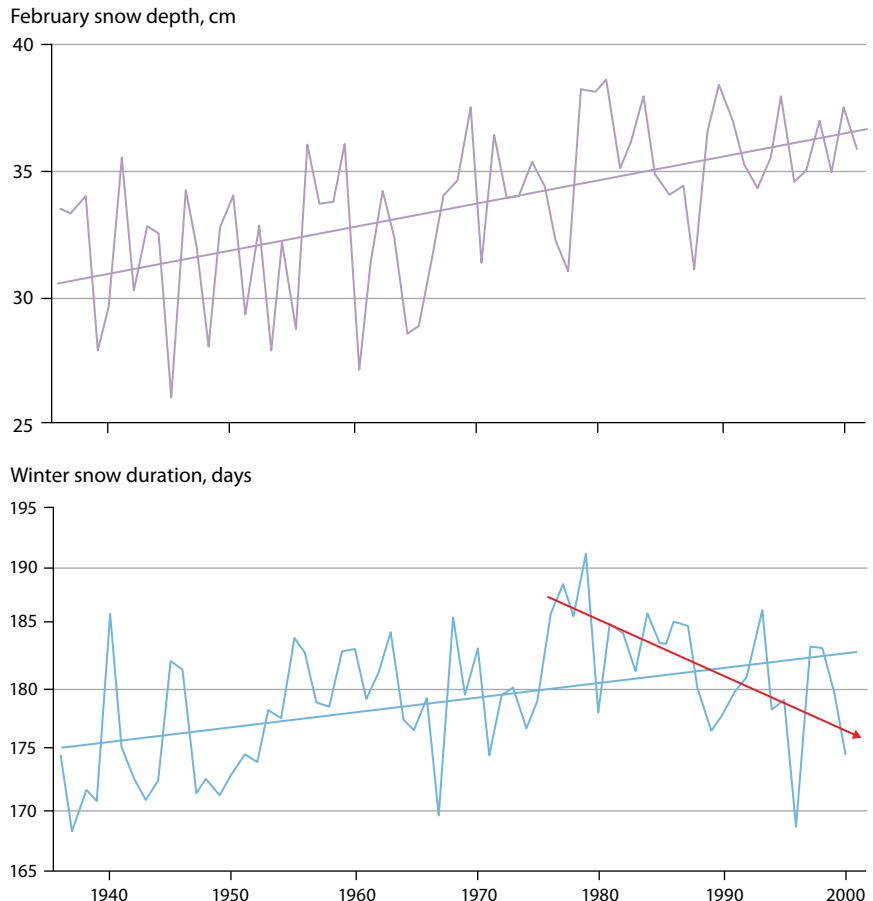
Winter snow depth is also increasing in some parts of the Eurasian Arctic. Over Russia, the number of days each year with snow more than 20 cm deep increased between 1966 and 2007 (see box). In western Siberia and the coast of the Sea of Okhotsk, snow has been this thick for around a day longer for every year since 1966.

Why is snow getting deeper over northern Scandinavia and Russia?

In most of the Arctic, there is less snow on the ground, for less time than forty years ago, because of rising air temperatures. So why is the opposite happening in northern Russia? The increasing snow depth in the Eurasian Arctic, and the earlier snowfall over northern Russia may be partly caused by the dramatic retreat in summer sea ice in the Eurasian part of the

Arctic Ocean. This has exposed more open water at the end of the summer, increasing evaporation from the ocean to the atmosphere, resulting in more humid air and greater snowfall further south. There have also been changes in weather patterns, with more frequent and more intense low pressure systems over northern Europe in recent years, linked to greater snowfall. These are associated with the Arctic Rapid Change Pattern described on page 32.

Long-term variation in snow depth and duration in northern Eurasia





Snowmelt at Zackenberg

Time-lapse webcam photographs taken at the Zackenberg monitoring site on Greenland are automatically analyzed to determine the timing and rate of snowmelt.



What difference does snow make?

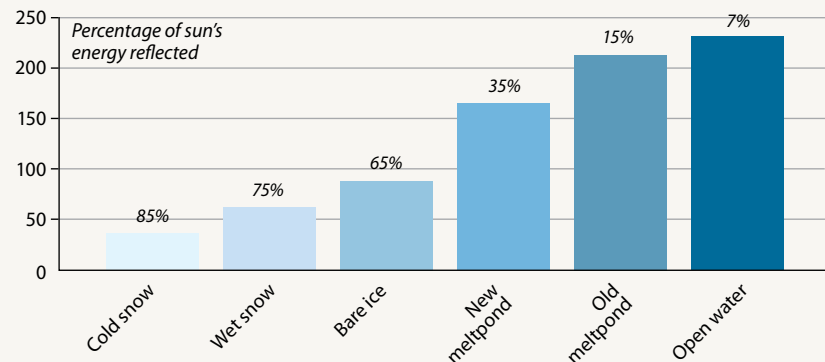
Snow acts as a reflective blanket over Arctic land and ice surfaces. It has two important effects. It reflects away the sun's heat, cooling the overlying air. And it insulates the ground in winter, preventing upper soil layers in some areas from freezing solid and protecting underlying vegetation from damage by severe frost.

Snow reflects more of the sun's energy because it is white and more 'reflective' than the darker ground surface beneath. In fact, snow is the most reflective natural surface on Earth. By reducing the amount of energy that reaches the ground, snow cover reduces the temperature in the lower atmosphere, because much of the heat near the surface is derived from the warmth of the ground. The onset of snow cover in the Arctic in autumn is associated with an abrupt drop of up to 10 °C in surface air temperatures. At least half of this sudden temperature change is due to the reflective effect of the snow.

In spring and early summer, when the Arctic is warming and snow melts, the opposite happens. The soil, rock and vegetation beneath the snow are darker and absorb more of the sun's energy. The ground warms quickly once the snow has gone, warming the air above, which in turn causes more snow to melt, and so on until the snow has gone.

A major implication of decreasing snow cover across the whole Arctic is to increase the rate of warming, especially in spring. It has been estimated that the reduced duration of Arctic snow cover seen between 1970 and 2000 has created an increased warming effect equivalent to around 5% of the warming caused by human-induced carbon dioxide emissions each year.

Sun's energy absorbed per day, W/m²



What happens when snow cover decreases?

- In spring and summer more heat is absorbed by the underlying surfaces when snow extent and snow duration diminish (see section 2.2).
- In autumn and winter soils become colder where there is less snow, and warmer where snow lies deeper (see section 4.1).
- The supply of meltwater during spring and summer is reduced, affecting wetlands, freshwater resources and tree survival (see section 4.1).
- Short-term thaws during winter kill underlying vegetation, with serious consequences for grazing animals (see section 4.1).
- Plant growth and therefore carbon storage increase in areas where summer water supply is not limited (see section 5.1).
- Transport routes over snow are available for less time, impacting on the forestry and tourism industries (see section 4.3).



© GeorgeBurba / iStockphoto

1.4 PERMAFROST IS THAWING

Permafrost is soil, rock or sediment that remains below 0 °C for two or more consecutive years. Forty years of records show the permafrost has recently begun to warm and thaw in many areas.

Permafrost underlies most of the Arctic land area. In parts of Siberia, it lies up to 1500 m thick. Within permafrost, water is frozen and ties together the soil, rock or sediment. This impermeable layer of ice below the surface shapes the landscape. It prevents water from draining away in summer, leading to high water levels and wet conditions in many areas. It has also provided a solid foundation on which to build, ever since humans first inhabited the Arctic.

Temperature records from boreholes going back four decades show that permafrost under Arctic lands has warmed by up to 2 °C, particularly in colder sites (typical permafrost temperatures range from -16 °C to just below 0 °C, depending on the

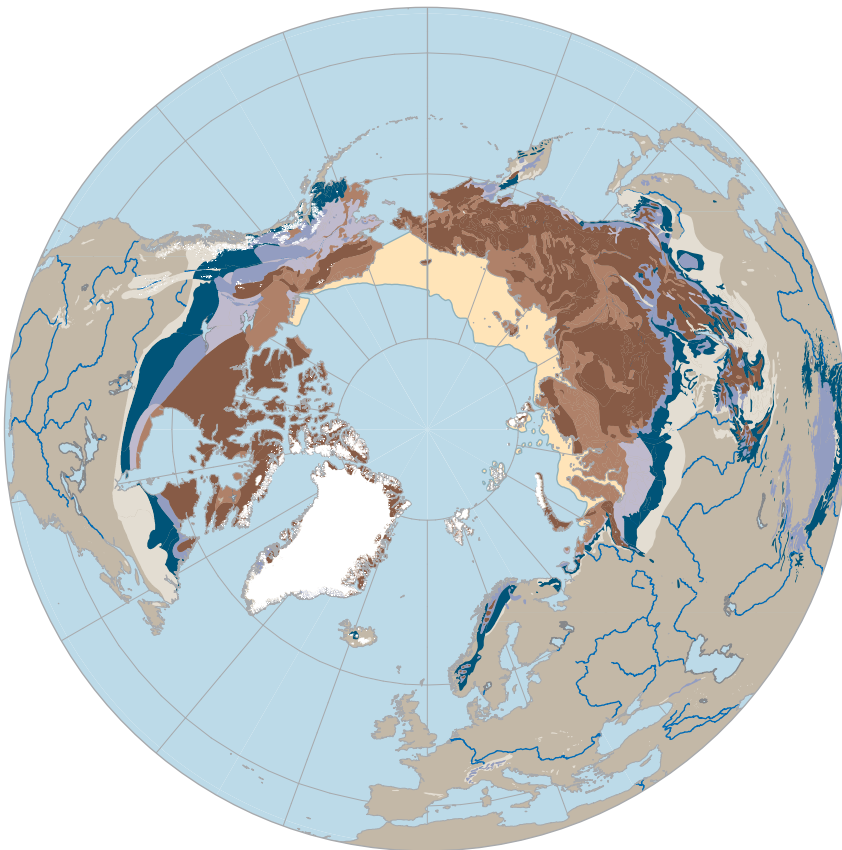
location). The upper few metres of permafrost have disappeared altogether since 1970 at several low Arctic sites, mainly on peatlands in Scandinavia, Russia and Canada. In some areas with a shallow layer of permafrost, it has thawed completely. The southern limit of permafrost moved northward by 30 to 80 km in western Russia between 1970 and 2005, and by 130 km in Quebec, during the last 50 years.

There is permafrost beneath the Arctic Ocean too. It is called subsea permafrost and mostly occurs where land was inundated by ocean at the end of the last ice age, 10 000 years ago. Its thawing could lead to large releases of methane to the atmosphere (see section 5.1).

The active layer above the permafrost is thickening in some areas

The layer above permafrost that regularly freezes and thaws (called the 'active layer') has become progressively thicker over the last 20 years in Scandinavia and Arctic Russia. It is now up to 20 cm thicker in some places. It has been measured at 168 sites around the Arctic since the early 1990s. In the North American Arctic, the active layer is relatively stable at most sites, but it has become thicker at some places in inland Alaska over the past five years.

Where is permafrost found?



Extent of permafrost, % of area

- Continuous (90-100%)
 - Thick overburden cover (>5-10 m)
 - Thin overburden cover (<5-10m) and exposed bedrock
- Discontinuous (50-90%)
 - Thick overburden cover (>5-10 m)
 - Thin overburden cover (<5-10m) and exposed bedrock
- Sporadic (10-50%)
- Isolated patches (0-10%)
- Subsea permafrost
- Arctic glaciers and ice sheets

TECHNICAL TERMS EXPLAINED

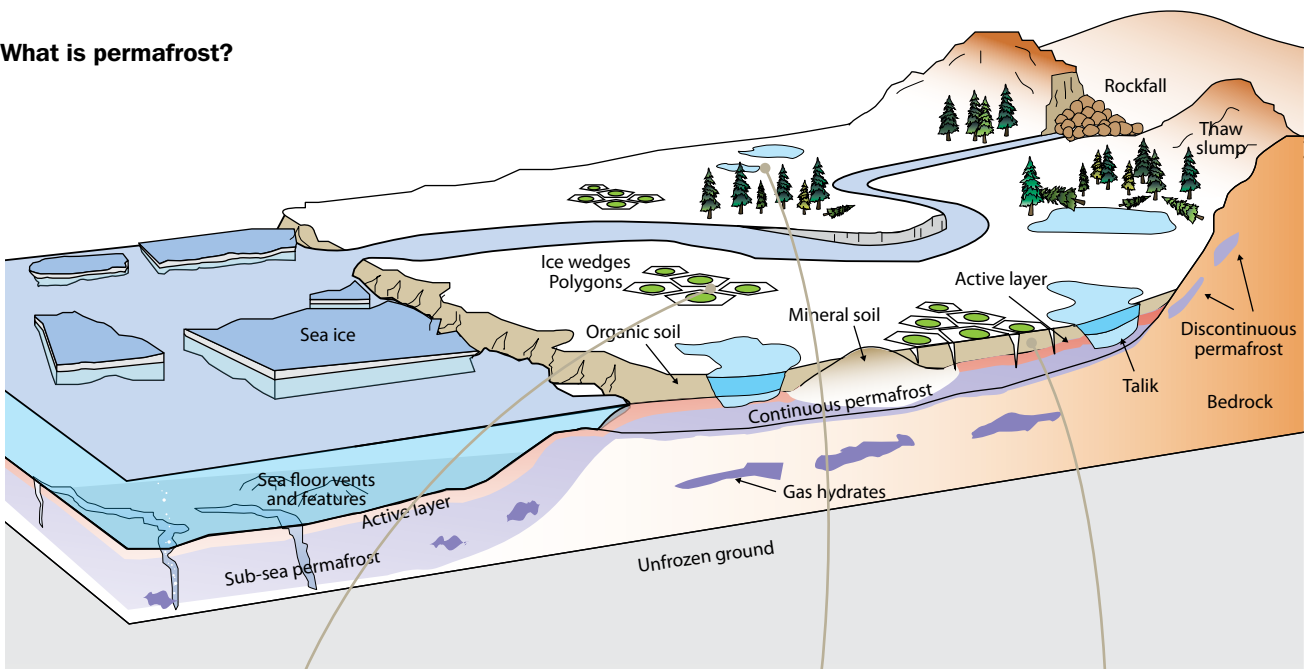
Permafrost

Soil, rock or sediment that remains frozen (below 0 °C) for two or more consecutive years.

Active layer

A layer up to several metres thick above the permafrost that thaws and re-freezes each year.

What is permafrost?



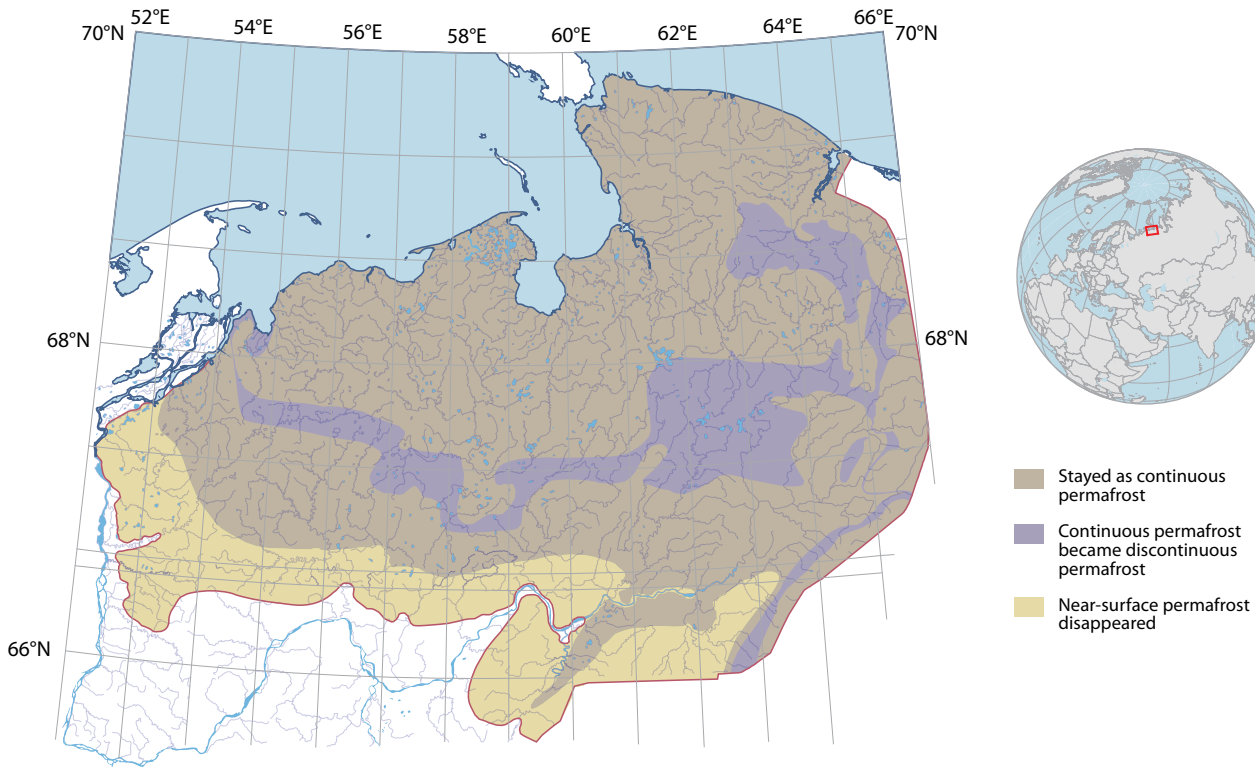
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The southern limit of permafrost moved northward by 30 to 80 km in western Russia, between 1970 and 2005.

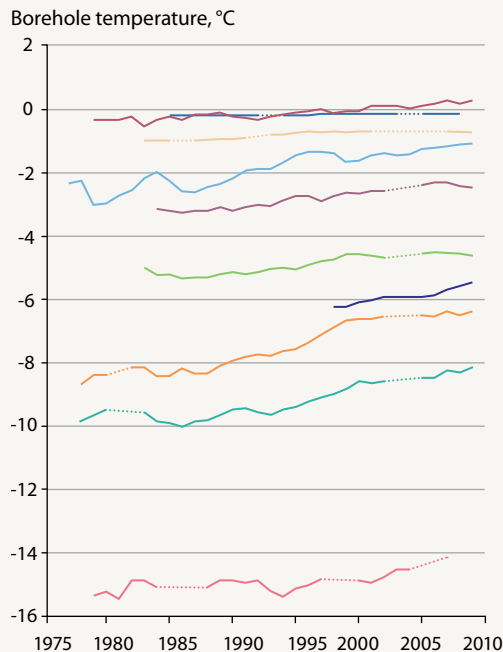
Changes in permafrost dynamics across north-western Russia between 1970 and 2005



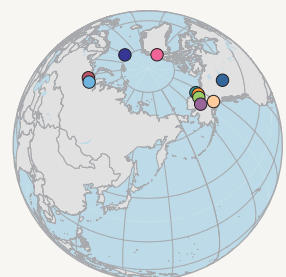
Permafrost temperatures are rising

The temperature of permafrost is measured at the shallowest depth where the temperature does not change throughout the year. This chart shows permafrost temperatures recorded at ten sites in Russia, Alaska, Canada and Svalbard. Most of these temperature sequences show warming, typically by between 0.5 and 2 °C over the last two to three decades, with greater temperature increases at colder sites. The range in permafrost temperatures between sites is 1 °C less than it was 30 years ago.

These changes are linked to changes in average air temperature. Over western North America, the rate of warming has slowed since 1998, which was the year with the highest air temperatures on record in that region.



- ZS-124 Russia
- 85-8A Canada
- Gulkana Alaska
- YA-1 Russia
- Oldman Alaska
- Happy Valley Alaska
- Svalbard
- Deadhorse Alaska
- West Dock Alaska
- Alert Canada





© Courtesy of Bo Elberling, Univ. of Copenhagen

During the International Polar Year (2007–2008), 300 new observatories were established across the Arctic to collect data on permafrost temperatures.

What happens when permafrost thaws?

- Methane and carbon dioxide emissions are enhanced (see section 5.1)
- The stability of buildings and infrastructure is threatened (see section 4.4)
- Land either dries out or becomes waterlogged (see section 4.1)
- Low lying coastal areas could collapse altogether (see section 4.4)

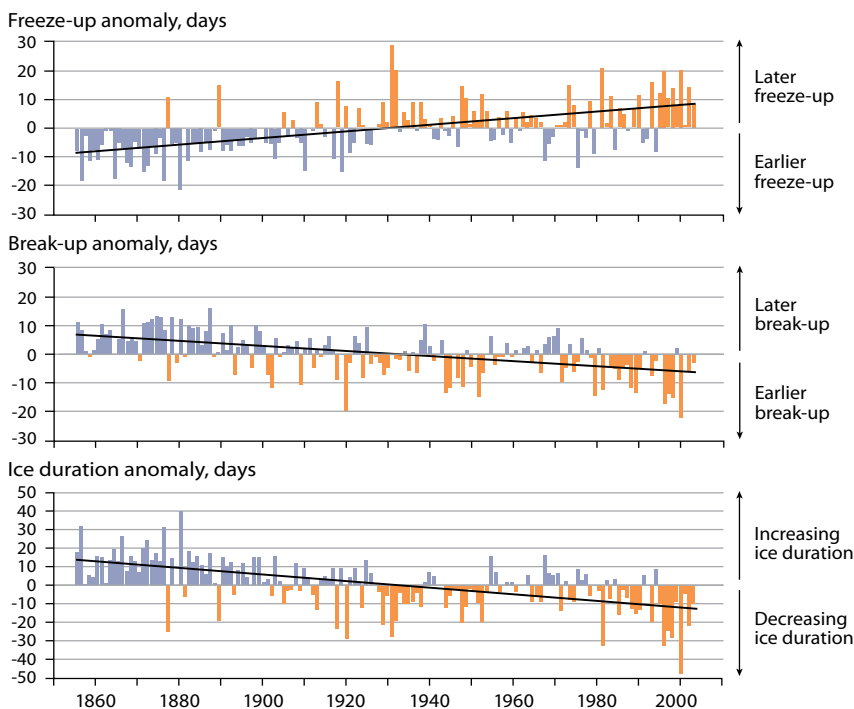


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1.5 LAKES AND RIVERS ARE LOSING ICE COVER

There are thousands of lakes, streams and rivers in the Arctic and many large river systems. They are interwoven into the terrestrial landscape, a complex network of freshwater flows and stores. All of them carry ice for some of the year, and most have ice cover for six to twelve months. The changing dynamics of this ice will have fundamental effects on the Arctic system.

Long-term change in ice on northern hemisphere lakes



Evidence of reduced ice cover on Arctic lakes and rivers comes from direct observations of the ice and from records of lake biology in sediments. Some very rapid changes have recently been observed for a group of lakes in the Canadian High Arctic.

For some northern hemisphere lakes freezing dates have become later and ice break-up dates earlier over the last 150 years. Lakes where both dates have been recorded were frozen over for an average of 17 fewer days in 2004/05 than they were 150 years before. But reliable long-term data sets are available only for a small number of lakes.

Data sets covering up to 100 years have been analyzed for larger groups of lakes and rivers in particular regions. They too show later freezing and earlier ice break-up, although there are regional differences.

For example, in the latter half of the 20th century, river ice has been breaking up significantly earlier on western North American rivers, but not on the eastern rivers in North America. This difference is linked to a persistent low pressure system over western North America that has caused warmer winters since the mid-1970s, and is related to large-scale ocean circulation patterns such as the Pacific Decadal Oscillation.

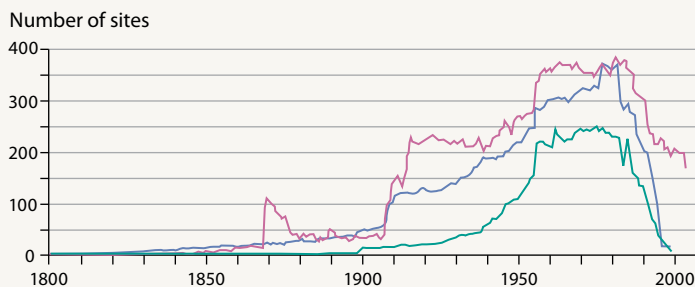
In Russia, the length of time lakes and rivers were covered with ice was between two and fourteen days less in the period 1980–2000, as compared to 1950–1979. The greatest reductions in ice-cover duration were found on lakes in Asian parts of Russia.

Rapid ice loss on Canadian High Arctic lakes

The most rapid reductions in the duration of ice cover on lakes have been observed for six lakes in the Canadian High Arctic, on which there has been ice cover for 1.75 fewer days each year on average, between 1985 and 2004. This means the lakes were ice-covered for over a month (33 days) less on average in 2004 than in 1985.

Declining observations of lake and river ice

Most of the information about long-term changes in lake and river ice comes from surface-based observations. These usually record dates of ice formation and break-up, and sometimes also ice thickness. Since the mid-1980s, the number of these surface-based observation systems has been in serious decline.



The chart above shows the number of sites included in three different databases of ice observations since 1800. The abrupt change is partly due to weather stations becoming automated and partly due to financial cutbacks. The effect is a discontinuity in the information on lake and river ice dynamics, which makes it very difficult to track long-term change.

Remote sensing from satellites has not yet replaced these surface observations at any national scale. The capability to monitor river and lake ice across the Arctic from satellites is expected to emerge in the future.

Algae in lake sediments indicate recent changes in ice cover

The sediments at the bottom of lakes preserve a record of the lake's history, because they hold the bodies of microscopic algae, called diatoms, that lived in the lake water. As ice-cover conditions on lakes change, so do the types of diatom living in the lake. Diatom communities in small to medium-sized lakes in the High Arctic Canada and Russia have changed over the last 100 years, in some cases dramatically. The changes indicate a strong reduction in ice cover.

For example, Sawtooth Lake, in the Sawtooth Mountains of central Ellesmere Island, has been rapidly colonized by microscopic algae since the 1920s, having had none for over 2000 years.



Some lakes in the Canadian High Arctic had ice cover for a month less by 2004 than they had in 1985.

What happens when lake ice disappears for longer periods?

- Lake waters become warmer during summer and autumn
- Methane and carbon dioxide emissions are enhanced (see section 5.1)
- Life in the lakes is exposed to different conditions, including higher levels of damaging ultraviolet radiation (see section 4.1)
- Transport links over river and lake ice are cut off for longer periods (see section 4.3)
- Changes to the way river ice breaks up can alter flooding regimes and entire landscapes (see section 4.1)



© Svetlana Privezentseva / Shutterstock.com

1.6 MOUNTAIN GLACIERS, ICE CAPS AND THE GREENLAND ICE SHEET ARE ALL DIMINISHING

There are 2930 000 km³ of ice locked up in the Greenland Ice Sheet, and about 250 000 km³ in ice caps and mountain glaciers in the Arctic. If they were all to melt, global sea level would rise by an estimated 7.9 m. Several sources of evidence indicate that these giant chunks of ice are diminishing in size as temperatures rise, although they are not expected to vanish altogether in the near future. It would take thousands of years for the Greenland Ice Sheet to melt entirely.



■ Pan-Arctic glaciers ■ Pan-Arctic glacier regions □ Greenland Ice Sheet — Arctic Circle



TECHNICAL TERMS EXPLAINED

Ice cap

A dome-shaped body of ice that entirely submerges the underlying rock and takes on its own shape. Covers less than 50 000 km² and is substantially smaller than an 'ice sheet'.

Glacier

A body of ice whose shape and size are controlled by bedrock – the ice is bounded by the edges of a valley, for example.

Gigatonne

One gigatonne (1 Gt) is 1 billion tonnes (1 000 000 000 t), or 1 trillion kilograms (1 000 000 000 000 kg).

A gigatonne of ice is 10% larger than a cubic kilometre (i.e., 1.1 km³).

How do we know how much ice is being lost?

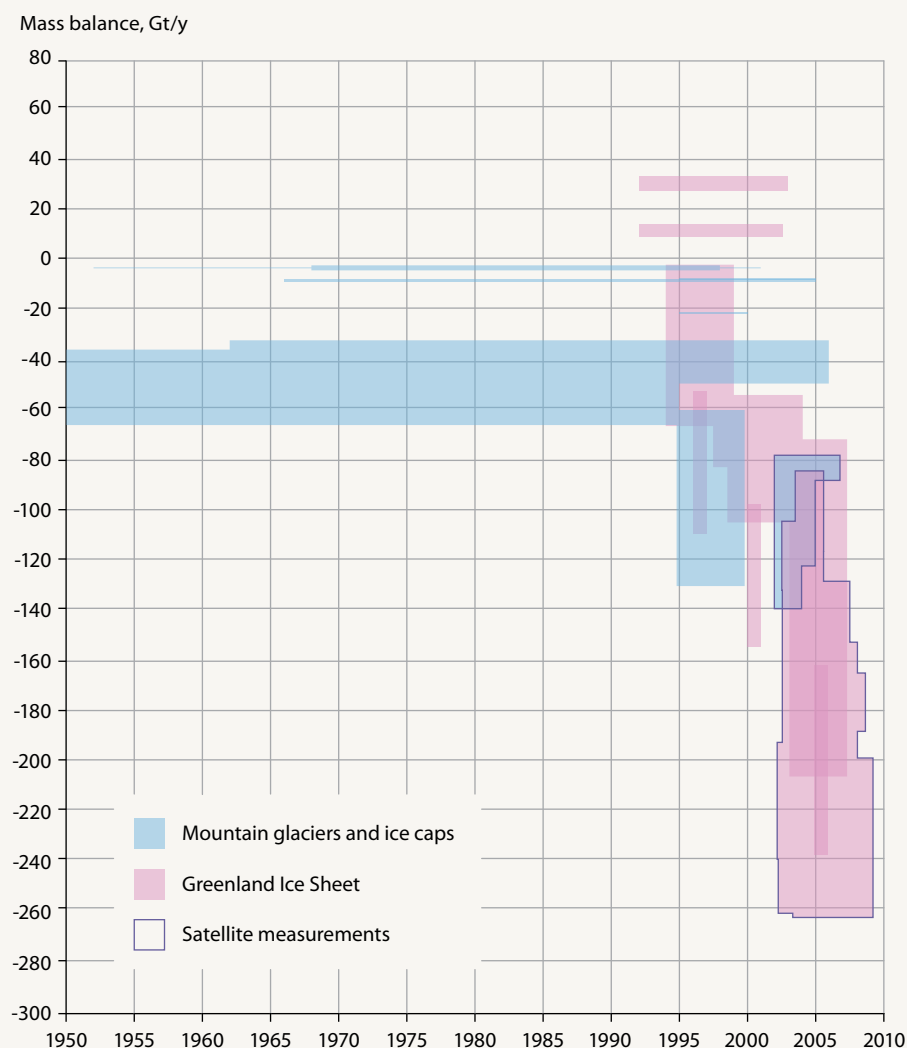
There are three ways to measure the change in amount of ice in a glacier or ice sheet.

- **Mass budget.** This approach directly measures the amounts of ice being added (as snowfall) and lost (as meltwater and icebergs) and uses them to calculate how much the total amount of ice is changing.
- **Surface altimetry.** 'Altimetry' uses reflected laser or radar beams from aircraft or satellites to map the exact height of the ice. Changes in the height of the ice over time are used to work out how much ice is held altogether, based on our knowledge of the density of ice.
- **Changes in gravity.** In 2002, a pair of satellites were launched in a mission called GRACE (Gravity Recovery and Climate Experiment). The GRACE satellites travel the same orbit 200 km apart and closely monitor the distance between themselves. The speed they travel is affected by the

Earth's gravity field, which is related to the distribution of solid mass (ice and rock) at the surface below the position of each of the satellites. Changes in the distance between the two satellites are used to calculate the actual mass of ice in different places, with fairly coarse resolution accurate to hundreds of kilometres. Changes over time are used to identify changes in ice mass.

As well as these methods, maps, aerial photographs and satellite images can be compared to show how areas covered by ice caps and glaciers have changed over time. Photographic records go back to the 1950s in the Canadian Arctic and maps can be even older. In Greenland there is photographic documentation of glacier margins from the 19th century. Landforms left behind by retreating glaciers also show how the extent of these glaciers has changed over time.

Ice loss from Arctic mountain glaciers, ice caps and the Greenland Ice Sheet



Retreating glaciers

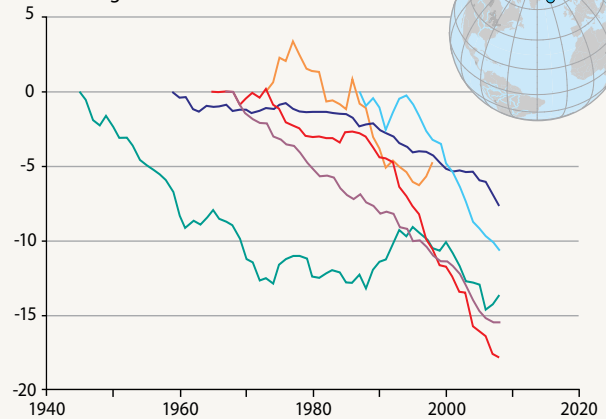
Changes in the size of hundreds of Arctic mountain glaciers and ice caps have been measured (photo below shows a time-lapse camera overlooking the terminus of the tidewater glacier, Kronebreen, in Svalbard). Nearly all have retreated over the past 100 years and the rate of loss has increased during the last decade across most regions. The overall mass of ice held in mountain glaciers has fallen since recording began about 60 years ago. Over half of the ice loss has taken place in southern Alaska and the Canadian Arctic and the rate of mass loss in Icelandic glaciers has strongly increased. In the Canadian Arctic, the average net loss of ice has increased three times since 2005.

When considered together, the total loss of ice from mountain glaciers and ice caps in the Arctic probably exceeded 150 Gt/y since 2000. This is not far off the estimated amount being lost from the Greenland Ice Sheet each year (~200 Gt/y), although the ice sheet is almost twelve times larger.

The mountain glaciers shown in the graph are those with the longest continuous record of ice mass for each Arctic region. These numbers are calculated using the mass budget

approach (see box on previous page). All six glaciers show a net loss of ice over time, and more rapid thinning after about 1990. The recorded periods of ice loss match increases in the length of the summer melt period and higher air temperatures.

Cumulative area-averaged mass balance, thousand kg/m²





© Lars Witting / ARC-PIC.COM

Net loss of ice from the Greenland Ice Sheet is now estimated to be four times faster than it was before the year 2000.

The Greenland Ice Sheet is the largest body of freshwater ice in the northern hemisphere. Ice is lost either at the surface, where it is melted by warm air and winds, or from the edge, where it breaks off as chunks of solid ice or flows into the ocean as meltwater. Rates of both types of loss from the Greenland Ice Sheet have increased.

Ice comes off the Greenland Ice Sheet in a series of fast-flowing glaciers that discharge to the ocean through fjords along the coast of Greenland. These glaciers have increased their rate of flow – some doubled their speed between 1995 and 2000. The trigger for these changes is thought to have been warming of the ocean water that is in contact with the outflowing end of these glaciers.

One well-known glacier, the one terminating in the Ilulissat Ice Fjord (*Sermeq Kujalleq* in Greenlandic), which drains ice from around 7% of the entire ice sheet, has doubled its flow rate and the ice front has retreated 15 km in the past eight years.

The amount of ice leaving the Greenland Ice Sheet as solid icebergs is estimated to have risen from 320 Gt in 1995 to 421 Gt in 2005, a jump of 30% in 10 years.

Surface melt occurs along the margin of the Greenland coast and has increased significantly over the past 10 years. The surface is lowering by up to 1 m each year along the margin.

To calculate the net loss of ice from the Greenland Ice Sheet, these measures of ice loss are offset against ice gains caused by snow falling onto the ice sheet's surface. The height of the Greenland Ice Sheet at its centre, measured from satellites, has risen slightly recently – probably reflecting an increase in snowfall – but this increase is more than outweighed by the increased loss of ice due to melting and ice discharge at lower altitudes and along the edges.

Recent measurements all show that the Greenland Ice Sheet is diminishing

When mass budgets were first calculated for the Greenland Ice Sheet in the 1960s, the ice sheet appeared to be in balance. Those early measurements were very uncertain, but they showed similar amounts of ice being added and lost each year. The latest measurements tell a very different story, with large net losses of ice every year.

The box on page 21 shows how estimates of net mass loss from the Greenland Ice Sheet have developed over the last 20 years. The net loss of ice has increased from an average estimate of 50 (± 50) Gt/y from 1995–2000 to 205 (± 50) Gt/y in 2005–2006. This is equivalent to 205 000 000 000 000 litres of freshwater, enough to cover the total freshwater withdrawal of the United States for five months.

What happens when land ice melts?

- Freshwater is added to the ocean (see section 5.1)
- Sea level rises globally (see section 5.2)
- Marine food chains are altered (see section 4.1)
- Opportunities for tourism and hydroelectric power generation change (see sections 4.2 and 4.3)
- New land areas are exposed (see section 4.2)



1.7 SUMMER SEA-ICE COVER HAS DECLINED DRAMATICALLY

The decline in Arctic summer sea-ice extent has accelerated since 2000 and the ice cover as a whole is now thinning.

Arctic Ocean sea ice is dynamic, expanding in the winter and contracting in the summer. The ice cover can be as much as three times larger in winter than in summer.

The extent of the sea ice remaining in the Arctic Ocean at the end of summer (in September) has been shrinking for the past 30 years. This change has accelerated since 2000 – observations show that the decline has been faster in the last ten years than in the previous twenty years.

In 2007, September sea-ice extent hit a record minimum³ since continuous satellite monitoring began in 1979. In fact, it has been at or near record low levels every year since 2001. The average area of sea ice in September is now about one third smaller than the average summer sea-ice cover from 1979 to 2000. It has declined faster than projected in global climate

models used by the Intergovernmental Panel on Climate Change.

The extent of the ice cover in winter has also declined, although less rapidly than during summer. The March sea-ice extent has declined by about 10% over the past 32 years.

Sea ice has started to melt earlier in spring. It is estimated that the melt began an average of 13 days earlier in the 2000s than it did in the 1980s. Across the entire Arctic, the length of the sea-ice melt season has increased by around 20 days since the 1980s.

The extent of Arctic sea ice has been consistently tracked from satellites since 1979.

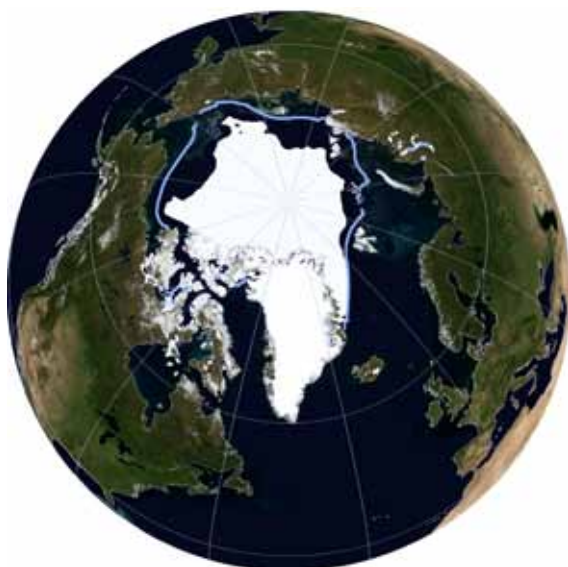
³ A new record minimum was observed in 2012.



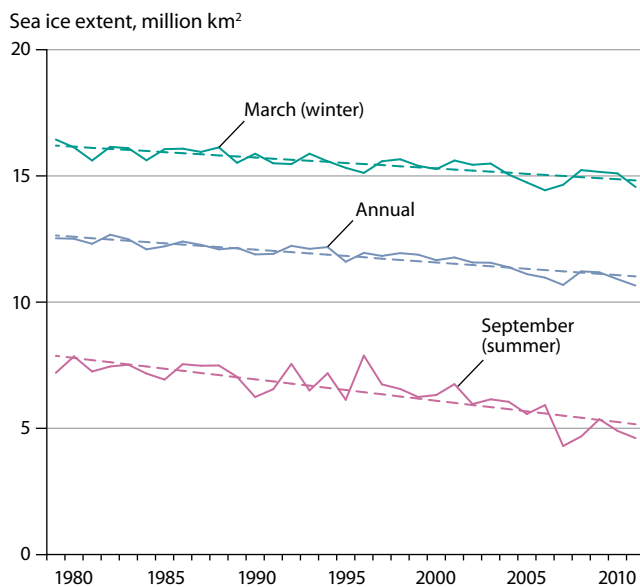
© Paul Souders / Corbis

In September 2007, the extent of the sea ice on the Arctic Ocean hit a record minimum.

September 2011 monthly sea-ice extent (white) and 1979–2000 September average ice-edge location (blue line)



Average sea-ice extent in March (end of winter), September (end of summer), and annually for 1979–2010

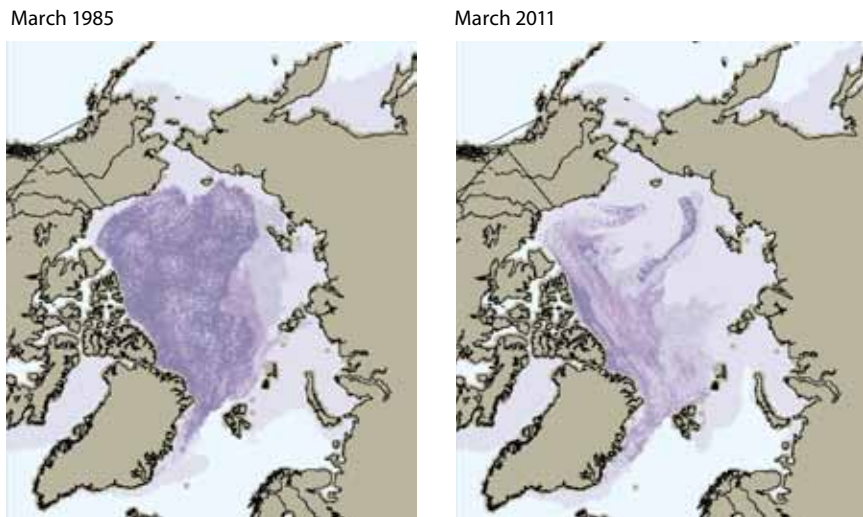
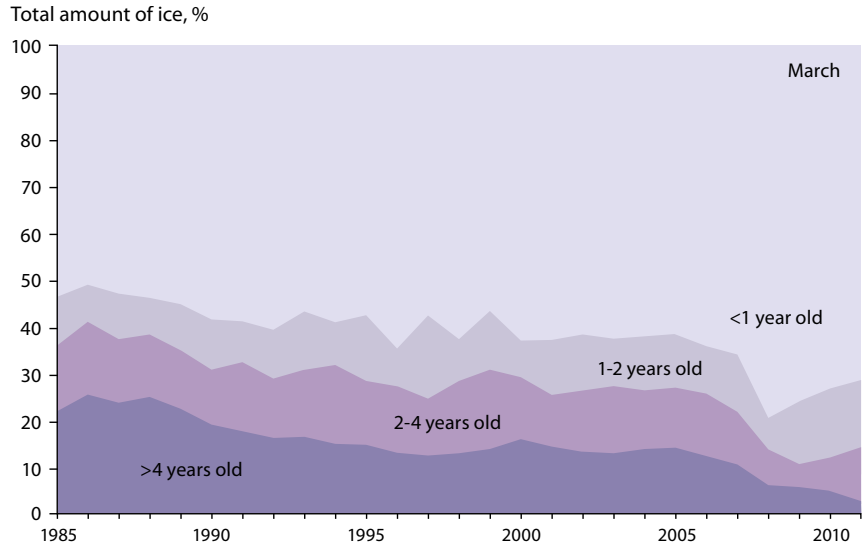


Changes in the age of sea ice

One of the most fundamental changes in the Arctic Ocean sea ice over the last decade has been a decrease in the amount of older ice. Ice that has survived at least one melt season, called multi-year ice, becomes thicker each year as new ice forms underneath it. In contrast, first-year ice, which develops through the winter and then melts completely during summer is relatively thin, making it more sensitive to changes in winds and air temperature.

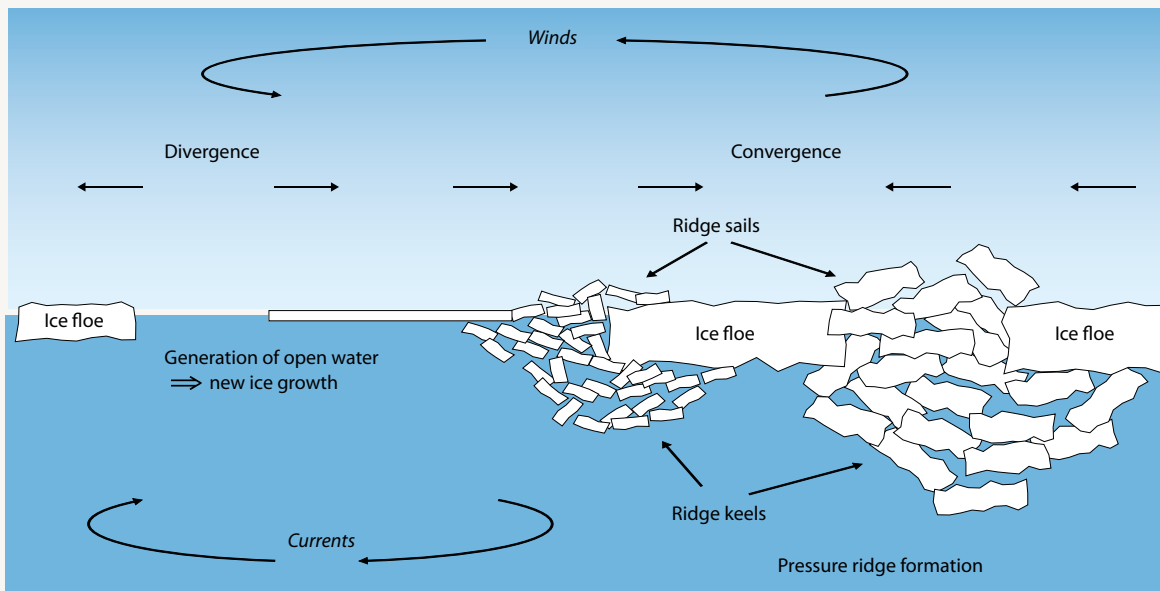
There was 42% less multi-year ice at the end of the 2008 summer melt season than there was in 2005. The volume of multi-year ice in winter shrank between 2005 and 2008, while the first-year ice gained volume, almost compensating for the loss of multi-year ice. First-year ice covered more than two-thirds of the Arctic Ocean in 2007.

These trends set the stage for further rapid declines in sea ice in future summers (see section 3.5).



Sea ice thickness

Sea ice is not a uniform layer. Its thickness varies considerably. How thick the ice is depends on a wide range of factors including wind, ocean currents and sea and air surface temperatures. Sea ice is covered by snow during the autumn, winter and spring. In summer, it has liquid water and melt ponds on its surface, which can ice over during the night.





Sea ice over the Arctic Ocean is thinning

New techniques developed over the last decade have allowed the measurement of the extent, age and thickness of sea ice more accurately than ever before.

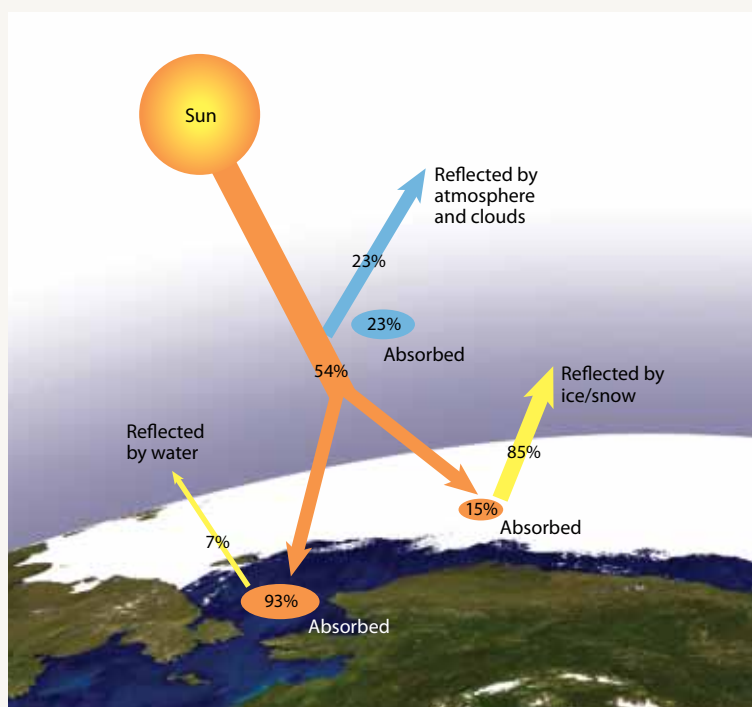
Measurements from satellites show that Arctic sea ice has rapidly thinned. Average winter ice thickness changed from 3.64 m in 1980 to 1.89 m during the last winter of measurements in 2008. This is a decrease of 1.75 m – almost half. Between 2003 and 2008, the ice cover thinned by an average of 0.2 m each year.

Changes were greatest over regions of multi-year ice, which became 0.6 m thinner each year on average. First-year ice, which is around 2 m thick in mid-winter, was not consistently thinning.

Why is sea ice declining?

Many factors have contributed to the decline in sea-ice cover, including the following processes:

- Open water absorbs heat from the sun more readily than sea ice, increasing the surface temperature of the ocean. This delays the start of ice formation in the autumn and winter, and contributes to loss of ice during summer.
- Warmer ocean currents entering the Arctic Ocean from the Pacific melt the sea ice from underneath. Recent research has indicated that they may play a greater role in the decline of ice cover than was previously thought.
- Increased ice export from the Arctic Ocean. This is linked to wind patterns and ocean currents associated with the recently described Arctic Rapid Change Pattern (see page 32).



What happens when summer sea-ice cover declines?

- More heat is absorbed by ocean areas where there is no sea ice, causing the water to warm (see section 2.2)
- More seawater can evaporate into the air, potentially changing local snowfall patterns (see section 1.3)
- Conditions in the ocean change and marine ecosystems become either more or less productive (see section 4.1)
- Animals that live, breed or in other ways depend on the ice or ice edges lose habitat (see section 4.1)
- Shipping routes across the Arctic Ocean, such as the Northern Sea Route, will be open for longer periods each year (see section 5.3)



PART 2:

WHY THE ARCTIC CRYOSPHERE IS CHANGING

Global climate change is the main driver of change in the Arctic cryosphere. Temperatures are increasing worldwide, mainly in response to accumulation of greenhouse gases such as carbon dioxide in the atmosphere. The Arctic has warmed twice as much as the rest of the planet since 1980, so it is not surprising that Arctic bodies of ice are melting. Parts of the Arctic cryosphere are interacting with other aspects of the climate to enhance this warming. The Arctic will experience the largest future increases in temperature on the planet, so the changes observed today are going to continue or accelerate.



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The Arctic climate is changing

- Higher surface air temperatures, and previously unseen weather patterns and ocean currents are driving changes in the Arctic cryosphere.
- The last six years (2005–2010) have been the warmest period ever recorded in the Arctic.
- Recent reconstructions based on lake sediments, tree rings and ice cores indicate that Arctic summer temperatures have been higher in the past few decades than at any time in the past 2000 years.
- There has been a modest increase in rain and snowfall over Arctic land areas since 1950. The five wettest years on record have all been in the past decade.
- Previously unknown inflows of warm water have been entering the Arctic Ocean from the Pacific and the Atlantic. These could be linked to the rapid loss of sea ice.
- Recent changes cannot be ascribed solely to recognized patterns of climate variability such as the Pacific Decadal Oscillation (see page 33). A previously unseen weather pattern has been observed over the Arctic by several groups of scientists since 2006.

The cryosphere interacts with other aspects of climate

- There is now evidence that two components of the Arctic cryosphere – snow and sea ice – are interacting with other parts of the climate system to accelerate warming.
- The greatest increase in temperature of the lower atmosphere has happened in autumn, in regions where sea ice has disappeared at the end of summer. This suggests that the absence of sea ice is causing further warming of air, because the sea absorbs more heat during the summer.
- The number of days with snow cover has changed most in the spring. This implies a feedback effect in which the surface absorbs more energy and warms more once snow has melted.

2.1 THE ARCTIC CLIMATE IS CHANGING

Temperatures recorded in the Arctic in the years since 2005 are higher than any on instrumental record. Rain and snowfall have increased, and previously unknown weather patterns and ocean currents have been observed. These changes are driving all the physical changes in the cryosphere.

Climate is the general pattern of weather experienced in a place over a long period, usually 30 years. Temperatures, rain or snowfall and wind patterns are usually predictable on these time scales. Climate change is when general patterns move away from expectations that have been built up by observation over decades or centuries.

Continuous instrumental records of Arctic air temperatures began around 1880. At most locations, temperatures measured since 2005 have been higher than at any time in the historical record. Annual average temperatures across the whole Arctic have been consistently around 1.5 °C or more higher than they were from 1961 to 1990. These temperatures exceed even those experienced during a warm period in the 1930s and 1940s.

The increase in average temperature since 1980 has been twice as high over the Arctic as it has been over the rest of the world.

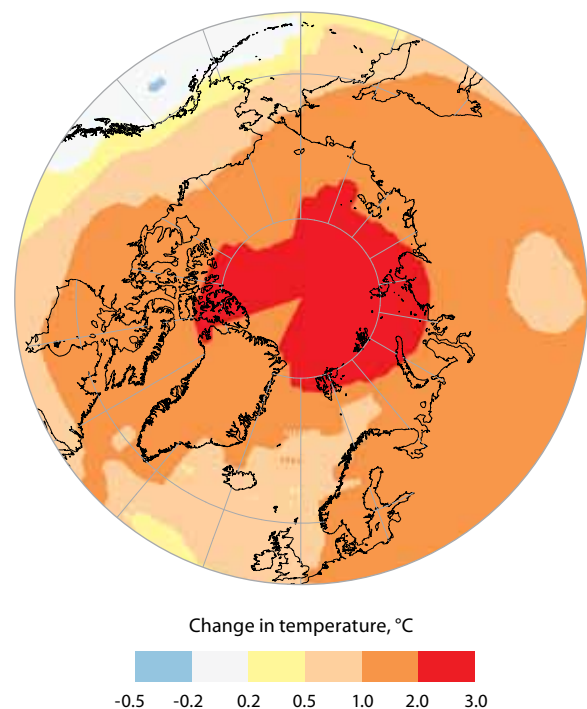
In attributing the cause of warming in the Arctic, SWIPA refers to the findings of the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC). This states that “Most of the observed increase in global average temperatures since the mid-20th century is very likely [$> 90\%$ probability] due to the observed increase in anthropogenic GHG [greenhouse gas] concentrations”.

The temperature changes are not uniform. Warming is greatest in autumn and early winter over the Arctic Ocean (see section 2.2), where temperatures over the past ten years have been over 4 °C warmer than the average for 1951–2000. This amount of warming is stronger than temperature increases at any time of year anywhere else on Earth.

Long-term cooling trend reversed

Direct measurements of temperatures in the Arctic only go back to 1880, but summer temperatures going back 2000 years can be estimated from biological remains found in lake sediments, from gas concentrations in air trapped in shallow ice cores, and from annual growth rings in tree trunks. Analysis of these measurements from across the Arctic (see the lower figure on the facing page) shows that a trend of slow summer cooling occurring until around 1800 AD has been dramatically reversed.

Change in recent surface air temperature (2005–2009) relative to the long-term mean (1951–2000)



The very long view

Change on this scale is not unprecedented in the Arctic. During Earth's history, there have been warm periods with no ice at all at the poles, and cold periods with thick ice over much of the planet. Analyzing air trapped in deep ice cores tells scientists that conditions in the Arctic have varied greatly over the last 125 000 years.

During the extra cold spell 25 000 to 14 000 years ago, during the most recent ice age, temperatures in Greenland are believed to have been 25 °C lower than today. Sea level was then 120 m lower. In that icy time there were some very rapid warming events, when average temperatures rose by 10 to 15 °C in a few decades. These relatively sudden changes show the potential for the Arctic cryosphere to change very rapidly.

In the light of geological history, the recent warming of 1.5 °C seems small. However, it represents a substantial change from the last 12 000 years (the period of human civilization), which has been a period of unusual temperature stability in the Arctic.

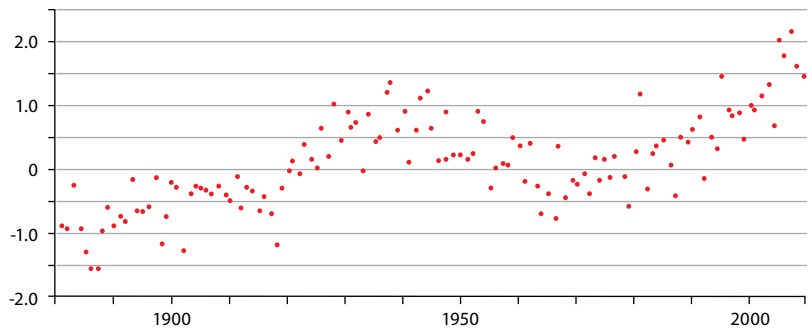


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Surface air temperatures measured in the Arctic since 2005 have been higher than for any five-year period in the last 130 years.

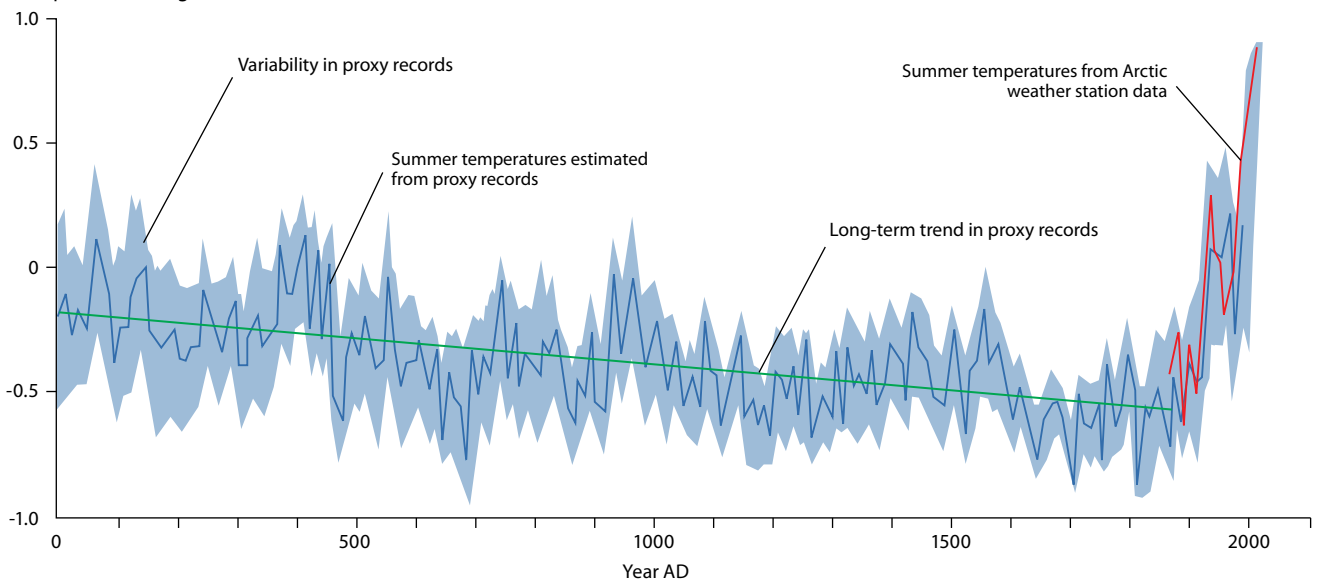
Air temperature records from land-based weather stations in the Arctic

Temperature change relative to the 1961–1990 mean, °C



Long-term change in summer Arctic air temperatures, as estimated from lake sediments, ice cores and tree rings ('proxy' records)

Temperature change relative to the 1961–1990 mean, °C



Increased rain and snowfall

There has been a modest increase in rain and snowfall over Arctic land areas since 1950, but measurements are not very complete. Change is hard to discern because there is large variability between years.

Some of the rain and snow falling over land ends up as water in rivers. The total amount of water flowing out of the six largest rivers in the Eurasian Arctic each year has increased by about 10% since 1935. The amount flowing out of the five largest American Arctic rivers has also increased, although this has been measured only since 1970.

The five wettest years since 1950 (in terms of rainfall, snowfall and river discharge) have all been in the past decade.

Storms

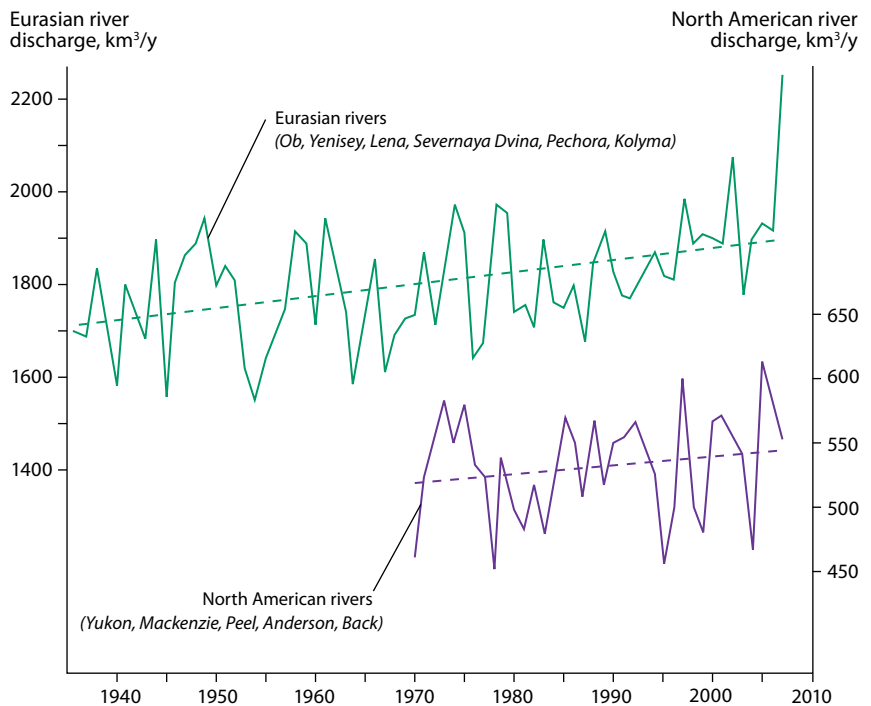
Storm activity appears to have increased at some locations, such as on the north coast of Alaska, but there are no analyses of storminess across the entire Arctic.

Climate patterns and ocean currents

Arctic weather is strongly influenced by two climate patterns known to oscillate between different sets of conditions: an air pressure pattern known as the Arctic Oscillation, and a pattern of sea-surface temperature called the Pacific Decadal Oscillation (see box on facing page). Neither of these drivers can explain the warming observed in Arctic air or sea temperatures in recent years.

A previously unseen weather pattern has been observed over the Arctic by several groups of scientists since

Trends in river discharge to the Arctic Ocean



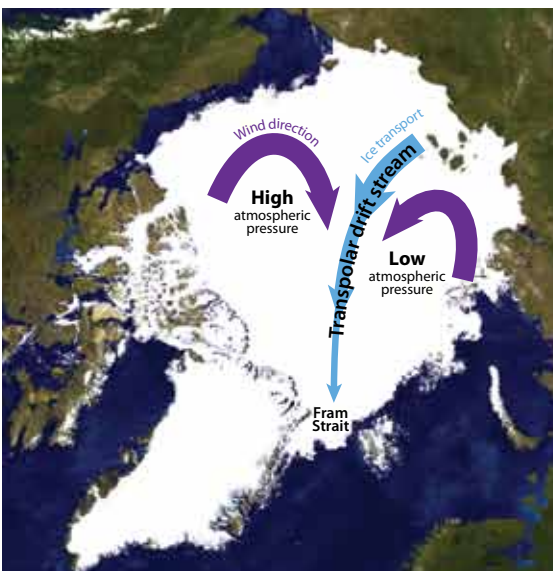
2006. Some have called it the 'Arctic Rapid Change Pattern' (others term it a 'dipole anomaly'). It is characterized by low air pressure developing during the winter months off the north Russian coast and higher pressure on the opposite side of the Arctic Ocean, over Greenland and north of Canada. These conditions create winds that blow across the North Pole from Greenland towards Russia, weakening the ocean circulation in the Beaufort Gyre.

The Beaufort Gyre is a slowly spinning whirl of cold, relatively fresh water and sea ice, partly driven by winds. It tends to hold sea ice in place for several years. Weaken the Beaufort Gyre and multi-year sea ice is more inclined to

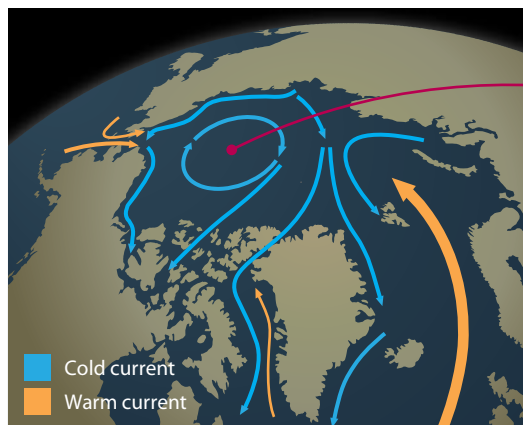
spill out through the Fram Strait into the North Atlantic, melting as it goes.

This appears to be happening. Rapid export of sea ice from the Arctic Ocean to the Atlantic has been observed in recent years.

At the same time, unusual flows of warm water have been measured entering the Arctic Ocean from both the Pacific and Atlantic Oceans. Although warmer, these water masses sink below the colder Arctic water, because they are saltier and therefore heavier. How they affect the behavior of Arctic Ocean circulations and sea ice is not known.



Pulses of warm water entering the Arctic Ocean from the Pacific may be contributing to the rapid reduction in summer sea-ice extent.



Beaufort Gyre – A circulating current of cold, relatively fresh water that traps sea ice.

CLIMATE PATTERNS THAT AFFECT THE ARCTIC

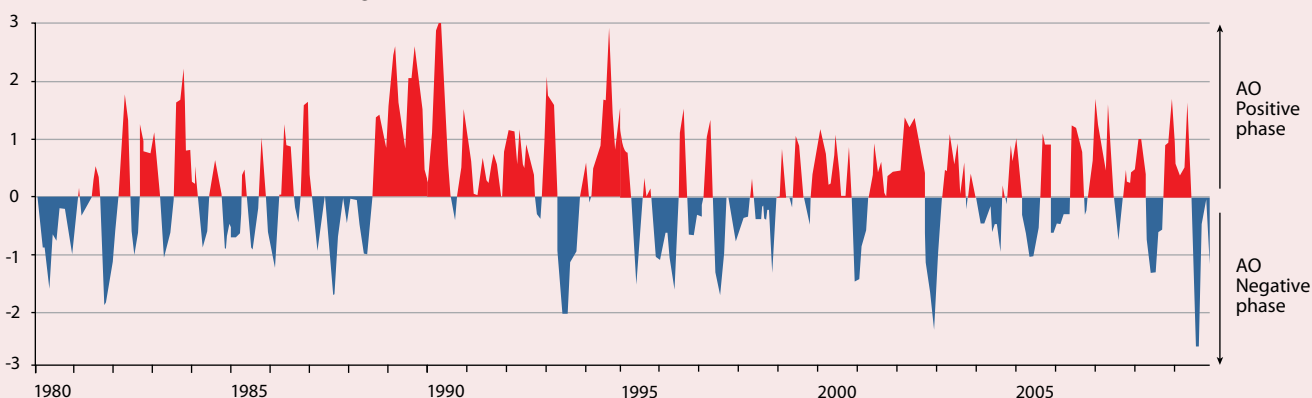
The Arctic Oscillation

The Arctic Oscillation is characterized by different air pressure over the High Arctic relative to lower northern latitudes. In the positive phase, low pressure over the High Arctic pulls warmer, wetter air northwards from lower latitudes. This pattern predominated during the 1980s and early 1990s, and could have partly explained rising temperatures over the Arctic during that time. The warming was strongest over the Eurasian Arctic, consistent with wind patterns associated with the positive phase of the Arctic Oscillation.

Since 1997, the Arctic Oscillation has frequently switched between positive and negative phases. In the negative

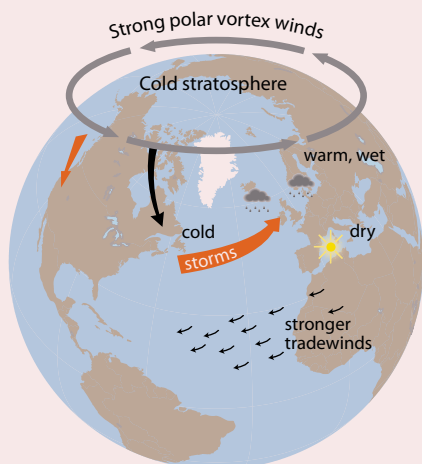
phase, pressure is high in the far North, keeping the Arctic cold and dry, and pushing frigid air southwards over North America and Eurasia. Despite frequent occurrences of this pattern, overall Arctic temperatures have continued to rise. In December 2009 and January 2010, and again in December 2010 and January 2011, the Arctic Oscillation was in a very negative mode, indicating higher pressure in the High Arctic. Central Europe was extremely cold, but the High Arctic stayed relatively warm. So increasingly high Arctic temperatures observed since 2005 cannot be explained by the Arctic Oscillation.

AO index (standardized 3-month running mean)



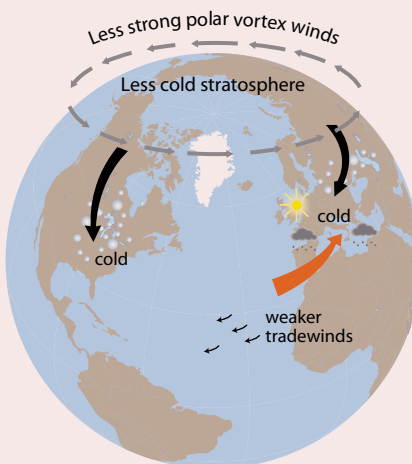
AO Positive Phase

Higher-pressure air mass over North America, Europe and Asia confines extremely cold air to Arctic.



AO Negative Phase

Air pressure systems weaken allowing colder air to move south and warmer air to move north.



The Pacific Decadal Oscillation

The Pacific Decadal Oscillation is characterized by differences in the temperature of the surface of the Pacific Ocean. They can last a decade or more, and have a strong influence on winter temperatures in northwest North America. From the mid-1970s until the most recent decade, the warmer northeastern Pacific Ocean was associated with higher temperatures over Alaska and northwest Canada. The same pattern is linked to lower temperatures in eastern Siberia. The over-riding trend of rising temperatures across the Arctic, particularly over the Arctic Ocean, cannot be explained in terms of the Pacific Decadal Oscillation.

Recent changes unexplained

The Arctic climate is influenced by some large-scale patterns of weather and ocean circulation that are relatively well understood, but these cannot explain recent temperature increases. Since 2006, new recurring weather patterns and ocean currents within the Arctic region have been observed that seem linked to the rapid melting of sea ice. These could have far-reaching effects.



2.2 THE CRYOSPHERE INTERACTS WITH OTHER ASPECTS OF CLIMATE

Ice and snow make such a big difference to the physical environment in the Arctic that they affect other aspects of climate, such as temperature. Changes in the amount of ice and snow can cause cooling or warming by a variety of mechanisms. These interactions between the cryosphere and other parts of the climate system are called feedbacks. They are the least well-understood aspects of the cryosphere system.

A feedback is when a change in one part of a system drives a change in another part, which then affects the first part of the system. In this case, the climate drives a change in the cryosphere and the cryosphere's response in turn changes that aspect of climate. Positive feedbacks enhance further change. Negative feedbacks inhibit further change.

An example of a positive feedback is when snow cover decreases, the surface of the Earth becomes darker and absorbs more heat. This enhances the warming that is melting the snow.

An example of a negative feedback is when less snow cover, caused by warming, means plants get a longer growing season. Greater plant growth means more carbon dioxide is absorbed, which cools the planet by taking that greenhouse gas out of the atmosphere.

There are more than 30 recognized feedback mechanisms at play in the Arctic. Of those expected to have strong effects, seven are positive, leading to further warming, and just one is negative, leading to cooling.

Feedbacks are of concern because their effects are difficult to predict. They have the potential to alter the rate or even the direction of climate change and associated changes in the cryosphere. The intensities of different feedbacks in the climate system are not yet well quantified, either within the Arctic or globally. It is not clear when they will happen or what the overall effect will be.

There is now evidence that two components of the Arctic cryosphere – snow and sea ice – are amplifying warming trends in the climate system to accelerate warming.

TECHNICAL TERMS EXPLAINED

Positive feedback

When warming causes a change that creates further warming, or cooling causes a change that creates further cooling. Positive feedbacks magnify or amplify change.

Negative feedback

When warming causes a change that creates cooling, or cooling causes a change that creates warming. Negative feedbacks slow or inhibit change.



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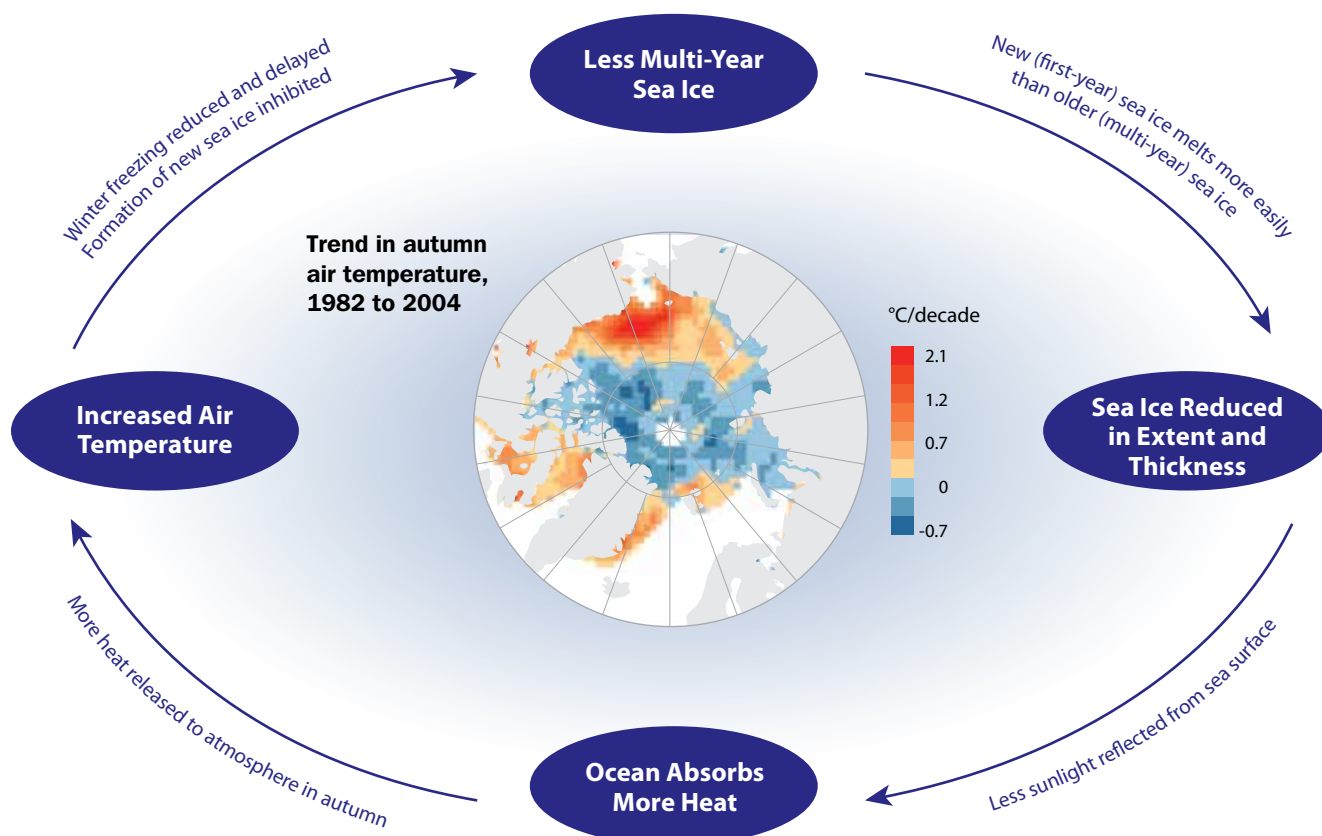
Snow is melting faster in the spring

Decreases in snow-cover duration are much more widespread and marked in the spring than in the autumn. This is exactly what would be expected, because the Arctic is seasonally becoming warmer at this time. When warming is taking place, some loss of snow cover accelerates the warming because the surface is darker. This means more snow is lost more quickly. In autumn, when the Arctic is becoming colder and darker, the effect of changes in snow cover on temperature is less.

Air temperature linked to melting sea ice

The greatest increases in temperature have happened in regions where sea ice has disappeared at the end of summer. This strongly suggests that the reduction in sea ice is itself affecting the air temperature. The surface of the sea absorbs more energy from the sun when it is not covered by ice. The warmer sea warms the air more, especially in late summer, which in turn inhibits ice growth the following winter. This evidence of a positive feedback effect means that complete melting of Arctic sea ice in summer is likely in the next few decades if warming continues as expected.

The direct observation of a positive feedback occurring between melting sea ice and rising air temperatures over the Arctic Ocean is a very important scientific development.





PART 3:

MORE CHANGE IS EXPECTED

The Arctic cryosphere is changing. Large bodies of ice are melting faster than they were before 2000 and there is evidence of ice and snow interacting with the climate to accelerate the change. Global climate models project that temperatures will continue to rise faster in the Arctic than elsewhere in the world. The observed changes in the Arctic cryosphere are all expected to continue during the 21st century, and may even accelerate.



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- Projections of Arctic snow and ice conditions are uncertain. This is partly because interactions between snow, ice and the atmosphere are not fully understood, nor represented the same way in different climate models. Also, future greenhouse gas emissions to the atmosphere are uncertain.
- The Arctic will experience the largest future increases in temperature on the planet. Average Arctic autumn-winter temperatures are projected to increase by between 3 and 6 °C by 2080.
- Arctic rain and snowfall are projected to increase in all seasons, but mostly in winter.
- Maximum snow depth is projected to increase over many areas by 2050, but snow will tend to lie on the ground for less time each year due to earlier melting in spring.
- The Arctic Ocean is projected to become nearly ice-free in summer within this century, likely within the next 30 to 40 years.
- Models project continued thawing of permafrost.
- The total volume of Arctic glaciers is projected to decline 13–36% by 2100.

WHERE IN THE ARCTIC?

*This page gives **SELECTED EXAMPLES** of projected future changes, where they are expected to affect specific regions.*

1 The greatest shortening of snow cover is projected over **Alaska** and **northern Scandinavia** where snow-cover duration is expected to be 30–40% less than it is today by 2050.

2 The greatest increases in maximum snow accumulation over the next 50 years are projected over **Siberia** (increase by 15–30%).

3 In Russia, ground temperature increases of 0.6 to 1 °C are projected to occur by 2020.

4 Regional models of **lakes between 40° and 75° N** indicate that in 2040–2079, lakes will be ice-covered for between 15 and 50 fewer days during the year.





- 5 Projected temperature changes along the length of the four largest Arctic rivers – the **Mackenzie in Canada and the Yenisey, Lena and Ob in Russia** – suggest that the length of time they remain frozen will progressively decrease between now and 2100.
- 6 Mountain glaciers in **northeastern Siberia** are projected to lose 78% of their area by 2070.
- 7 The greatest increases in rain and snowfall are projected over northeast **Greenland** followed by coastal **Siberia** and the **Canadian Arctic Archipelago**.



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3.1 MODELLING THE FUTURE

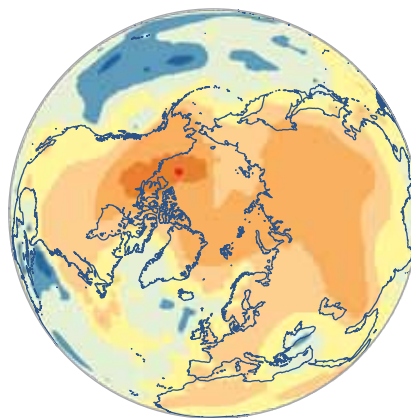
Every aspect of the Arctic cryosphere is changing, so what does the future hold? Projections from a number of computer models give an overview of how the cryosphere may change, and where those changes may occur. These models indicate an increase in Arctic-wide temperature, almost no summer sea ice on the Arctic Ocean by 2050, and a general increase in rain and snowfall.

The information about future change in the Arctic is based on results from 24 different computer models of the global climate system. These simulate the dynamic behavior of the atmosphere and the oceans.

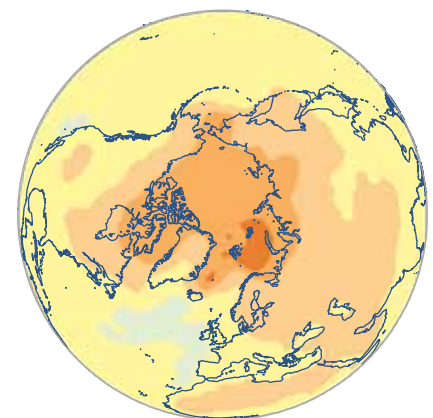
The climate models used in this report are based on optimistic scenarios where future greenhouse gas emissions are lower than they have been for the last ten years (see upper box on facing page).

To test how well a model simulates reality, the model is run for past periods for which we already know the outcome – this is known as hindcasting (see right-hand globe). Models that produce very different results from the majority of models, or very unlikely results like sea ice in the tropics, are excluded from this assessment.

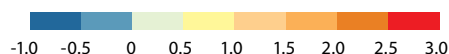
Actual 50-year change in temperature (1957–2006)



Hindcast 50-year change in temperature (1957–2006) based on a number of IPCC climate models



Mean temperature change, °C



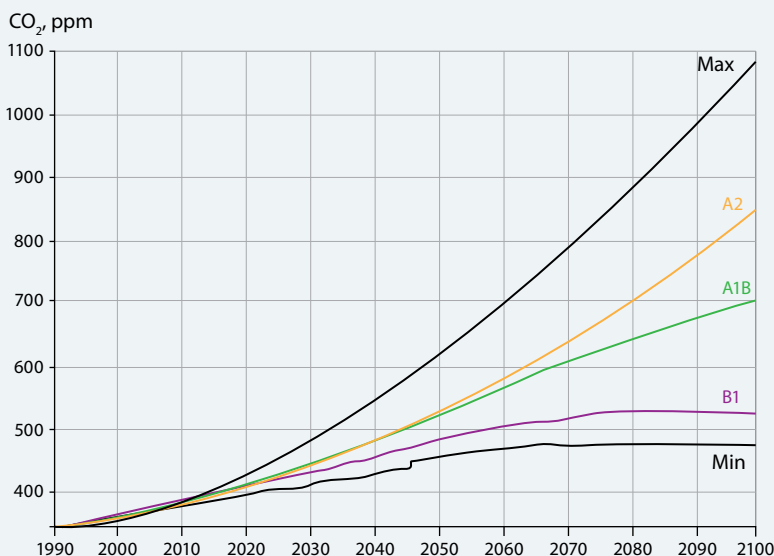
Emissions scenarios

The Intergovernmental Panel on Climate Change has produced 40 different emissions scenarios. Each assumes different patterns of future greenhouse gas emissions and land-use change. The scenarios also describe different future pathways of technological development, economic growth and levels of international co-operation.

The climate models in this report are all based on relatively optimistic scenarios where greenhouse gas emissions are projected to be lower than they have been for the

last ten years. As a result, these models are more likely to underestimate the rate and amount of change in the cryosphere than to overestimate it.

The emissions scenarios used generate relatively similar projections for the middle of the century. After 2050, they diverge, generating a greater range of possible futures. This means that the effects of international efforts to control emissions today will be felt more strongly in the Arctic and the rest of the World at the end of the century.



A2 describes a very heterogeneous world with high population growth, slow economic development and slow technological change.

A1B describes a world of very rapid economic growth, a global population that peaks in mid-century and rapid introduction of new and more efficient technologies. There is a balance across fossil intensive and non-fossil energy resources.

B1 describes a convergent world, with the same global population as A1, but with more rapid changes in economic structures toward a service and information economy.

Dealing with uncertainty

Climate scientists deal with uncertainty by presenting a range of possible futures. The greater the range of possibilities, the more uncertain the result. The main sources of uncertainty in projecting Arctic cryosphere changes are:

Incomplete understanding of the climate-cryosphere system.

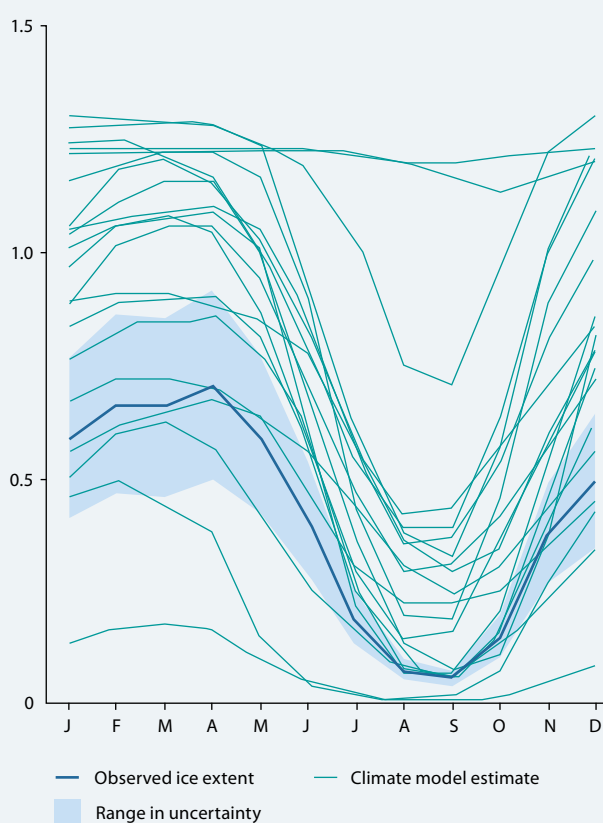
Each model makes assumptions about how the climate and cryosphere system works. But the complex interactions between snow and ice, oceans and the atmosphere are not yet fully understood. Without knowing which set of assumptions is most correct, it is best to use several models and present a range of possible futures.

Different ways to represent the real world. Climate models vary in the way they represent specific features of the cryosphere, such as ice extent (see graphic), snow cover or water flows. Different sets of models are chosen to project changes in different features. Regional climate models have been built for some areas, which can show change on a much finer scale.

In-built natural variability. When the same model is run over and over again it will produce different results because it is built to simulate the natural variability of the real-world climate system. Models are run many times and provide a range of possible future conditions that includes this simulated variability.

Uncertain future emissions. Future climate change depends heavily on the amounts of greenhouse gases emitted by human activity in the future. This is one of the largest sources of uncertainty (see box above).

Average Barents Sea ice extent for 1980-1999, million km²



3.2 FUTURE CHANGES IN TEMPERATURE, RAIN AND SNOWFALL

While many factors contribute to changes in the Arctic, atmospheric temperature, rain and snowfall are among the key drivers that affect all aspects of the cryosphere.

Temperature

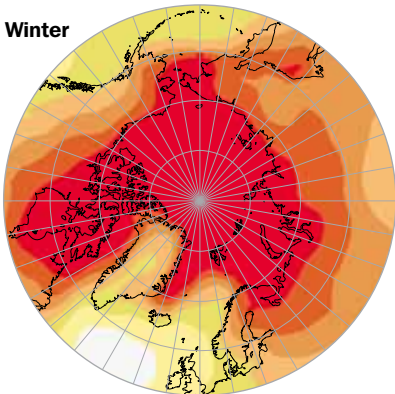
Average surface air temperatures in the Arctic have warmed at around twice the rate of the global average over the past few decades. Multiple climate models lead us to expect that this trend will continue and the Arctic will warm faster than anywhere else in the world.

Average Arctic air temperatures in autumn and winter are expected to increase by between 3 and 6 °C by the

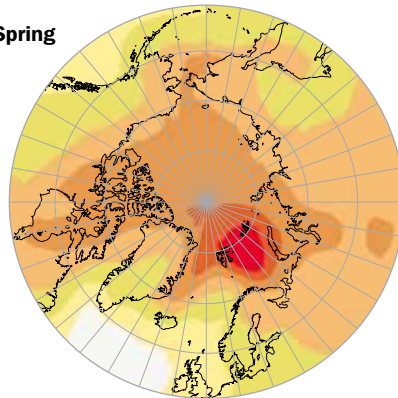
late 21st century (2080). The range refers to the temperature change experienced in different regions of the Arctic, including land and ocean areas. For most land areas, warming in winter is projected to be slightly less than it is over the ocean – between 2 and 3 °C by 2080. The greatest increases are expected in autumn and winter over areas where sea ice is being lost.

Projected change in seasonal surface air temperature for the late 21st century (2070–2090) relative to 1960–1990

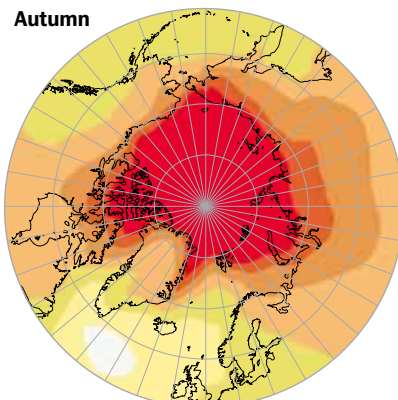
Winter



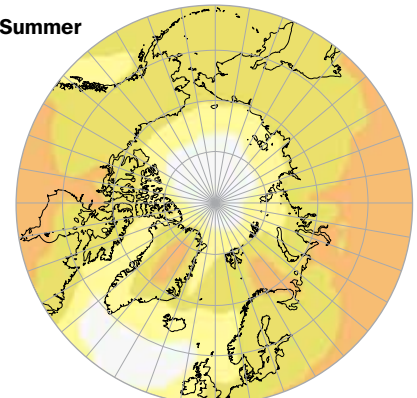
Spring



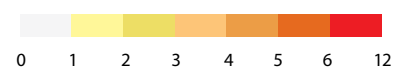
Autumn



Summer



Projected temperature change, °C



Computer models project that the Arctic will warm faster than anywhere else in the world.





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Rain and snowfall

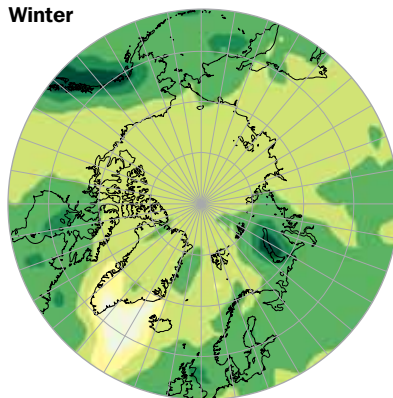
All models and scenarios project that Arctic rain and snowfall will increase throughout the 21st century. These increases are larger than projected for the rest of the world.

There are distinct regional patterns within the Arctic. There will be somewhere between 5% and 70% more rain or snowfall in the period 2080–2099, depending on where you are in the Arctic and which emissions scenario is used. The greatest relative increases in rain or snowfall will be in winter and autumn, and the smallest in summer.

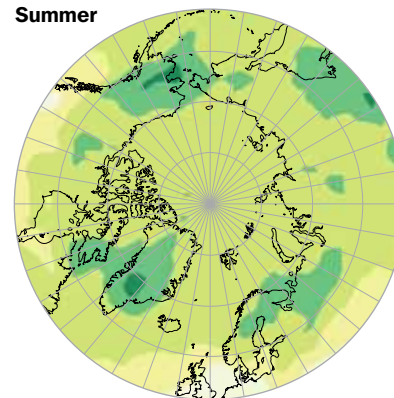
Despite the increases in rain and snowfall, Arctic land areas are generally expected to dry out more during summer. This is partly because warmer air results in more evaporation from the surface.

Projected change in winter and summer rain and snowfall for the late 21st century (2070–2090 relative to 1960–1990)

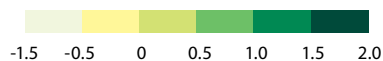
Winter



Summer



Precipitation, cm/month



3.3 FUTURE CHANGES IN SNOW, PERMAFROST, LAKE AND RIVER ICE

Increased temperatures and more rain and snowfall will affect the amount of snow and the extent of frozen ground.

Snow

Snow-cover duration is projected to decrease by 10–20% over most of the Arctic by 2050.

Over Alaska and northern Scandinavia, snow-cover duration in 2050 is expected to be 30–40% less than it is today. Rapid decreases in snow-cover duration are also expected along the Pacific coast region of Russia. Siberia is projected to experience the least change (less than 10%).

The maximum amount of snow accumulating on the ground will increase slightly. An increase of 0–15% is projected over much of the Arctic with the largest increases (15–30%) occurring over Siberia.

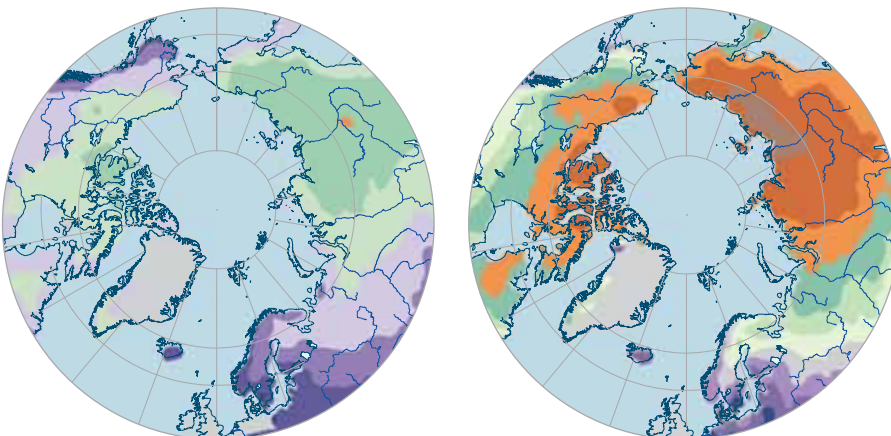
The frequency of rain falling on snow – called rain-on-snow events – is projected to increase over all regions of the Arctic over the next 50 years.



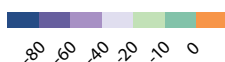
The projected changes in rain and snow fall coupled with changes in temperature will affect every aspect of the hydrological cycle – how water moves – within Arctic environments.

Projections show maximum snow depth increasing over many areas by 2050, but snow will tend to lie on the ground for less time each year.

Projected changes in snow-cover duration (left) and the total amount of snow falling (right) over the Arctic by the mid-21st century (2049–2060 relative to 1970–1999)



Projected change in mean annual SCD from 1970-1999 to 2049-2060, %



Projected change in mean monthly SWEmax from 1970-1999 to 2049-2060, %



Models of future snow conditions are limited

Current computer models can project large-scale changes in snowfall and aspects of snow cover that depend on temperature. Their ability to project the details of future Arctic snow cover is limited by two main factors. First, there is no systematic monitoring of snow conditions across the whole Arctic. This makes it difficult to develop and test models that project snow conditions. Second, current models are based on a relatively simple representation of snow dynamics. Intense research is going on to develop models that can simulate detailed properties of snow, such as ice layers in the snowpack.



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Permafrost

Projections indicate that ground temperatures will increase across much of the Arctic between now and the end of the 21st century. In Russia, ground temperature increases of 0.6 to 1 °C are projected to occur by 2020.

This compares with increases of between 0.5 and 2 °C since the mid-1970s. This warming will lead to the thawing and reduced extent of permafrost.

As permafrost thaws, the active layer – the top soil layer above the permafrost that thaws each summer – becomes thicker. This makes land

more vulnerable to becoming degraded or permanently drying out.

Regional climate models suggest that by 2100, the top two to three metres of permafrost will have thawed over 16–20% of the area that currently has permafrost in Canada. Permafrost is expected to have degraded (either thawed or partially thawed) over 57% of the area of Alaska.

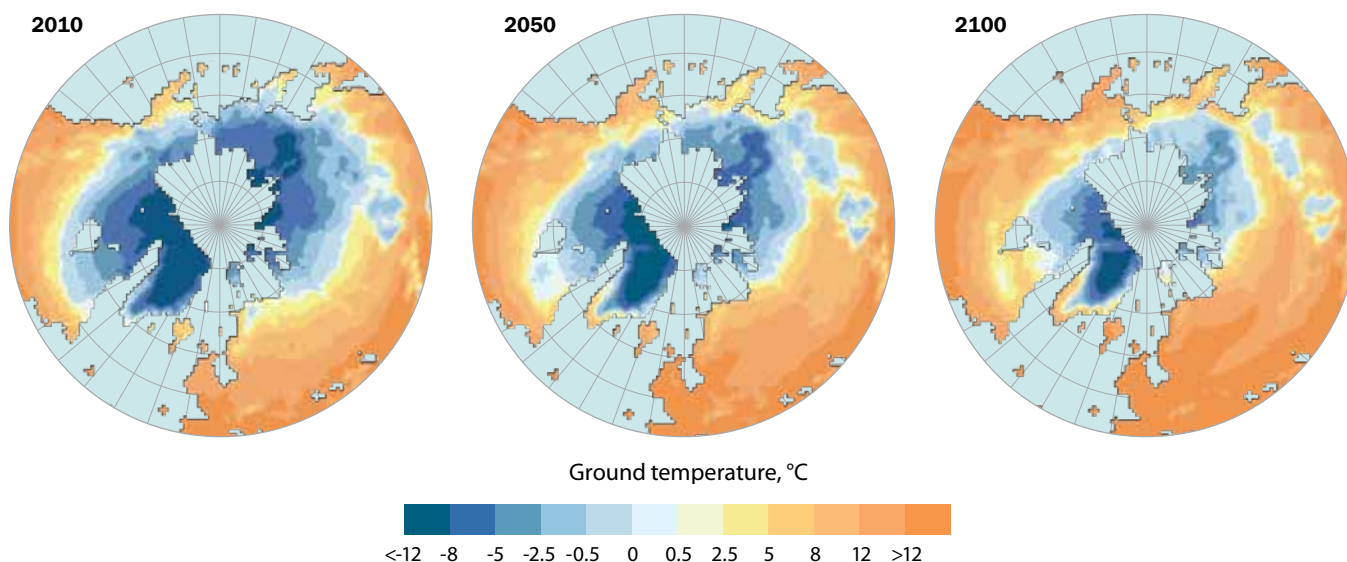
Lake and river ice

A few preliminary studies have used regional climate models to project future changes in freshwater lake ice. These studies project increases in lake

water temperature such that ice breaks up 10 to 30 days earlier in spring and freezes 5 to 20 days later in autumn by 2040–2079, in land areas between 40° and 75° N. The thickest lake ice is projected to be 10 to 50 cm thinner than it is now.

Future changes in river-ice regimes have been studied for a few individual rivers. The severity of ice break-up and related ice-jam flooding may be reduced on some large Arctic rivers, but these events are also affected by the size and speed of the spring snowmelt.

Projected ground temperature through the 21st century



3.4 FUTURE CHANGES IN MOUNTAIN GLACIERS, ICE CAPS AND THE GREENLAND ICE SHEET

Loss of ice from Arctic mountain glaciers, ice caps and the Greenland Ice Sheet affects the whole world because as land ice melts meltwater is added to the ocean and sea level rises. Loss of Arctic land ice is responsible for over 50% of the recent global sea-level rise. As the rate of loss is expected to continue or even accelerate, the effect on sea level is a major concern.



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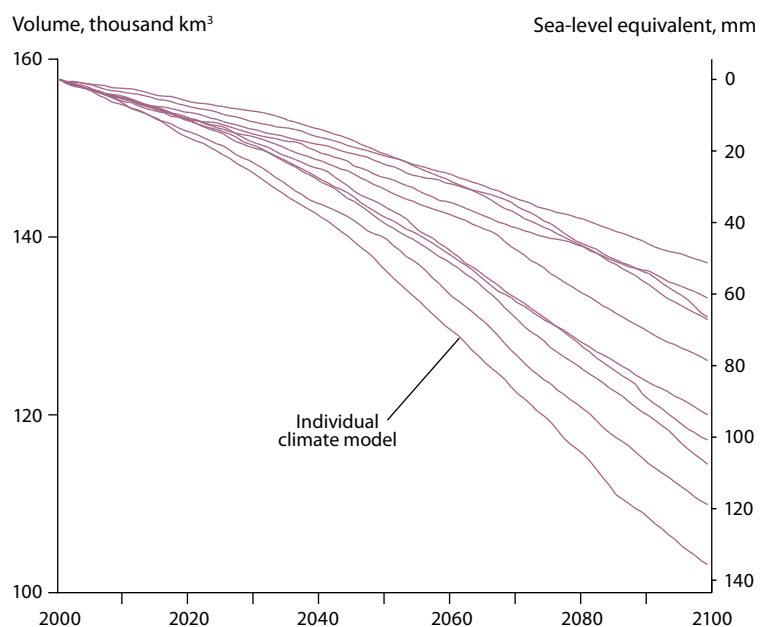
Mountain glaciers and ice caps

The total volume of ice in mountain glaciers and ice caps in the Arctic is projected to decline by between 13% and 36% by 2100, depending on which climate model is used. There is considerable regional variation in the amount of glacier melt expected. The smallest changes are projected for ice caps and isolated glaciers in Greenland (8%), and the largest in Svalbard (54%). These projections do not take account of the loss of icebergs from the end of the glaciers, so, if anything, the ice loss is likely to be greater.

Mountain glaciers in northeastern Siberia have been projected to lose 78% of their area (different from volume) by 2070.

As for snow cover, these models lack information about many of the processes important to glaciers and ice sheets, such as the way they respond to changes in ocean temperature.

Projected change in volume for Arctic mountain glaciers and ice caps through the 21st century and sea-level equivalent



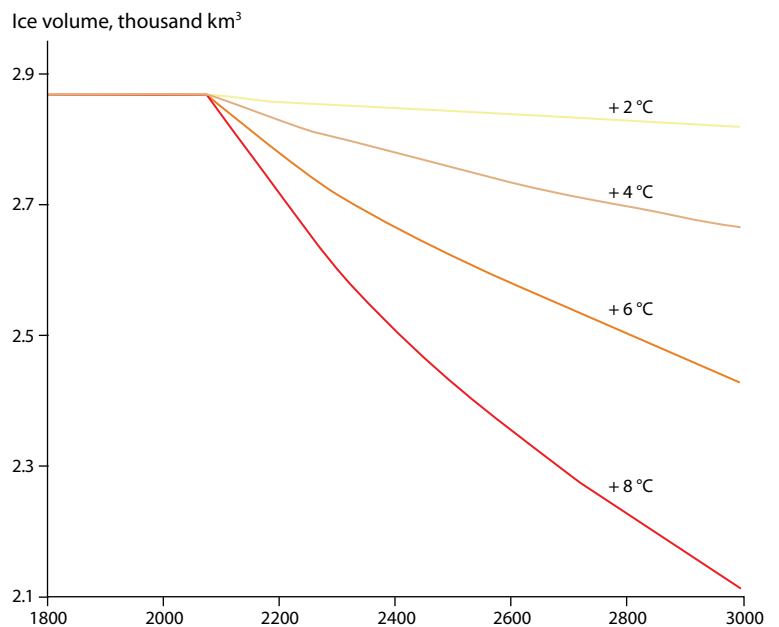


Greenland Ice Sheet

The Greenland Ice Sheet is expected to melt faster than it is melting now, but no current models are able to provide details of how it will respond to further Arctic warming.

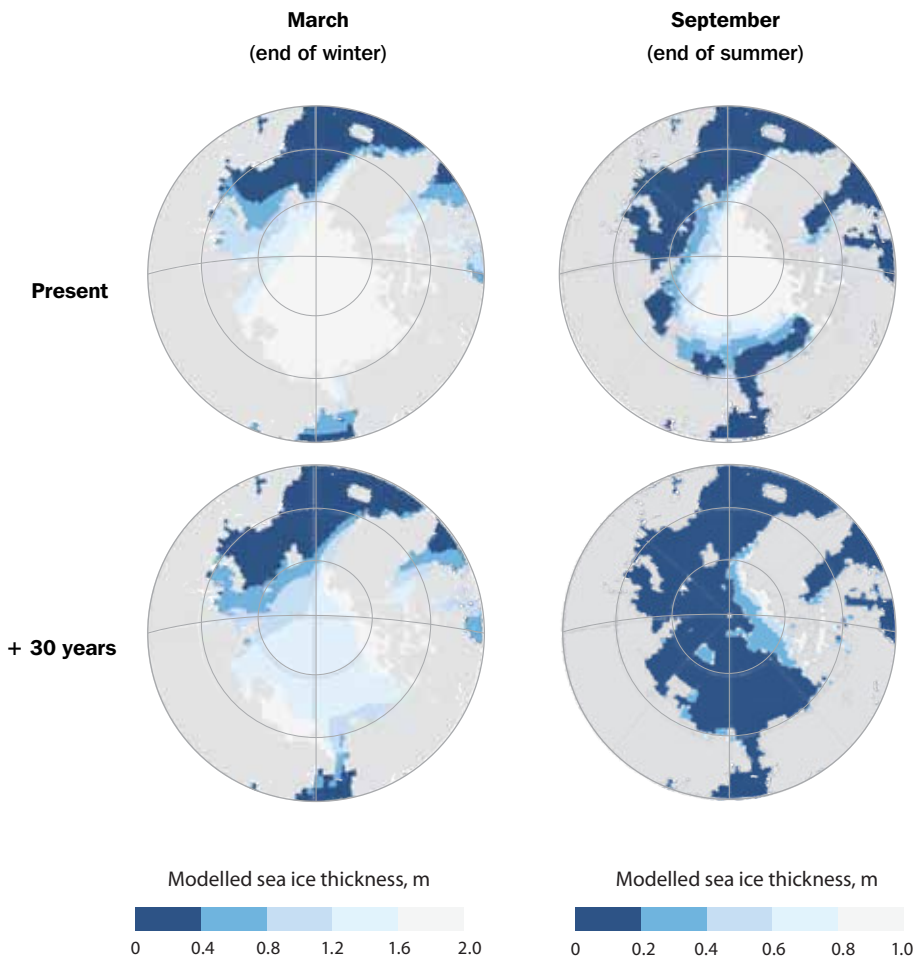
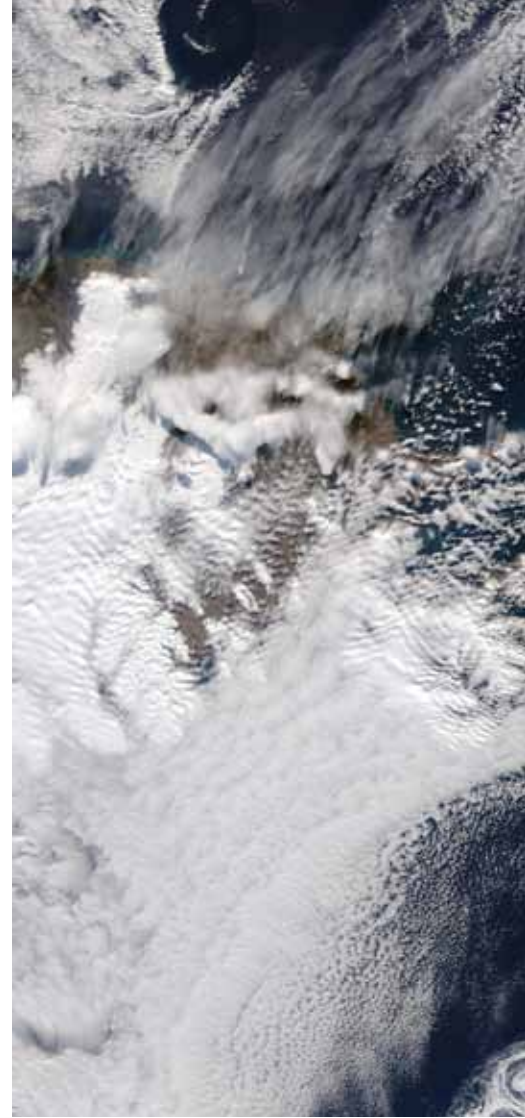
Models run over longer timescales show how the Greenland Ice Sheet might retreat by 5000 AD, with summer temperature increases no higher than 5 °C. These models capture an accelerating loss in the late stages of retreat, as the centre of the Greenland Ice Sheet collapses. However, they suffer from a very incomplete understanding of the interactions between the ice sheet, the oceans and the atmosphere. More research is needed to make these projections more certain.

Greenland Ice Sheet simulations over the long-term under different temperature (greenhouse gas emissions) scenarios



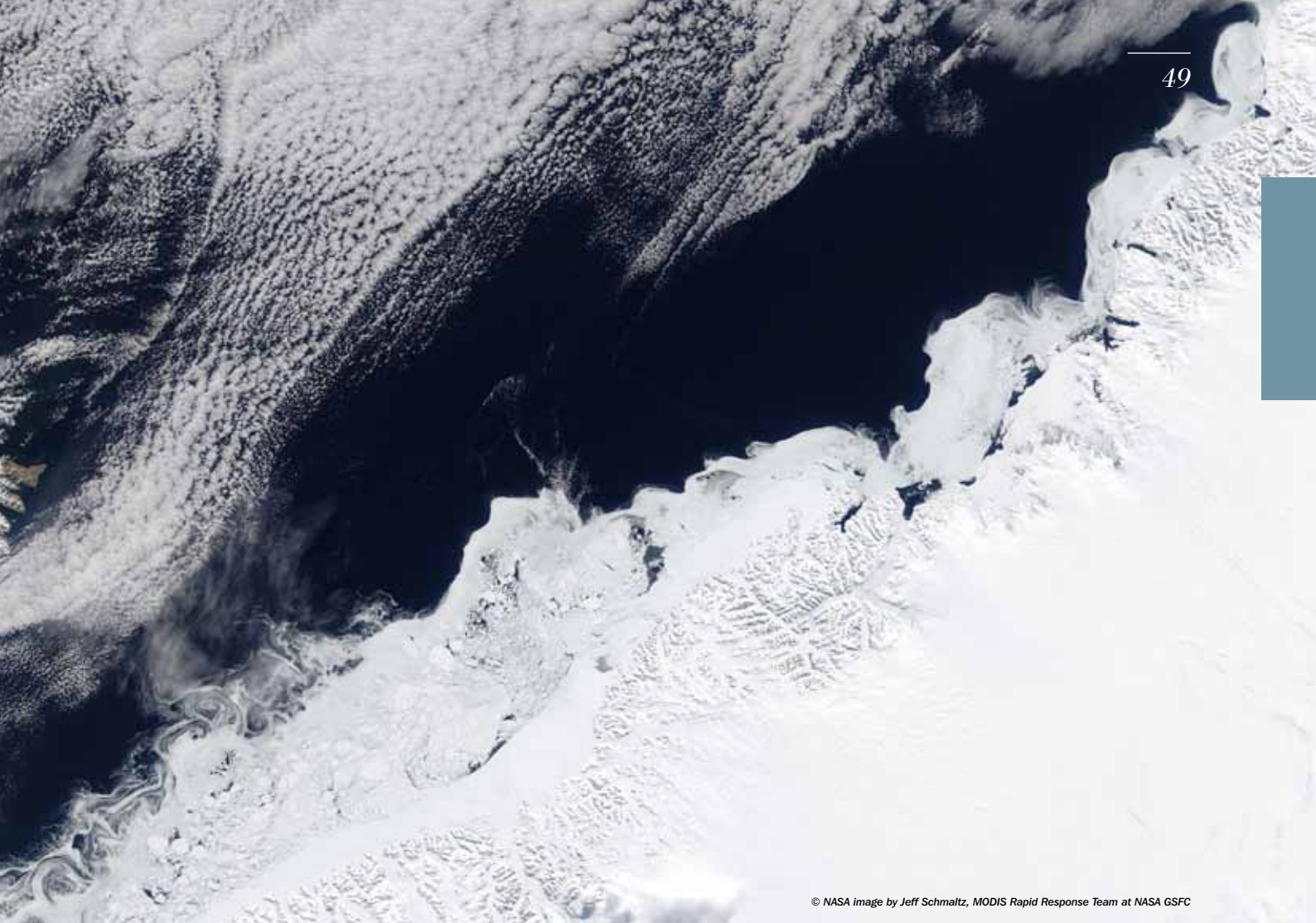
3.5 FUTURE CHANGES IN SEA ICE

Summer sea ice will continue to decline. This is likely to lead to an Arctic Ocean with almost no sea ice in summer within the next 30 to 40 years.



Projections from climate models show that sea-ice thickness and summer sea-ice extent will continue to decline in the coming decades. It is possible that the rate of decline will accelerate. We can expect a nearly ice-free summer for the Arctic Ocean by mid-century. Small amounts of sea ice are expected to remain through the summer in isolated regions, such as north of the Canadian Archipelago.

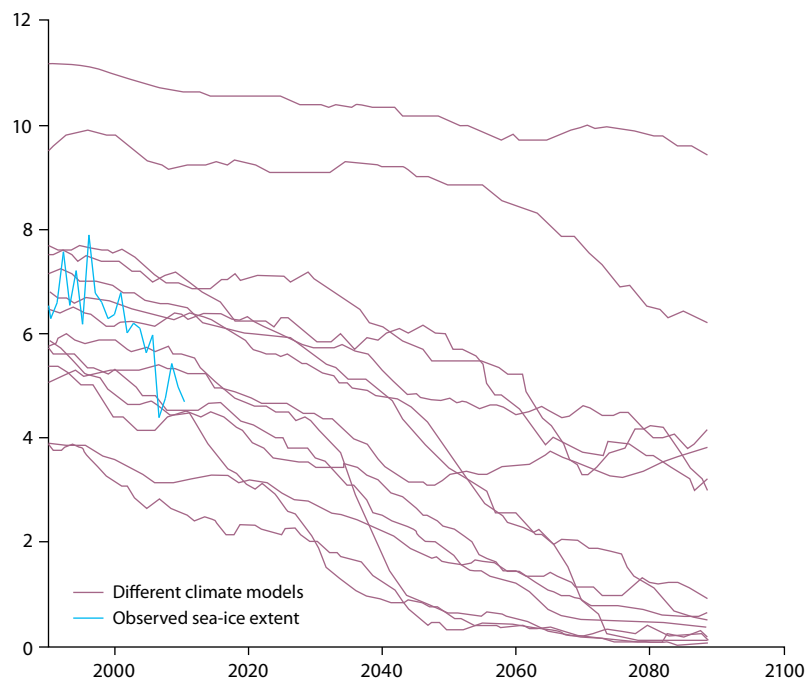
There is likely to be considerable variation between years in the extent of sea ice over the coming decades.



© NASA image by Jeff Schmaltz, MODIS Rapid Response Team at NASA GSFC

Projected change in sea-ice extent through the 21st century

September sea-ice area, million km²



Understanding sea ice has improved climate models

One of the major developments in Arctic climate modelling over the last five years has been the addition of sea ice dynamics to global climate models. Almost all state-of-the-art models now include elaborate sea ice dynamics. Some allow several possible sea-ice thickness categories.



PART 4:**HOW THESE CHANGES AFFECT PEOPLE AND NATURE**

The past, present and future changes described in the previous sections have major effects on ecosystems and people. Every aspect of society is likely to be affected by these changes, including transport, livelihoods, buildings and industry. Effects will be felt at all scales, from local to global. This section focuses on the local and regional effects. The following section will explore global effects in more depth.

Arctic ecosystems and supplies of natural resources

- Changes in the Arctic cryosphere cause fundamental changes to the characteristics of Arctic ecosystems and in some cases loss of entire habitats.
- The loss of sea ice represents devastating habitat loss for some species, including polar bears, seals and some microbial communities.
- Supplies of natural resources from ecosystems, such as timber and commercial fish stocks could change. Uncertainty about how they will change makes it difficult to plan for the future.
- Increased glacier melt creates new opportunities and challenges for hydroelectricity generation.

Access

- As summer sea ice declines, the Arctic Ocean is opening up to shipping, with benefits for the oil, gas and mining industries, commercial fisheries and tourism.
- A shorter ice road season creates large costs for Arctic communities and industry, particularly in northern Canada and Russia.
- Travel is becoming more dangerous as ice roads melt, sea ice breaks up and hazards from icebergs increase.

Risks to buildings and land

- Buildings and other infrastructure in the Arctic are at risk from thawing permafrost, heavier snow loads and floods caused by ice-jams in rivers and glacial run-off.
- Arctic coastlines are becoming more vulnerable to erosion as land-fast sea ice melts earlier and permafrost thaws.

Movement of contaminants

- The ways that contaminants move into and around the Arctic are altered by cryospheric change. For example, melting snow and ice can release contaminants stored over decades.
- Expansion of shipping, resource exploitation, industry and tourism in the Arctic will bring risks of additional contaminants entering the Arctic environment.

Living conditions

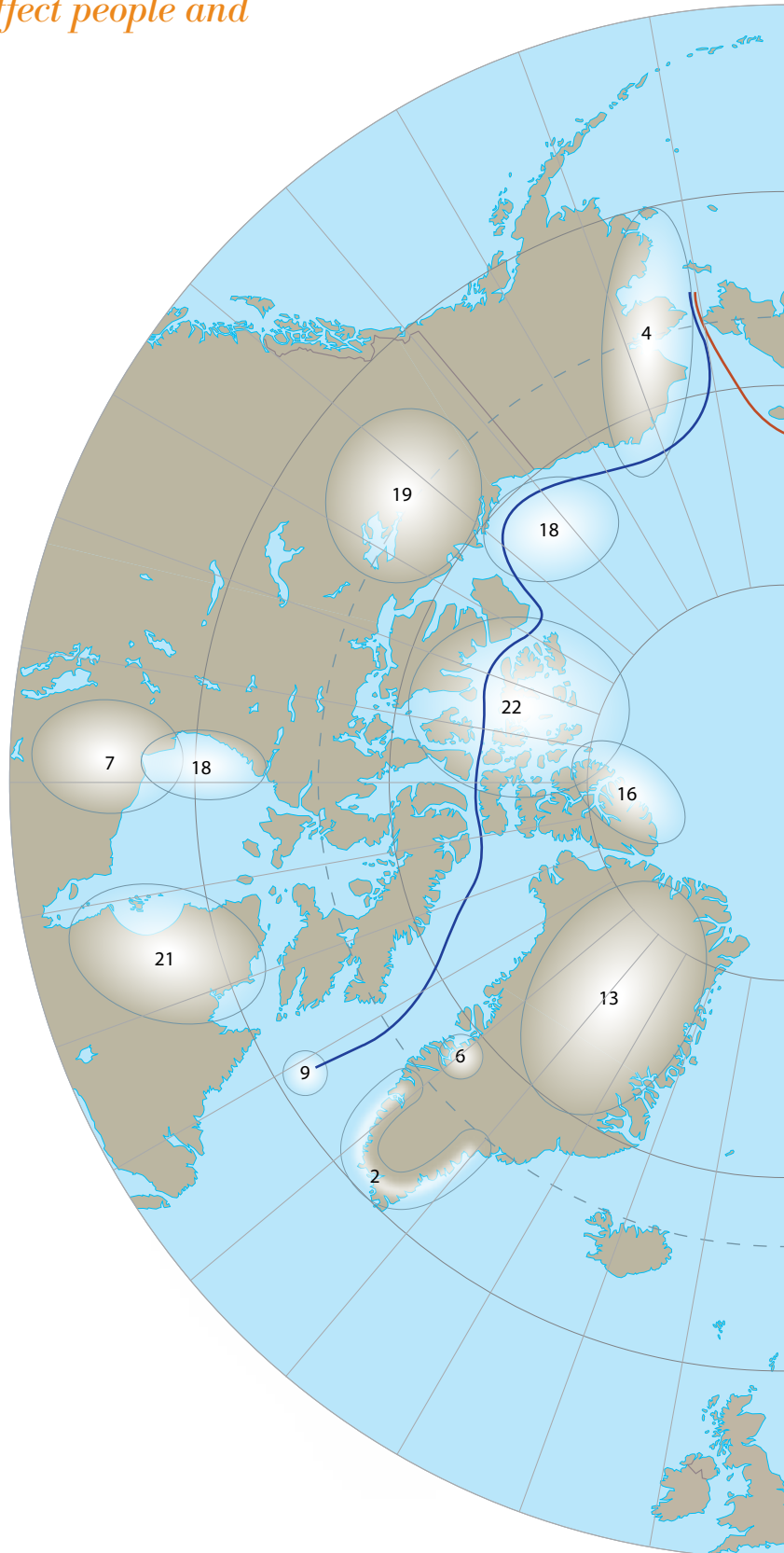
- The observed and expected future changes in the Arctic cryosphere impact Arctic society on many levels. There are challenges, particularly for local communities and traditional ways of life. There are also new opportunities.

WHERE IN THE ARCTIC?

This page gives SELECTED EXAMPLES of how and where changes in the Arctic cryosphere affect people and ecosystems.

Impacts on people

- 1 Russian infrastructure (including large cities e.g. Yakutsk) is susceptible to thawing of permafrost. Many large towns, cities and oil pipelines are built on permafrost.
- 2 Hydroelectricity generation is increasing in **Greenland** using water from the melting ice sheet. It is set to provide more than 50% of the country's domestic energy consumption.
- 3 Erosion due to melting sea ice and permafrost thawing will particularly affect the **coasts bordering the Laptev and East Siberian Seas in Russia**.
- 4 A number of Inuit villages in **Alaska** are preparing to relocate in response to the coastal erosion.
- 5 More widespread tree diseases and heavier snow loads affect forestry in **Fennoscandia**.
- 6 More tourists are visiting the **Ilulissat Ice Fjord** in **Greenland**, to see the retreating glacier margin and flowing icebergs.
- 7 There are problems with the ice road network as lake and river ice melts earlier. Mild weather in March 2010 caused the province of **Manitoba, Canada**, to close a 2200-km winter-road network.
- 8 Hunting is becoming more difficult in northern Canada, as a shorter snow season impedes travel to hunting areas and the building of snow shelters.
- 9 The **North-West Passage** and the **Northern Sea Route** are opening more often for short periods in summer, allowing ships to pass.
- 10 Cruise ship tourism is increasing in the **Arctic Ocean**.
- 11 New mandatory guidelines for ships operating in ice-covered waters (such as the Arctic Ocean) are being developed by the International Maritime Organization in response to the changing sea-ice conditions.
- 12 The west coast of **Svalbard** was completely ice free in winter between 2005 and 2009. This increased the evaporation of contaminants from the water into the air.
- 13 Loss of ice from Arctic mountain glaciers, ice caps and the **Greenland Ice Sheet** now accounts for over 50% of global sea-level rise.





Impacts on ecosystems

- 14 Degradation of permafrost has caused the collapse, drainage and complete disappearance of many water bodies in **Siberia**.
- 15 Increasing snow depth is enhancing soil microbial activity in **Siberia**.
- 16 Along the northern coast of **Ellesmere Island**, unique communities of microbes in ancient ice shelves are threatened with extinction as the ice shelves are disappearing.
- 17 In **Fennoscandia**, a unique Arctic wetland habitat known as palsa mire is declining fast because of thawing permafrost, and could be entirely gone by 2050.
- 18 Polar bears are raising fewer young and surviving less well in the **southern Beaufort Sea** and **West Hudson Bay**, due to the loss of sea ice.
- 19 Rain has been falling onto snow more often during winter in **northwestern Canada** and **Fennoscandia**. It creates an ice crust that can prevent grazing animals from feeding.
- 20 In the Russian Arctic, west of the **Taymir Peninsula**, ice layers on the ground that prevent reindeer from feeding are forming less frequently, because snow is melting faster at the end of winter. This improves the quality of reindeer grazing grounds.
- 21 New ponds and lakes are appearing over waterlogged soils in **Nunavik, northern Quebec**, as permafrost thaws.
- 22 Water bodies are drying up due to summer drought in **Nunavut, northern Canada**.
- 23 Pink-footed geese on **Svalbard** laid eggs earlier and raised more young in years with less snow cover between 2003 and 2006.
- 24 Species that depend on small crustaceans that thrive close to the ice edge (such as ivory gull, bowhead whale and capelin) will have less food as the sea ice recedes.
- 25 Changes in sea conditions across the Arctic Ocean will have enormous ecological implications.
- 26 Hooded seals, harp seals, ringed seals and Pacific walrus are all showing signs of decline in areas with retreating sea ice.





4.1 CHANGING ARCTIC ECOSYSTEMS

The ways water and ice move within and between Arctic ecosystems profoundly affect plants, animals and habitats, as well as influencing supplies of fish, timber and pastures that are crucial for Arctic people.

The forests, tundra, lakes, rivers, wetlands and oceans of the Arctic contain species found nowhere else on Earth and provide rich feeding and breeding grounds for migratory animals from further south. Several hundred million birds migrate into the Arctic every summer, while whales and seals congregate in the nutrient-rich waters along ice edges to feed on plankton and fish.



© W. Lynch / ArcticPhoto

LAND-BASED ECOSYSTEMS

The changes particularly affecting land-based ecosystems are decreasing snow-cover extent and duration, changes in the water cycle, warmer winters and thawing permafrost.

As the duration of snow cover decreases, the growing season will become longer and Arctic vegetation may change, with more shrubs and fewer lichens. Animals, including caribou/reindeer, generally benefit from fewer days of snow cover

– both pink-footed geese and reindeer have been shown to produce more young when there has been snow on the ground for less time.

The depth of snow affects soil ecology. Experiments show that deeper snow (currently being recorded in the Eurasian Arctic) means warmer soil because the snow layer insulates against the cold air. The consequence is more soil microbial activity and so more carbon dioxide released from the soil.

Sudden thaws in winter remove snow and expose plants to sudden sub-freezing conditions that may kill shrubs and even trees.

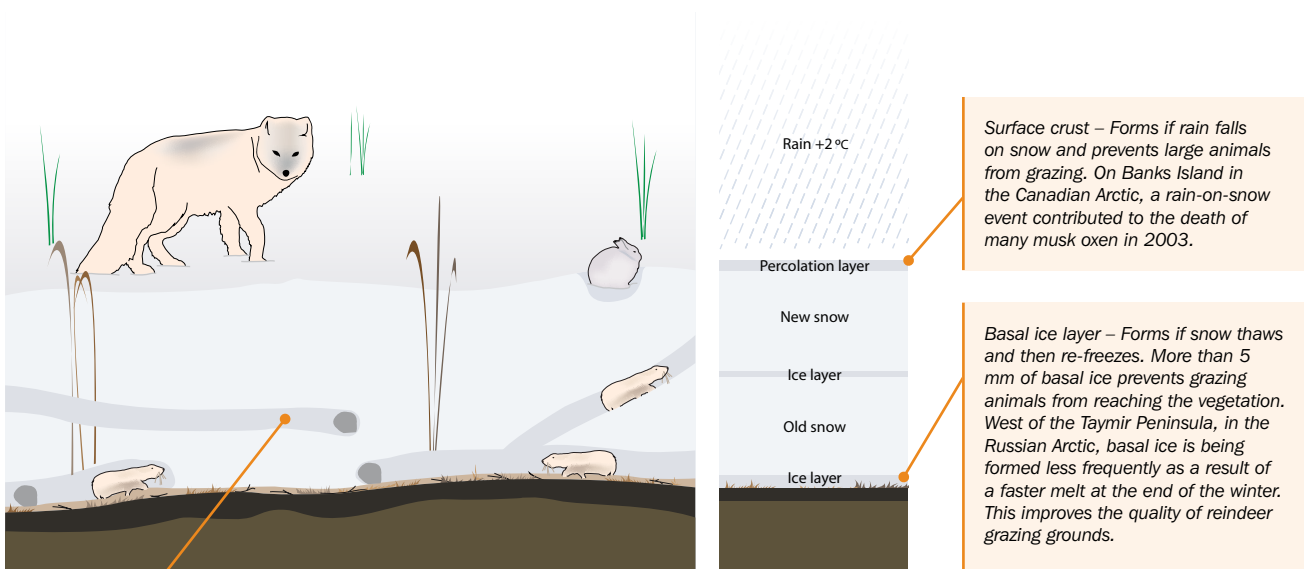


© Susanne Liebner

Palsa mire

This mire habitat ('palsa mire') with frozen peat hummocks is rapidly declining in Fennoscandia due to thawing permafrost. It is expected to disappear almost completely by 2050, removing an important feeding ground for migratory wading birds.

Under the snow



Rodent burrows – Lemmings and other rodents spend the winter and raise their young in 'nests' or burrows under the snow. If the snowpack is too icy in spring, as is prone to happen with rainfall events and mid-winter snow thaw events, the snow is less insulating and young lemmings are more likely to die of cold. Fewer lemmings means less food for Arctic foxes and birds of prey that eat them.

Ramifications of winter rain

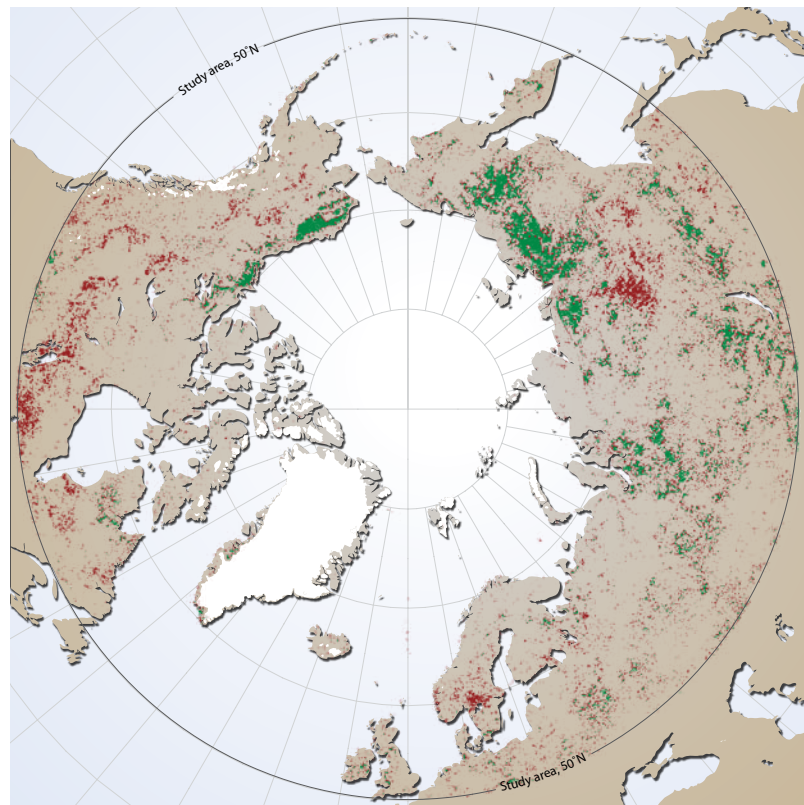
The occurrence of winter rain, instead of snow, is projected to rise in the Arctic as the climate warms, and more frequent rain-on-snow events have already been recorded at sites in north-western Canada and Fennoscandia. Rain falling on snow changes the snow's structure and affects grazing animals (see upper graphic), a fact well known to the reindeer herders of Fennoscandia.

Sudden thaws in winter are also happening more often, exposing vegetation to potentially fatal blasts of harsh frosty air. Many Alaskan yellow cedar trees, a valuable commercial timber source in British Columbia and Alaska, have died recently because of early thaws. They emerge from winter dormancy and lose their frost resistance during unseasonal February thaws, only to have their roots frozen to death by returning cold.

Advancing shrubs

Evidence from photographs and satellite images shows that the Arctic tundra vegetation is in transition. Large shrub species like willow, alder and birch are advancing northwards in Alaska, Canada, Scandinavia and parts of Russia.

Vegetation productivity trends 1982–2005



- Increases in peak productivity and growing season
- Decline in productivity (forested areas not recently disturbed by fire)



© Jan Vermeer / Foto Natura / Minden Pictures / Corbis

FRESHWATER AND MARINE ECOSYSTEMS

The reduced ice cover on Arctic lakes and rivers, and the rapid reduction in the extent of summer sea ice observed in recent years, could generate substantial changes in both freshwater and marine ecosystems (see right-hand box on facing page). The disappearance of ice, particularly large areas of sea ice, will have a devastating effect on some animal species.

Changes in the dynamics of permafrost, ice and meltwater are altering physical and chemical conditions in freshwater systems and the oceans of the Arctic.

More lakes and ponds, or fewer?

Freshwater lakes, ponds and mires are important features of Arctic ecosystems. They support the larval stages of insects, such as mosquitoes, which provide food for birds and other animals. Thawing permafrost can either cause these lakes, ponds and wetlands to drain and dry out, as has happened in parts of Siberia and Canada, or create new shallow ponds and lakes over waterlogged soils, which is happening elsewhere in the Arctic, such as in Nunavik, northern Quebec. Whether habitat is lost or created depends on the underlying soil conditions. One unique Arctic wetland habitat, known as palsa mire because of its frozen peaty mounds (palsas), is declining fast because of thawing

permafrost, and could be entirely gone by 2050.

Many lakes and wetlands are supplied with water during summer by melting snow. As there is less snow, and what snow there is melts faster and earlier, this supply of water may dry up. With warmer air and less ice cover, which both enhance the surface evaporation, some wetlands in the High Arctic are drying up altogether.

Ice – a unique habitat

As well as affecting the water beneath, ice is itself a unique habitat (see box). Sea ice provides an important substrate. It is a physical surface for mammals and birds to rest on, raise young on and in some cases a platform from which to hunt. Smaller animals that live near sea ice (fish and tiny crustaceans) are a particularly fat-rich food source. If the Arctic Ocean becomes entirely ice-free in the summer within a few decades, such a dramatic change will have enormous ecological implications.

Species that live on or near sea ice

Many species depend on tiny crustaceans that thrive close to the sea ice. These species include birds such as ivory gulls, whales such as the bowhead whale and fish such as capelin, Arctic cod and polar cod. As the ice recedes, their food source will decline, or at least become less

easy to find. Arctic cod and polar cod are key species in the Arctic marine food web, providing prey for seabirds, seals, whales and other fish such as the Atlantic cod. Capelin and Atlantic cod are important commercial species, and so loss of sea ice has implications for commercial fisheries as well as for biodiversity.

Hooded seals, harp seals, ringed seals and Pacific walrus are all showing signs of decline in some areas, related to loss of sea ice. The Canadian population of ivory gull has dropped by 80% in the past 30 years. This species is tightly associated with sea ice, feeding and migrating along its edges. Ice-breeding seals (hooded, harp, ribbon and spotted seals) are expected to fail to reproduce more frequently as their breeding habitat becomes less stable.

The polar bear is highly dependent on sea ice. A decline in the condition and reproductive success of polar bears in Western Hudson Bay has been associated with earlier break up of sea ice, while survival of female polar bears is substantially lower when there are more ice-free days in the southern Beaufort Sea north of Alaska. Drastic reductions in polar bear numbers are expected, even loss of the species altogether from places where it is currently common.



The loss of summer sea ice has enormous ecological implications.



© Josef Wiktor / Norwegian Polar Institute

Ancient communities under threat

Unique communities of microbes and invertebrates live in lakes on ancient ice shelves such as those along the northern coast of Ellesmere Island. These communities are severely threatened by loss of habitat, and are thought likely to become extinct. On Ellesmere Island, 23% of the ice shelf habitat was lost in the warm summer of 2008.

Taking the lid off – how reduced ice cover affects life in water

When ice cover is lost from a body of water, more sunlight, oxygen and nutrients enter the water, and it becomes warmer. The ecological effects of these changes are:

- Algae near the surface (phytoplankton) grow more. Satellite observations suggest that the total amount of phytoplankton may have increased in the Arctic Ocean since 2003 in response to more open water.
- Microbes, including ice-adapted algae, suffer more damage from exposure to harmful ultraviolet rays.
- There is more evaporation from the surface. For lakes, this can mean lower water levels or even a risk of drying out in summer. For the sea, the effect is to increase rainfall on nearby coastlines.

Consequences of receding sea ice

Winners	Losers
Plankton grow more in open water	Ice-dwelling microbes lose habitat
Animals that feed on plankton have more to eat	Small crustaceans lose protective cover
Predators that hunt in open water benefit	Birds and fish that eat ice-associated crustaceans have less to eat
	Seals lose breeding grounds and protection from predators
	Polar bears and Arctic foxes lose hunting and scavenging ground
	Bowhead whales, beluga and narwhal may have to change their feeding patterns
	Walrus eat bottom-dwelling clams found in waters up to 100 m deep. If sea ice occurs only over deeper water, walrus will not be able to rest close to their food source

CHANGES IN MARINE PRODUCTIVITY

As summer sea ice declines, ocean productivity may increase (see right-hand box on page 59). This would mean more food for many species, including whales, seals and birds that feed in open water. But the location and timing of food sources are likely to change, so animals will have to adjust and locate new feeding grounds.

Areas where glaciers and rivers flow into the sea are nutrient-rich, partly because the water carries nutrients and organic matter, which can stimulate growth of plankton and invertebrates. These areas form important feeding grounds for larger animals such as fish, seals and beluga. The increased rate of melting from glaciers and ice caps increases the flow of sediment in freshwater from rivers and glaciers into the sea, so nutrient supply could increase.

However, the amount of nutrients carried by some rivers could be reduced as a result of changing ice dynamics in freshwater systems (see box). Freshwater tends to form a stable surface layer that lies over the heavier salty sea water, potentially cutting off the normal supply of nutrients flowing up from the sea floor, and so reducing productivity.

The net effect of these changes on marine ecosystems, for example around the Greenland Ice Sheet, is only partly understood and remains an important area for future research.

Ultimately, as tidewater glacier fronts melt back feeding grounds at their margins will be lost.

The Arctic is home to three species of whale found nowhere else on Earth – the bowhead whale, the beluga and the narwhal. Narwhal are the most vulnerable to change. They specialise in eating fish in deep water beneath the sea ice.



Why rivers may carry less nutrients to the sea

In larger Arctic rivers such as the Mackenzie River in Canada (see photo) and the Lena River in Russia, the spring break-up of ice is dramatic. Ice-jam floods, caused when chunks of ice pile up and dam the channel, have shaped the landscape, creating lakes and wetlands only filled because of ice-jams. In these lakes, plants and microbes process soil-derived sediments and produce organic matter, creating a rich supply of nutrients that ultimately feeds into the ocean. The frequency of ice-jam floods in the Mackenzie River has decreased and some of the higher lakes are not being re-filled as often. The effect is to reduce the nutrient supply to the sea.



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© Paul Nicklen / gettyimages.co.uk

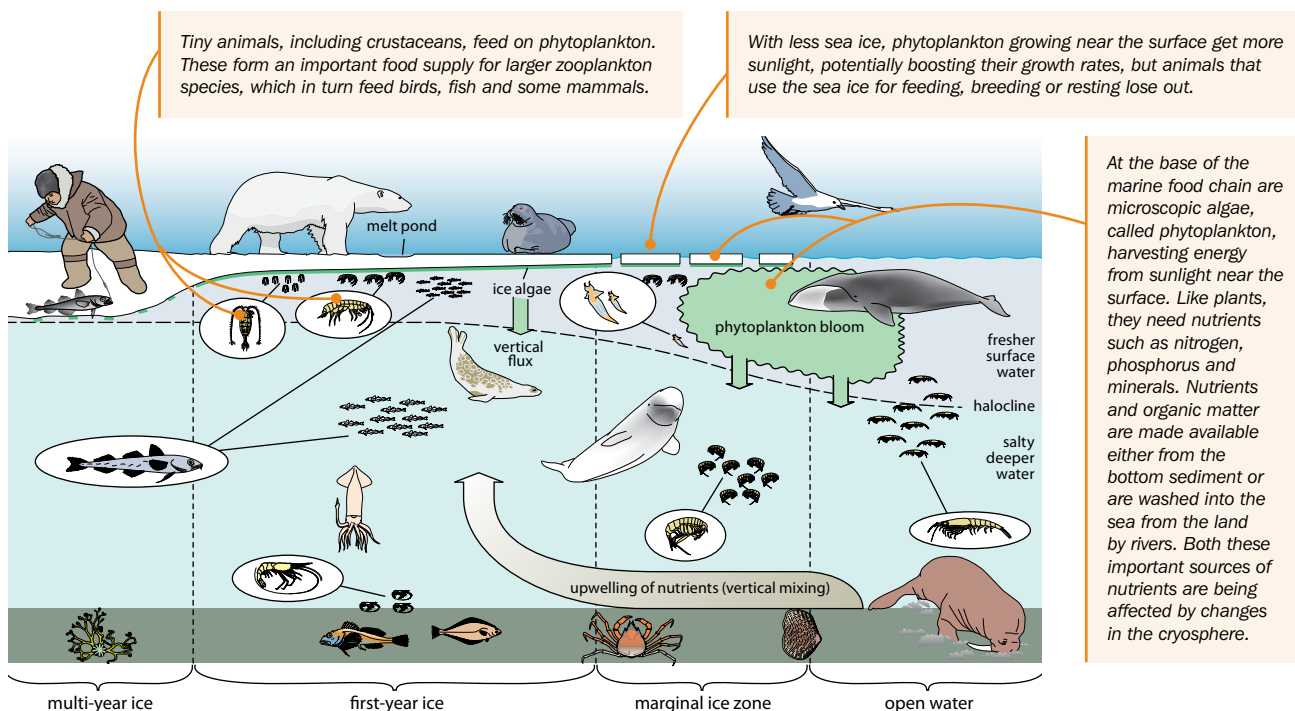
Invaders from the south

Many marine species currently confined further south, such as types of whelk, mussel and barnacle, will be able to spread into the Arctic Ocean as it warms and the sea ice recedes. Species from the Bering and Chukchi seas are expected to cross the Arctic Ocean and invade the Atlantic Ocean, where they will compete with similar Atlantic species. The potential invasion of Pacific sea urchins causes concern, because sea urchins are voracious grazers. They could seriously damage or even destroy populations of slow-growing Arctic seaweeds. Larger animals are also moving north. For example, the grey seal was recorded on southern Greenland for the first time in 2009. With these new arrivals come new diseases and parasites that may threaten unique Arctic species like the narwhal.



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The Arctic marine foodweb





4.2 CHANGING SUPPLIES OF NATURAL RESOURCES

Renewable resources are directly affected by cryospheric changes: melting snow and ice affect animals and fish, thawing permafrost affects forests, and melting glaciers provide water for hydroelectric power. Non-renewable resources, such as oil, gas and minerals, are affected indirectly by changes in the cryosphere, through changing access to extraction sites and changing transport options for the products.



RENEWABLE RESOURCES

Renewable resources are directly affected by changes in the cryosphere.

Fisheries

Melting sea ice affects the location and behavior of fish stocks, as their seasonal migrations are related to the formation and melting of the ice. Earlier sea-ice retreat and a longer ice-free season may result in some commercially important species moving north, opening up new fisheries. For example, sea ice changes may lead to larger and more northern populations of Atlantic cod, increasing their value to fisheries. However, numbers of other species, such as Greenland halibut, may go down.

Freshwater fisheries will also change. Commercially important fish that live in lakes and rivers will be affected by a shorter ice-cover season. Species that prefer cold temperatures, such as Arctic char and lake trout, may decline.

Harvested wildlife

Hunting is an important traditional livelihood carried out by people throughout the Arctic, and provides an essential source of local food.

Changing snow, ice and permafrost conditions directly affect both hunters and the animals they hunt, as travel to hunting areas becomes more difficult, and animals move to new locations in response to cryospheric change.

Access to some important hunting areas for seal, walrus and caribou has been affected by changing sea-ice conditions, particularly in spring and autumn. In Greenland, hunters travelling by dog-sled are forced to travel overland because sea-ice routes are no longer possible; journeys take longer and can be more dangerous. Similarly, in northern Canada, a projected shortening of the snow-cover season will shorten the period that snowmobiles can be used for hunting. The building of snow shelters used during hunting trips will also be affected.

Some species that are hunted for food are declining as their habitat changes. For example, polar bears and ringed seals are hunted for food, but are declining because of changing sea-ice conditions.

Reindeer husbandry

Reindeer husbandry is an important livelihood for Sámi across Fennoscandia and Indigenous Peoples in Arctic Russia. Changing snow, permafrost, river and lake ice conditions will directly affect reindeer pastures.

More frequent rain-on-snow events and midwinter melts result in an earlier start to the growing season, benefiting reindeer pastures. However, the earlier break-up of river and lake ice makes it more difficult for reindeer to move from winter to summer pastures, particularly for new-born calves.

Deeper snow and ice crusts can also make it harder for reindeer to feed in the winter. In Fennoscandia, winter mortality among reindeer has been high and fewer calves have been born in spring when heavy ice crusts have formed. Overall, cryosphere changes seem to be predominantly negative for reindeer husbandry.



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© B&C Alexander / ArcticPhoto



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Forestry

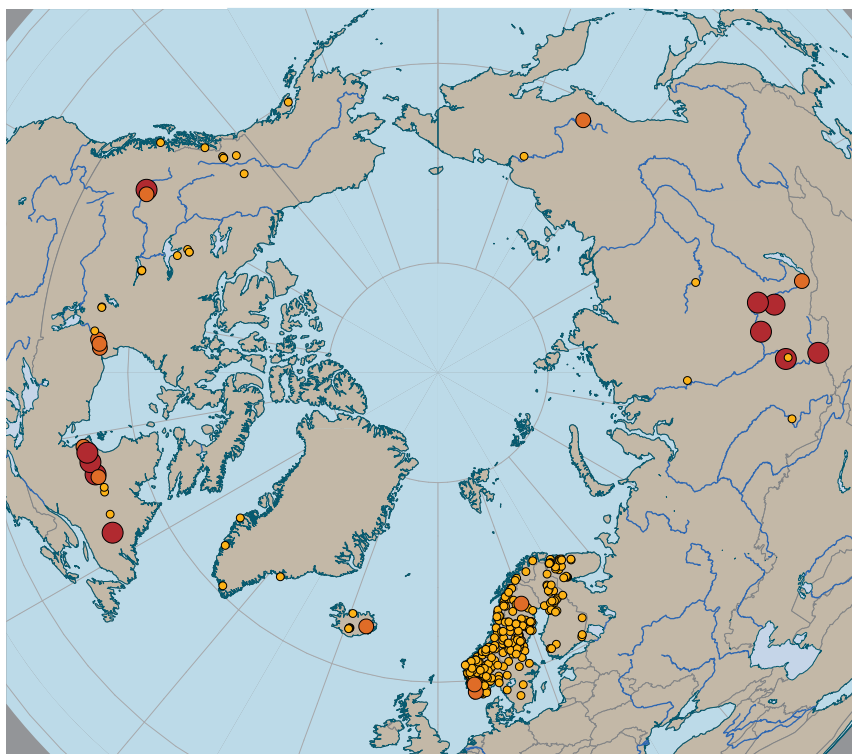
Commercial forestry is an important economic activity in many parts of the southern Arctic, particularly Sweden and Finland. As the permafrost thaws, the tree line is expected to move north, opening up new areas for forestry. However this northward movement will be uneven, because in many parts of the Arctic, there is not enough water in the soil to support tree growth. Areas where sufficient water is available include eastern Canada, western Russia and Fennoscandia.

Many existing forests are growing more slowly, because more frequent winter snow melts result in a smaller spring melt, when trees most need water to grow. Conifers, such as pine, spruce and juniper, are particularly affected, while broadleaf trees, such as birch, aspen and alder, can make better use of summer rainfall for growth.

Trees are more susceptible to insect pests as a result of drought stress, forest fires and damage caused by heavier snowfalls. The Siberian silk moth now represents a serious threat to coniferous forests in Scandinavia, and the North American engraver beetle has caused heavy mortality of white spruce trees in many parts of Alaska.



Major hydroelectric facilities in ice-dominated river systems



Installation, MW:
 ● < 600 ● 600 - 2000 ● > 2000

Hydroelectric power

Hydroelectric power is developing rapidly in response to increased availability of water, as glaciers melt more quickly and snow melts more often during winter (see box). More than 80 GW of hydroelectric power is already generated in Arctic regions.

Currently, much of the energy from the highest spring flows is wasted, because these flows are beyond the operational capacity of the power

plants. More frequent melting and freezing of ice and snow in winter will produce a more even supply of water throughout the year, increasing the potential for energy generation.

Increased water availability for hydroelectric power is expected to last for several decades in most areas. However, as glaciers and ice caps shrink, the volume of meltwater will eventually decrease, reducing how much energy can be generated.

Hydroelectric power in Greenland

Meltwater from the Greenland Ice Sheet is being used to generate hydroelectric power. Hydroelectric power plants have been built in Nuuk, Tasiilaq, Qaqortoq/Narsaq, and Sisimiut. A fifth plant is under construction north of Ilulissat. This plant will supply the Ilulissat area with renewable energy in 2013.

Currently, 60% of public energy production in Greenland is from renewable sources. This share will increase to 70% by 2013. Hydroelectric power plants have displaced energy production based on fossil fuels.

Other plants are being planned. Future plants could generate enough energy to supply activities such as aluminum smelting, with the ore brought in by ship from Australia or South America.

As the ice sheet edge changes position, meltwater drainage patterns may alter, diverting water away from dams. This potential threat needs to be understood, to ensure that future hydroelectric power plants are economically viable.

NON-RENEWABLE RESOURCES

Access to oil, gas and minerals is easier, but many challenges remain for these industries in the Arctic.

Extraction of non-renewable resources in the Arctic is limited by access to sites and transportation of products. Loss of sea ice and shrinking of the Greenland Ice Sheet are opening up access to oil, gas, and mineral deposits that were previously difficult to reach. However loss of ice roads and increased shipping hazards create new challenges for transporting products to market and for operating oil platforms at sea.

Oil and gas

Reduced sea-ice cover and a longer ice-free season will ease transport to and from offshore platforms using barges and tankers. More exploration for oil and gas using seismic surveys from boats will be possible. There will be increased access to ports and some onshore oil facilities. However, increased wave action, storm surges and icebergs pose significant hazards to offshore platforms and associated

ships. Erosion of coastal areas, where many oil and gas facilities are based, is also likely to increase.

Onshore production will be affected by thawing permafrost and melting ice roads. Many oil facilities, including buildings, pipelines and roads, are built on permafrost. When it thaws, they are likely to suffer damage (see section 4.4 and box). A shorter ice road season will also restrict exploration and construction activities (see section 4.3).

An indirect effect of cryospheric change on the oil industry is that environmental regulations may get stricter, because fish stocks, marine mammals and other wildlife species are likely to move north into areas where oil and gas are extracted. The oil and gas industry will have to contend with these, as well as with the risks of oil spills and spill remediation costs that accompany increased activity.

Minerals

While the mineral extraction process itself is unlikely to be affected by cryospheric change, other parts of the mining process, such as the transport of products and management of waste, will be affected more.



Nearshore mining operations are likely to benefit from easier transport of materials to and from mining sites by ship. Mining usually follows a seasonal cycle: in the winter, ores are extracted, concentrated and stored, ready for export in the summer



© B&C Alexander / ArcticPhoto



© www.gazprom.com

when shipping lanes open. Melting sea ice will provide a longer window for transport.

But overland transport to and from remote mines will become more difficult. Ice roads will be operational for a shorter period, and roads built on permafrost will require more maintenance if the permafrost thaws (see section 4.3). Roads that will be particularly affected include the Tibbitt to Coatwoyto Winter Road in northern Canada and a 360-km long winter road in the Chukotka region of Russia. Both roads are open only for short periods each year during the coldest months, but are needed to transport thousands of tonnes of ore from mines.

Mining operations will need to find alternative ways of storing waste. In the past, some mines relied on the permanently frozen ground to prevent contaminants entering the environment. Now, as the ground starts to thaw, mining operators will need to invest in structures that can contain their waste.

Effects on oil pipelines

In Russia, pipelines built above ground are susceptible to problems related to thawing permafrost and 'frost heave', when ice forms beneath their foundations gradually pushing them out of the ground. It has been estimated that thawing permafrost is annually responsible for around 7000 pipeline failures in western Siberia. Oil pipelines in Alaska and Canada are less likely to be affected by permafrost thawing. However more maintenance work may be required to ensure that they remain operational in the face of these challenges.



© Rolf Hicker



4.3 CHANGING ACCESS

Change in access is an inevitable consequence of cryospheric change in the Arctic, and is probably the most influential factor affecting Arctic society. Some areas will be more accessible, such as areas previously covered by sea ice, whereas ice roads will be less accessible. Human activities will be affected in a variety of ways: while some people and businesses will benefit from the changes, others will lose out.

Increasing access by sea

The Arctic is becoming more accessible by sea, as melting sea ice creates larger areas of open water for longer periods of time in the summer. Trans-Arctic shipping routes are opening up between the Pacific and Atlantic Oceans (see section 5.3 for this global aspect). However the relatively shallow water depth along the Siberian coast limits the size of ships, reducing the opportunities for shipping in this area.

Currently, most Arctic shipping is to or from ports in the Arctic. An increase in shipping will have benefits for industry, particularly the oil, gas and mining industry (see section 4.2). People who live near the coast are likely to benefit from increased access by sea, as supplies can be brought in more easily by ship, and over a longer season. Sea-ice decline could also improve access to fishing areas by boat, increasing harvests and incomes.

Cruise ship tourism is increasing, aided by easier passage through areas with less ice. However cruise ships provide limited benefits to Arctic residents as passengers often remain on ships throughout their journey. A particular issue relating to cruise ships is the limited Search and Rescue service available in the Arctic. If a large ship should find itself in trouble, local residents do not have the means to provide assistance.

An increase in shipping will also create new problems. The risk of accidents such as oil spills from tankers will increase as more tankers pass through Arctic waters. When icebreakers and ships make tracks through the sea ice, they fragment the habitats of animals and destroy local travel routes over the sea ice. More shipping in connection with warming waters will also increase the risk of bringing new invasive species to the Arctic.



© B&C Alexander / ArcticPhoto

Challenges for shipping

While ships will be able to access new areas, they will still face a number of hazards from icebergs and drifting sea ice. The number of icebergs in Arctic waters has increased, and with less sea ice, these icebergs will be more mobile. Icebergs represent a major hazard for shipping, commercial fisheries, seismic surveys and oil platforms.

More clouds and fog can form when cold air sits on top of large areas of open water, after the summer sea ice has melted. This will make navigation more difficult and can cause ships to ice up.

Search and Rescue services will need to expand their operations as the number of ships passing through the Arctic increases. Ships and their crews need to be appropriately equipped and prepared, as Search and Rescue services can be slow to arrive due to the vast distances involved. There will also be an increased demand for seasonal ice-breaking of harbors and sea routes,

and more investment will be needed in ships and ports.

Travel over sea ice

The area covered by summer sea ice is declining rapidly, and sea-ice conditions have become more unpredictable and dangerous for travelers. Traditional knowledge of travel routes over the ice is becoming less useful, and concerns about safety create a need for new technology such as satellite phones and GPS (geographic positioning systems). Travelers over ice must act with greater caution, and certain journeys are no longer possible, leaving some communities more isolated.

For example, in the western Canadian Arctic, a reduction in sea ice and unpredictable fogs have made coastal travel over sea ice more dangerous. To cope with these changes, some people choose to travel by boat, but high fuel costs put an extra strain on household budgets.

While the Arctic is opening up to shipping, travel over land or sea ice is becoming more difficult.

Travel over land

While sea travel is becoming easier, travel by land is getting more difficult. Ice crossings over rivers and lakes are melting earlier and freezing later, shortening the period when ice roads can be used. Roads built on permafrost are more vulnerable to cracking and subsidence as the permafrost thaws beneath them.

Although winter road networks are used only for a few months a year, they are of considerable economic importance. Winter roads are used to transport millions of tonnes of supplies to and from Arctic communities. For some, they act as a lifeline and play a critical role in connecting remote communities with each other and with those outside the Arctic, allowing both local and international trade.

Ice roads are also critical for the transport of heavy loads, fuel and equipment to and from mining centers and industrial facilities, and for the export of goods (see section 4.2). Even relatively small-scale changes in ice thickness or mechanical strength can have major implications for the transport of heavy goods across frozen lakes and rivers.



© U.S. Coast Guard



Losing lake and river ice road networks

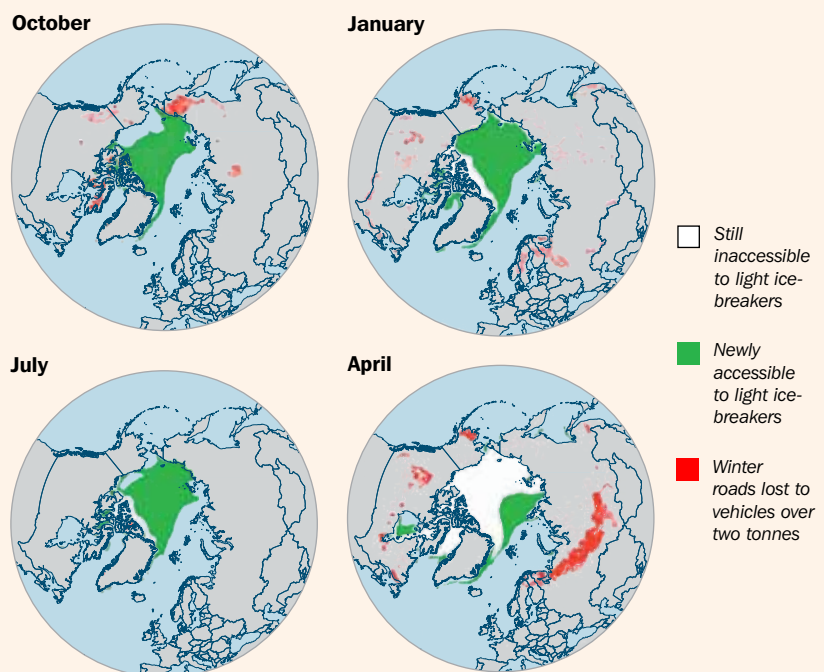
The network of winter roads over frozen bogs, lakes and rivers in the Canadian province of Manitoba typically carries more than 2500 shipments each year to more than 30000 indigenous people. Mild weather during the winter of 2009/10 stranded numerous freight-haulers and local drivers on thawed winter roads and led to the closure of a 2200 km section of the network. In response to dwindling construction supplies, rising food and fuel prices and a related rise in unemployment, a state of emergency was declared in eleven communities. Adapting and maintaining networks to prevent situations like this is possible, but the speed and scale of the changes is making it increasingly challenging and expensive. According to the Government of Manitoba, approximately 600 km of this winter road system has been relocated to land since 2001, and spending on winter roads in the province has tripled since 1999.

Alternatives to ice roads and routes over permafrost

As transport across ice roads and permafrost becomes more difficult, river transport is likely to become more important. Rivers will be navigable for more days in the year, and the volume of traffic is likely to increase. In some areas of the Russian Arctic, waterways are already so commercially important that nuclear-powered ice breakers are used to extend the shipping season. On the Mackenzie River in Canada, a six to nine week reduction in the ice road season could result in as much as a 50% increase in river-based transport in the area.

For land-locked areas, the only feasible option for transporting heavy loads may be by rail or on land-based all-weather roads. Construction of these roads is very expensive, and costs are likely to increase in the future.

Projected change in access for maritime and land-based transportation by mid-century



4.4 CHANGING RISKS TO BUILDINGS AND LAND

Changes in the cryosphere, such as thawing permafrost, changing snowfall patterns and changes in ice dynamics, will affect buildings and other structures that are essential for human survival in the Arctic. In most cases, engineering solutions are available but expensive. In the areas where permafrost is thawing most quickly, economically viable solutions are hard to find. The uncertainty associated with projections of change also increases the cost of new building projects in the Arctic.

Many people in the Arctic live in permafrost regions. The buildings in which they live and work, and the structures on which their societies depend, stand on frozen ground. Even some large towns and cities with populations between 50 000 and 200 000 inhabitants are built on permafrost.

When the permafrost thaws, the ground becomes softer and often changes shape. Buildings and other structures such as bridges, dams, pipes and water treatment plants are affected, as their foundations become less stable. They may sink further into the ground, or tilt as one part sinks more than another, or cracks may form because different parts of the structure are sinking at different rates. Structures weakened by these processes require more maintenance, which is often expensive. In rare cases, buildings have to be abandoned.

In order to cope with the changing conditions, new design methods are being developed that take into account the likelihood of change as well as the consequences of structural failure. For example, if a pipeline is to be built in an area where permafrost is already thawing, great care needs to be taken to design the structure to last even if the ground thaws completely, because of the risk of pollution if the pipeline ruptures.

Thermokarst

Thermokarst is the name for a type of landscape that forms when parts of the ground collapse because underground ice has melted. Thermokarst is increasing in some parts of the Arctic. When thermokarst occurs in towns and cities, it can cause a lot of damage. For example, in 2006, several cars fell into a huge thermokarst crater that had formed under a car park in Yakutsk, Russia.

Increasing snow loads on buildings

The amount of snow building up on the ground and on buildings is projected to increase across much of the Arctic, with the largest increases in Siberia. Heavier snow loads can result in damage to buildings. For example, in the severe snow winter of 2007/08 in Quebec, several people were killed when buildings collapsed. Buildings are usually designed to withstand snow loads based on the maximum snow depth in previous years. As snow conditions change, building designs need to take increases in snow depth into account. Snow load calculations are being reviewed and updated in Canada and other countries to meet this need.

The risk of floods

Floods caused by the release of ice-jams in rivers in spring have changed in frequency and size. In east Siberian rivers there is a trend towards more severe flooding. For example, the city of Lensk had to be rebuilt after a catastrophic flood of the Lena River in 2001.

Flash floods and mud flows can also occur as glaciers shrink, releasing water from ice-dammed or sub-glacial lakes. These are a particular hazard in volcanic areas such as Iceland, Alaska and Kamchatka. Retreating glaciers could lead to

Causes of building failure: climate change or poor design?

Poor design has been blamed for failures of buildings and other structures in the Arctic. Recent evidence points to thawing permafrost resulting from higher temperatures as a major cause of building deformation in some cases. The design of many existing buildings assumed that the ground would remain frozen. In areas where the ground now thaws regularly, the lifetime of such buildings will be shorter.



Less sea ice in recent years has resulted in more storm damage to buildings in the coastal settlement of Uelen, Chukotka, Russia.

an increase in these outburst floods, and a few potentially dangerous glacial lakes have been documented in Norway and Canada.

Hazards caused by the movement of sea ice

The action of wind on sea ice can cause ice to pile up on shore, sometimes extending more than a hundred metres inland. Although rare, these pile-ups are particularly dangerous because they occur quickly and unexpectedly, accumulating in less than an hour. They can cause significant damage to buildings and other shore-line structures, and can cause injury or death. Thinner sea ice will be more likely to pile up in this way. Despite a shortening of the ice season, ice pile-ups will remain a hazard for coastal areas.

Coastal erosion

Erosion is an increasing problem for Arctic coastlines. 65% of Arctic coastlines are made up of loose materials, held together by ice within or above the soil. When this ice melts, the soil can easily be eroded. Land-fast sea ice also protects the coast from erosion, preventing waves and storms from washing the soil away. As the ice melts for longer periods each year, coasts are left unprotected. The result is rapid erosion in some areas. This will mostly affect Russian coasts bordering the Laptev and East Siberian Seas. Parts of the Alaskan and Canadian coastlines will also be affected.

Coastal buildings, roads and other structures are in danger of being flooded or washed away by storm waves. In some areas, communities

are left with no choice but to move to new locations. About 30 Alaskan native villages have been identified as facing immediate flooding and erosion threats. Several are exploring relocation options, and four must relocate as a matter of urgency. Their case highlights the need for government involvement. In particular, there is a need for government agencies that have the authority to relocate communities, and that can provide financial assistance and help communities to choose new locations.



© Ryerson Clark / iStockphoto

Arctic buildings and other structures are at risk from thawing permafrost, heavier snow loads, flooding and erosion.

4.5 CHANGING MOVEMENT OF CONTAMINANTS

Changes in snow, ice and permafrost affect how contaminants enter and leave the Arctic, and how they move around within the Arctic.

Contaminants from activities outside the Arctic

Contaminants found in the Arctic include heavy metals, radioactive compounds, black carbon (soot from fires or other industrial activity) and man-made chemicals known as persistent organic pollutants that remain stable in the environment for long periods of time. Most of these result from human activities outside the region. They are carried north by air and ocean currents. Once in the Arctic, many remain locked in surface soils, water, ice and sediments.

Contaminants from activities within the Arctic

In permafrost regions, the permafrost itself has been used to contain waste, such as sewage, rubbish and waste from oil drilling and mining activities. When the permafrost thaws, the contaminants can be washed into groundwater, rivers and ultimately the sea. In Canada, some of the 300 to 400 sumps storing drilling fluid from oil and gas exploration have been found to be leaking.

Shipping, exploitation of resources, industrial activities and tourism are all increasing in response to reduced summer sea ice in the Arctic Ocean. They bring risks of additional contaminants such as antifouling chemicals and ship exhaust fumes. The risk of accidents is also likely to increase as more ships pass through the Arctic, and this could result in oil spills from tankers. There are no effective means of cleaning up oil spills in broken ice. Responding to such spills in winter is currently impossible, given limited daylight and severe weather.



Contaminants from the major source regions in the northern mid-latitudes are mostly carried into the Arctic by the prevailing winds and ocean currents.





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Polar bears in the Hudson Bay were found to have higher levels of persistent organic pollutants (POPs) during years of early ice break-up, when they were primarily hunting seals that live closer to shore (whose prey also has higher levels of POPs).

Contaminants that were deposited many years ago can re-enter the environment when the ice and snow that contained them melt.

Contaminants moving differently

Contaminant movements into, out of and around the Arctic are affected by changes in the cryosphere. There are various ways this can happen.

Movements between air and sea. Sea ice forms a barrier between seawater and air, preventing some contaminants from evaporating into the air, and others from being deposited into the sea. When sea ice melts, this barrier is removed, and the potential for exchange of contaminants between sea and air increases. Along the coast of Spitsbergen (Svalbard), loss of

continuous ice cover in the Fram Strait has allowed a contaminant called hexachlorobenzene (HCB) to evaporate out of the sea during winter.

Movements through food webs.

Mercury and many organic contaminants accumulate in animals' bodies, building up in fatty tissues. If the animal is eaten, the contaminants travel up the food chain and become more concentrated. Top predators such as seals, polar bears, humans and sea birds can be exposed to dangerously high levels, with the potential to affect their health. When people or

animals change their diets in response to cryospheric changes such as disappearing sea ice, their exposure to these contaminants can be affected.

Release of contaminants from snow, ice and permafrost. Contaminants can become trapped in snow, ice and permafrost for months or years. Contaminants trapped in glaciers and ice caps, including black carbon and lead, could remain there for centuries or millennia. When the snow and ice melt or the permafrost thaws, these contaminants are released back into the environment.



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TECHNICAL TERMS EXPLAINED

Persistent Organic Pollutants (POPs)

Persistent organic pollutants are resistant to being broken down by biological and chemical processes or by exposure to light and ultra-violet radiation. They remain in the environment for long periods and can be transported long distances, either in the air or in water. POPs include industrial chemicals such as PCBs (polychlorinated biphenyls) and organic pesticides including DDT (dichlorodiphenyltrichloroethane) and lindane (hexachlorocyclohexane or HCH).

Coastal erosion washing away a former dump site, possibly containing toxic PCBs, on Barter Island, Alaska.



© Steven Kazlowski / Science Faction / Corbis



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4.6 CHANGING ARCTIC LIVING CONDITIONS

Changes in the cryosphere can substantially alter livelihoods and living conditions in the Arctic. Huge uncertainty remains over how the changing cryosphere will affect Arctic societies and the quality of life of Arctic residents, and when impacts will be felt. The concerns of Indigenous Peoples need particular attention in this regard.



© B&C Alexander / ArcticPhoto

Changes in the cryosphere will result in changes to many aspects of life and society.

Economic opportunities and challenges

The changing conditions in the Arctic bring economic opportunities and challenges. Livelihoods based on living resources are likely to suffer. Animals and plants will be directly affected by rising temperatures, thawing soils and changing snow and ice conditions, and also harvesting activities will be more difficult due to cryospheric changes. New opportunities, such as increased shipping, resource extraction and cruise tourism, are expected to benefit companies based mainly outside the Arctic. Tourism may also bring local benefits in some areas (see box).

Challenges for Indigenous Peoples

Many indigenous communities are being challenged to maintain their way of life, both by changes in their environment and by the influx of people and industry. The indigenous communities living in the most northerly areas are experiencing the most extreme environmental changes.

Traditional knowledge and skills, such as those associated with fishing and hunting on ice, continue to evolve. But it is a challenge to ensure that this knowledge is being passed on to younger generations as lifestyles change. Some aspects of traditional knowledge become less applicable as the cryosphere and other components of the Arctic system change even more rapidly and become less predictable.

Health risks from a changing cryosphere

Cryospheric changes may increase the risk of food poisoning in some areas, because storage of foods in permafrost ice-houses is no longer possible during some parts of the year. Waterborne diseases can also spread if drinking water and sewage pipes are damaged when permafrost thaws or during floods.

Tourism – a new livelihood opportunity

Tourism is increasing as it becomes easier for people to get to the Arctic, largely due to melting sea ice and easier access by ship. Tourism creates new economic opportunities for communities and residents, guiding tourists on hunting and fishing trips, providing food and accommodation, and producing and selling indigenous handicrafts. Cruise ship tourism is also increasing (see section 4.3).

Many tourists come to see Arctic glaciers and to witness firsthand the impacts of climate change, as glaciers retreat, sea ice melts and snow cover reduces. Ilulissat has become Greenland's leading tourist destination as people come to see the ice flux at Ilulissat Ice Fjord (*Sermeq Kujalleq* in Greenlandic), now a UNESCO World Heritage Site. In Alaska, tourism contributes 39 000 jobs and over USD 1.15 billion in salaries and benefits to the economy every year.

But disappearing snow and ice also threaten tourist attractions. Arctic wildlife and scenery that people expect to see are being lost in some areas. Examples include the decline of iconic species such as the polar bear, and the rapid retreat of mountain glaciers in national parks in Alaska and Canada.

Tourism development will also bring changes to the Arctic, such as more pollution from cruise ships, thousands of passengers on short-term visits in small communities and increased disturbance of landscapes and wildlife.

PART 5:

WHY CHANGES IN THE ARCTIC MATTER GLOBALLY

Cryospheric changes will be felt initially within the Arctic region, as described in the previous section. The effects of cryospheric change will also be felt globally over longer timescales, through effects on the global climate and on sea-level rise. A continued rise in sea level will increase the risk of flooding for millions of people around the world.

Changes in the Arctic cryosphere affect global climate

- The disappearance of white snow and ice accelerates warming because the planet's surface becomes darker, so that it absorbs more of the sun's heat. This feedback process seems to be happening already over the ocean as the sea ice retreats.
- Overall emissions of the greenhouse gases methane and carbon dioxide from the Arctic could increase substantially due to warming soils and water bodies, and changes in permafrost extent on land and under the sea.
- The total amount of freshwater entering the Arctic Ocean has increased. The increased freshwater input could alter large-scale ocean currents that affect climate on a continental scale.

Melting Arctic land ice is contributing to sea-level rise

- Ice loss from Arctic glaciers, ice sheets and the Greenland Ice Sheet contributed over 50% of the global sea-level rise between 2003 and 2008.
- High uncertainty surrounds estimates of future global sea-level rise. Latest models predict a rise of 0.9 to 1.6 m above 1990 levels by 2100, with Arctic land ice making a significant contribution.

Consequences for global society

- Global sea-level rise is increasing the risk of flooding for hundreds of millions of people living in coastal deltas and low-lying islands around the world.
- Melting sea ice is opening up new global transport routes through the Arctic Ocean in the summer. Increased opportunities for transpolar commercial shipping will benefit transport and trade.





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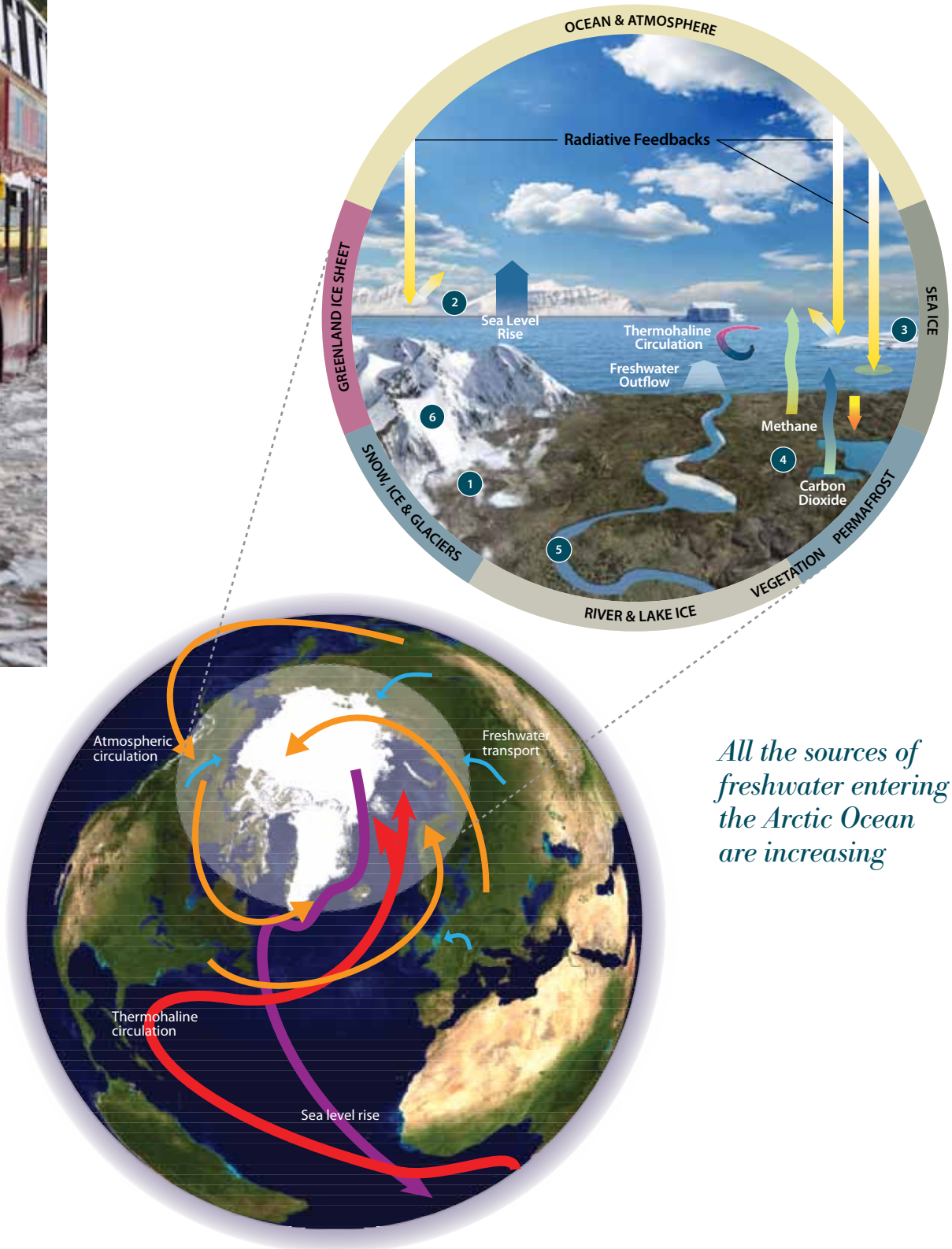


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5.1 CHANGES IN THE ARCTIC CRYOSPHERE AFFECT THE GLOBAL CLIMATE

The Arctic is an important part of the Earth's climate system. Changes in the amount of ice, snow and frozen soils in the north could have substantial impacts on the climate in other parts of the world.

The Arctic cryosphere stores water as ice and snow, and prevents a massive amount of organic matter from decomposing because of the cold. As the ice and snow melt, they add freshwater to the Arctic Ocean. At the same time, organic matter stored in the Arctic is starting to decompose as the permafrost thaws, resulting in high methane emissions in some areas.



All the sources of freshwater entering the Arctic Ocean are increasing

Impacts and processes

- 1 Melting and retreating snow cover and more shrub growth increases heat absorption, a radiative feedback.
- 2 Melting of large ice sheets contributes to sea-level rise and the freshwater flux with potential effects on thermohaline circulation and global climate.
- 3 Retreating sea ice contributes to increased radiative absorption (ice-albedo feedback) and heat and moisture fluxes to the atmosphere.
- 4 As permafrost degrades, methane production may increase. With wetland drying, carbon dioxide emissions may increase, and the atmosphere warms over time.
- 5 Increasing precipitation plus melting snow and ice increases river flow and changes the freshwater flux.
- 6 Retreating glaciers initially increase runoff but lower flows eventually result as ice masses diminish.

The changes taking place in the Arctic cryosphere are having planetary-scale effects on both climate and sea level (see section 5.2). There are three main ways that changes in the Arctic cryosphere can affect the world's climate.



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1 **Losing the Earth's white cap**

The Arctic has a cooling effect by giving the planet a white reflective surface at the top, created by snow and ice over land and sea. This reflects away more of the sun's warmth than a dark surface would. The effect of losing the white coating is to enhance the warming that is already taking place. Patterns of temperature change in the lower atmosphere since 2005 indicate that this feedback effect is already happening over the sea. Temperatures are rising fastest where the sea ice is retreating (see section 2.1). Over land, model projections have shown that loss of snow cover and more shrub growth could increase temperatures as much as doubling the amount of carbon dioxide in the atmosphere would, just because of a change in surface color.



© Fred Hirschmann / Science Faction / Corbis

2 **Increasing emissions of greenhouse gases**

As the Arctic warms, emissions of carbon dioxide and methane from land and water could increase because decomposition happens faster at higher temperatures (see box on facing page). Some of the extra carbon dioxide emissions will be countered by plants and algae in the sea absorbing and storing more carbon dioxide as they grow faster in a warmer Arctic.

Clear lake ice reveals frozen methane bubbles rising from the bottom of Lake Lucille, Alaska.



© Dr. Marif Miller / Visuals Unlimited / Corbis

3 **Changing ocean currents**

When freshwater flows into the Arctic Ocean from rivers and melting land ice, it does not mix well with the salty sea water, but sits near the surface and insulates the sea ice from warmer Pacific and Atlantic water beneath. All the main sources of freshwater entering the Arctic Ocean are increasing: river discharge, rainfall and melt water from land ice. Calculations estimate that an extra 7700 km³ of freshwater – equivalent to one metre of water over the entire land surface of Australia – has been added to the Arctic Ocean in recent years. It is not known what will happen to this freshwater (see section 6.2). However, large-scale ocean currents, such as the Atlantic thermohaline circulation that brings warm water to northwest Europe, are sensitive to freshwater flows from the Arctic, and can affect climate and rainfall patterns on a continental scale.

Positive feedbacks

The first two of these climate effects – decreasing whiteness and increasing release of greenhouse gases – are positive feedbacks. This means that the initial change causes effects that amplify the change. Both processes could magnify or accelerate global climate change.

WILL SINK TURN TO SOURCE?

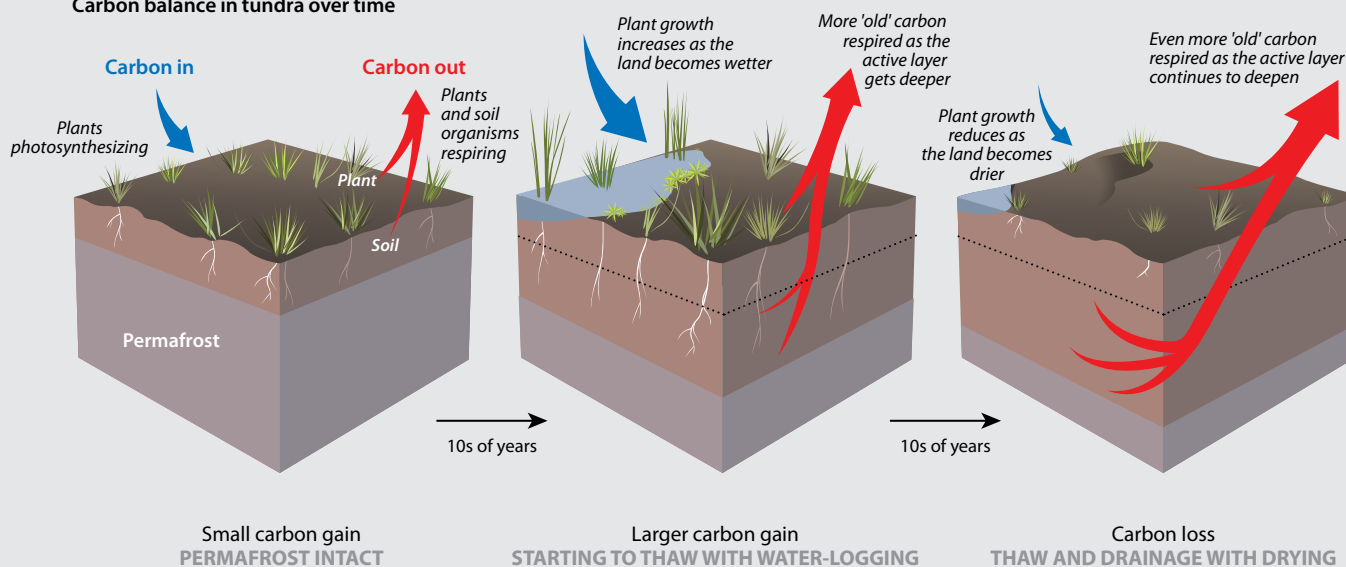
Carbon dioxide (CO₂) and methane (CH₄), two of the most important greenhouse gases currently causing the planet to warm, are both emitted when organic matter decomposes.

Carbon dioxide

At present, Arctic land areas are slowly absorbing carbon dioxide from the atmosphere and preserving it in plant tissues that gradually become peat or part of the soil. This has been happening for thousands of years. Around 44% of the world's near surface soil carbon is stored in Arctic soils – about twice as much carbon as in the entire Earth's atmosphere.

If the permafrost thaws on a large scale this century or later, a substantial amount of this soil carbon will be converted to carbon dioxide, potentially increasing the amount of carbon dioxide in the atmosphere. This process could override the gradual storage of carbon due to plant growth on land and algal growth in water.

Carbon balance in tundra over time



Methane

In conditions without oxygen, such as at the bottom of a lake or the sea, decomposition turns organic matter into methane, rather than carbon dioxide. Large increases in methane emissions would be a grave concern, because methane is 25 times more effective at warming the planet than carbon dioxide (over a 100 year time scale).

Lakes, ponds and mires in the Arctic can release methane and carbon dioxide at high rates if conditions are right. Decreasing

ice cover over lakes is known to increase methane production. Large releases of methane from permafrost areas were first recorded in autumn 2007 in northeast Greenland, and thaw lakes in Siberia are known as hotspots for methane production.

Future rates of methane production from Arctic wetlands and thawing permafrost are difficult to predict because it is not clear whether more wetland and lakes will be formed due to the thawing of ice-rich permafrost, or fewer, because of summer drying.

Large quantities of methane are stored in sub-sea permafrost layers as methane hydrates. In the last three years, high levels of methane have been discovered emerging from below the bed of the Laptev Sea, pluming upwards to 1800 m high in the atmosphere. This methane has been stored since the end of the last ice age when sea level started to rise. It has been calculated that a release of just 1% of the methane estimated to be present in permafrost below the seabed of the East Siberian shelf would have a warming effect equivalent to doubling the amount of carbon dioxide in the atmosphere.



Methane hydrate is water and methane combined under low temperature and high pressure. It is a frozen, lattice-like crystalline substance, which looks like ice but burns readily if lit by a match.



© Ralph Lee Hopkins / National Geographic Society / Corbis

5.2 MELTING ARCTIC LAND ICE CONTRIBUTES TO SEA-LEVEL RISE

How do we know sea level is rising?

Global sea level is measured from satellites and at coastal stations. The contribution from thermal expansion of water is difficult to work out, but a new network of robotic probes in the world's oceans has made such measurements possible. The contribution to sea-level rise from melting glaciers and ice caps is estimated from the amount of ice lost when icebergs break off from glaciers and when surface ice melts. Approximately 360 gigatonnes of melted ice is equivalent to 1 mm of global sea-level rise.

The Arctic is now the main contributor to global sea-level rise.

Global sea level has been rising since the mid-1800s. During the 1900s, the average rate of sea-level rise was 1 to 2 mm each year. Since 1990, the rate of sea-level rise has increased. Global sea level is now rising faster than most of the projections in the Intergovernmental Panel on Climate Change's Third and Fourth Assessment Reports (published in 2001 and 2007).

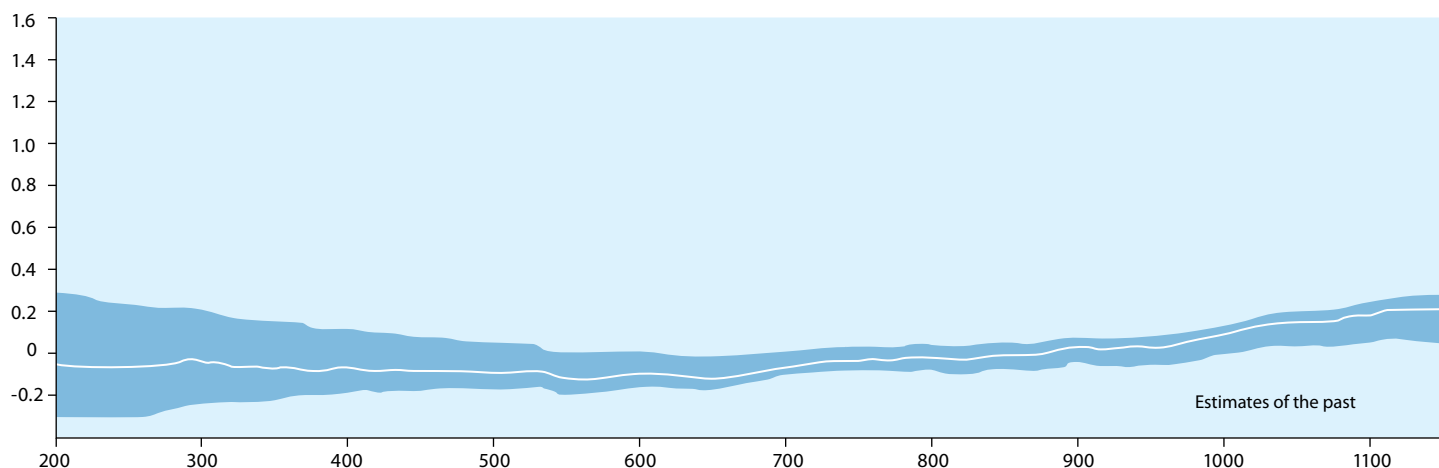
Two main processes contribute to sea-level rise. First, ocean water expands as it warms up ('thermal

expansion'). Second, when land-based ice melts and flows into the sea, the volume of the sea increases.

The contribution of Arctic land ice to sea-level rise

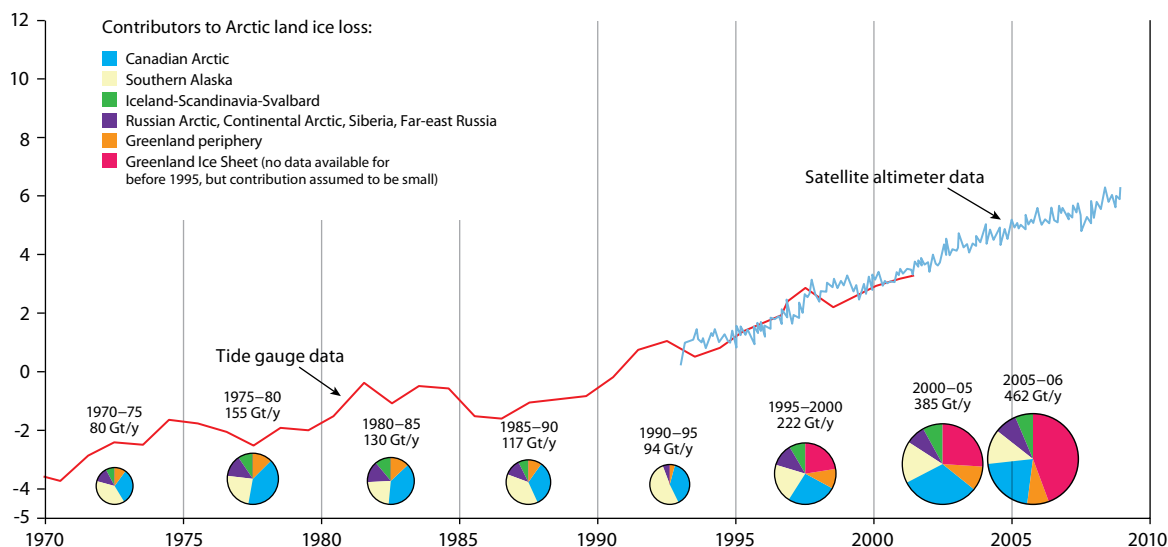
Between 2003 and 2008, global sea level rose by 2.5 mm/y on average. The melting of Arctic land ice, including the Greenland Ice Sheet, contributed 1.3 mm/y to this – over half (52%) of the total rise. Thermal expansion of the ocean contributed just 0.25 mm/y, and the Antarctic Ice Sheet an estimated 0.5 mm/y. Other contributors to sea-level rise are mountain glaciers in other parts of the world and changing amounts of water storage on land.

Global sea level relative to 2000, m



Change in global sea level and loss of Arctic land ice

Global sea-level change relative to the average for 1970–2008, cm



The contribution from the Greenland Ice Sheet is accelerating

Between 1995 and 2000, the Greenland Ice Sheet contributed 0.14 mm to global sea-level rise per year – less than 5% of the global total. However, the Greenland Ice Sheet is shrinking at an increasing rate and its net loss of mass has increased four-fold since then. Its contribution to global sea-level rise in 2005–2006 was 0.57 mm annually. The Greenland Ice Sheet alone now contributes over 20% of global sea-level rise.

Sea-level rise in the future

Given the scale of changes seen in the past 20 years, what does the future hold? Current models project a rise in sea level of between 0.79 and 2.01 m above 1990 levels by 2100. It is estimated that between 0.05 and 0.13 m of this rise will come from Arctic glaciers, and 0.17 m will

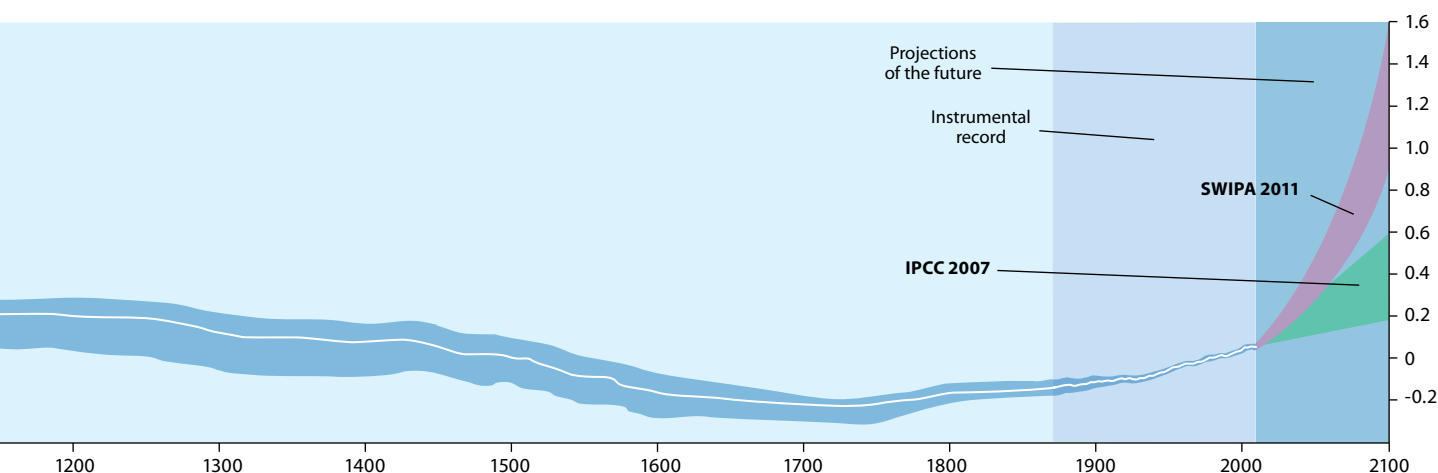
In 2005–2006, the Greenland Ice Sheet alone contributed over 20% of global sea-level rise.

come from the Greenland Ice Sheet. However, a great deal of uncertainty surrounds these projections. It is not possible to predict exactly how individual ice caps, ice sheets and glaciers will respond to changes in global climate, and different models lead to very different projections. An estimate ranging between 0.9 and 1.6 m sea-level rise seems the more plausible.

Despite these uncertainties, all the models agree that Arctic glaciers and the Greenland Ice Sheet will continue to make a significant contribution to future sea-level rise beyond the end of this century. These projected increases in sea level are expected to have major consequences for coastal communities in some parts of the world (see section 5.3).

Does sea level rise equally all over the world?

Sea level may rise at different rates in the northern and southern hemispheres. This is because the Arctic and Antarctic ice sheets are large enough to exert a gravitational pull on the water around them. When they melt and their mass is reduced, this pull gets less and water moves away. If land ice melts faster in the Arctic than in the Antarctic, sea level will rise more in the southern hemisphere. If the Antarctic ice sheet melts faster than the Arctic land ice, the opposite will happen.





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5.3 CONSEQUENCES FOR GLOBAL SOCIETY

Changes in the Arctic cryosphere will have major consequences for people and ecosystems in other parts of the world.

Physical changes to the cryosphere influence global climate and weather, and this is very likely to affect human society beyond the Arctic over the coming decades and centuries. The effects of a rising sea level are already being felt in some parts of the globe, such as some small island states. Cryospheric change also threatens global biodiversity as some species that are found only in the Arctic are threatened.

Other effects of cryospheric change include increased access to the Arctic Ocean. Shipping through the Arctic Ocean will benefit resource extraction, trade and tourism and may reduce energy consumption and thus carbon dioxide emissions. At the same time

increased access to the Arctic Ocean will result in increased pollution in Arctic waters and disturbance of people and wildlife.

The effects of sea-level rise

Sea-level rise is one of the most serious societal impacts of cryospheric change. About 200 million people live less than one metre above sea level, in low-lying coastal areas such as the Ganges-Brahmaputra delta (Bangladesh), the Mekong delta (Vietnam), and the Rhine delta (the Netherlands). Higher average sea level and more frequent storm surges increase the risk of flooding in these areas.

Sea-level rise severely threatens the existence of a number of small

island states, such as the Maldives in the Indian Ocean, the Bahamas in the Caribbean and Tuvalu in the Pacific. They are in danger of becoming completely submerged or facing increased coastal flooding. Adaptation will be difficult in many island settings, and in some places not feasible at all.

Projections of sea-level rise vary with geographical location. In the north-eastern United States, eastern China and Japan, sea level is projected to rise more than in other parts of the world, placing large coastal cities such as Shanghai and New York at greater risk of flooding.

While new shipping routes offer global opportunities for trade, rising sea level increases the risk of coastal flooding around the world.



Effects on global shipping and trade

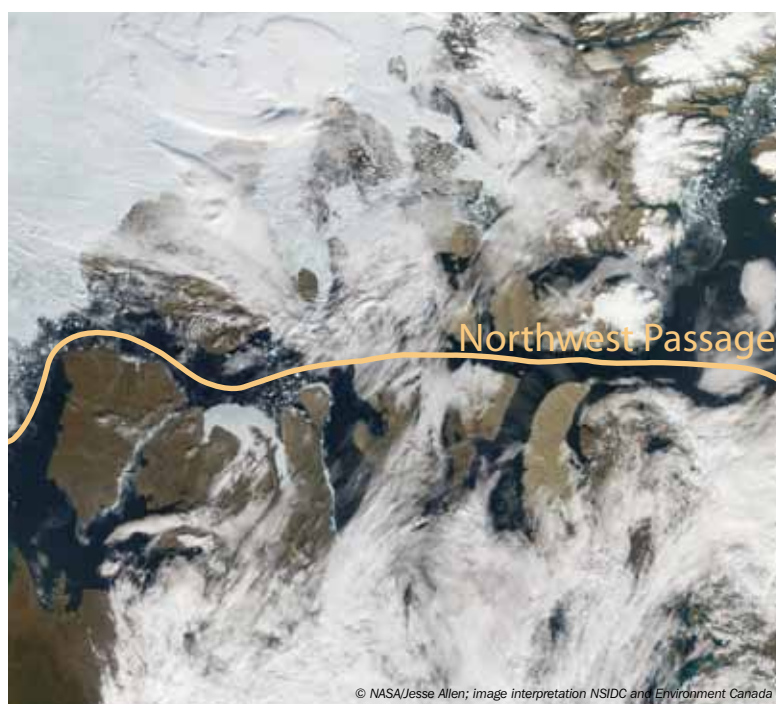
Global economic activity may benefit from cryospheric changes in the Arctic. The melting of the sea ice is opening up the Arctic Ocean to shipping for longer periods each summer, increasing opportunities for transpolar commercial shipping. New shipping routes could reduce energy use and global emissions of greenhouse gases, while also promoting trade. However local emissions will increase.

An increasing number of trans-Arctic summer voyages have taken place, mainly for science and tourism. Two merchant ships recently passed through the Northern Sea Route, which is 40% shorter than current shipping routes between Europe and the Pacific. The volume of transport along this route is predicted to increase by up to 12.8 million tonnes by 2020.

The development of transpolar commercial shipping is likely to be slow. It will probably be driven by economic factors such as the global demand for natural resources and the price of these resources. The ships using these routes will continue to face considerable hazards, such as challenging weather conditions and drifting sea ice and icebergs.

Effects on global biodiversity

Some unique Arctic species, such as the narwhal and the polar bear, face particular threats as the cryosphere changes. The decline of cryospheric habitats such as sea ice and wetlands over permafrost will impact on migratory species of marine mammals and birds from elsewhere in the world. These adverse effects on biodiversity are of global concern. More information on the status of Arctic species can be found through the Conservation of Arctic Flora and Fauna Working Group (CAFF).





PART 6:

WHAT SHOULD BE DONE?

This report so far has described how and why the cryosphere is changing, and how the changes affect ecosystems and people. This section considers what should be done to adapt to these changes, and what information is still needed to understand how the cryosphere is likely to change in the future.

Adapting to change

- Everyone who lives, works or does business in the Arctic will need to adapt to changes in the cryosphere.
- Arctic communities are resilient and will actively respond to cryospheric change. However, rapid rates of change may outpace people's capacity to adapt.
- Adaptation requires leadership from governments and international bodies, and increased investment in infrastructure.
- Knowledge and research are needed to foresee how living conditions are likely to change and to evaluate possible adaptation options.
- Cryospheric change and climate change occur in the context of societal change, which may be even more challenging. The combined effects of societal, climate and cryospheric change must be accounted for in adaptation strategies.

The big unknowns

- There remains a great deal of uncertainty about how fast the Arctic cryosphere will change and what the ultimate impacts of these changes will be.
- Interactions (feedbacks) between the cryosphere and other aspects of the climate are key elements of uncertainty and may greatly accelerate rates of change and their consequences in unpredictable ways.



© B&C Alexander / ArcticPhoto

6.1 ADAPTING TO CHANGE

Global mitigation of climate change is likely to take decades. Therefore local communities and businesses, as well as transnational companies with commercial interests in the Arctic, will all need to adapt to changes in the cryosphere.

A focus on adaptations

Adaptation means finding ways to cope with change, moderate change or take advantage of it. Adaptation to cryospheric change in the Arctic will be necessary to maintain a good quality of life and to protect people's livelihoods and their environment.

At the local level, cryospheric change affects people immediately. Individuals, communities and businesses have to prepare for changes proactively and adapt to changes as they occur. Local adaptation is already taking place. For example, people are changing their travel routes to avoid areas where sea ice is melting.

At the regional, national and international levels, adaptation will require increased collaboration as well

as leadership from governments and international bodies, in the form of new laws and regulations and increased investment in infrastructure.

What influences the ability to adapt?

Indigenous Peoples and other residents of the Arctic have adapted to changes in their environment, and continue to do so, despite uncertainty about the future. Arctic inhabitants are innovative and exploit opportunities, for example, by switching to open-water fishing, welcoming tourists, and embracing new technology. Traditional knowledge can help to detect change and adapt to it. However changes are occurring so fast that this is putting a strain on the ability to keep up.

Changes in the cryosphere occur in combination with societal changes such as increasing extraction of resources, population change, technological developments and globalization. Together these produce



Preparing for change

People need to prepare for change by planning and putting adaptive measures in place. But uncertainty about changing conditions and future supplies of natural resources makes planning difficult.

Short-range forecasts at the local scale are needed to help residents, communities, businesses and government agencies make decisions about which actions to take.

Better communication between local residents and the researchers who generate future projections can help to provide forecasts tailored to the needs of people living and working in the Arctic. Traditional knowledge and scientific research can be combined to improve projections of change, particularly at the local level. However the speed of change can make it difficult to keep information up-to-date, and there are large uncertainties about the timescale and size of changes.

At the larger scale, national bodies, such as co-management agencies, and

international organizations, such as the Arctic Council, can play important roles in reaching across boundaries to bring together non-governmental organizations (such as Indigenous Peoples' organizations) and different levels of government (village councils, state governments) to facilitate the sharing of knowledge. These groups need to work together to decide how best to prepare for changes.

Adapting to cryospheric change at local level

Some actions that Arctic communities can take:

- Re-locate coastal villages and developments inland, to reduce risks due to coastal erosion.
- Design building foundations to protect them from the effects of thawing permafrost. For example, use passive cooling systems to maintain low temperatures beneath buildings.

cascading effects throughout Arctic societies, influencing the ways that people can adapt and increase resilience to cryospheric change.

For example, reindeer herders traditionally adapted to changing snow conditions by altering migration routes, but oil pipelines and national boundaries now prevent herders from reaching some areas of pasture.

Adaptation is often expensive. For example, changing to open-water fishing requires a sea-worthy boat and larger nets. Buildings cost more when they are designed to cope with thawing permafrost or increased snow loads. Transport costs rise when long detours are necessary to avoid melting ice roads. Other barriers to adaptation include the loss of traditional knowledge among younger generations, lack of education relating to emerging industries and changed wildlife management regulations.



Inuit park warden welcomes tourists from helicopters. Quttinirpaaq national park, Ellesmere Island, Canada.



© ULRIK BANG / epa / Corbis

Co-ordinated effort is needed to enable people and businesses to adapt to change.

Managing change

Local, regional and national governments play an essential role in directing how societies respond to change.

New policies and forms of governance are needed to meet the variety of social, economic and cultural challenges and opportunities associated with cryospheric change. Existing governance mechanisms will also need to adapt and transform. Representation of Indigenous Peoples in decision-making bodies is essential, so that indigenous issues are included in discussion and decisions.

Monitoring change

Cryospheric changes need to be monitored and assessed in order to form strategies to adapt to their effects. For example, a recent assessment of the risk of avalanches in Nunavik, Canada, recommended that some houses be relocated and that a defense structure be built, to reduce the risk of future avalanches in the area.

The need for regulation

Regulations will be needed to reduce conflicts between industrial activities, local communities and residents, to maintain levels of safety and to reduce

environmental hazards. Without proper guidelines and regulations for industrial development, commercial fisheries, cruise traffic and shipping, local communities will become more vulnerable.

For example, fisheries and oil and gas activities are already competing over space at sea to a certain extent. This will continue and perhaps become more acute in the context of cryospheric change. Regulation of these activities is needed to reduce the risk of accidents and pollution. New fishing regulations may be required to prevent over-fishing and to allow fishing in new areas as fish stocks move and change.

As more ships enter the Arctic Ocean, new standards will be needed to ensure shipping safety and prevent damage to the marine environment. The International Maritime Organization is devising new mandatory guidelines for ships operating in ice-covered waters. These will be the first internationally recognized guidelines for the construction and operation of ships in Arctic waters.

Rights of access to the Arctic Ocean

The reduction in sea ice has increased access for ships into the Arctic Ocean,

making it easier to extract oil and gas, and creating a need to define who has the right to extract resources from the different areas of the Arctic Ocean. In the Ilulissat Declaration (May 2008), five Arctic states agreed that the United Nations' Convention on the Law of the Sea (1982, current version 1994) was sufficient to provide a legally binding framework to resolve potential territorial disputes. This convention defines the key territorial boundaries of coastal nations, dividing the sea into zones that can be regulated and exploited.

Arctic Indigenous Peoples are also seeking recognition of their collective rights in the Arctic region. They have been the sole users of Arctic sea ice and waterways for thousands of years, including both the living and non-living resources. As industrial activities expand and trans-Arctic marine shipping increases, regulations will be needed to reduce conflict between traditional and commercial uses.

The UN Declaration on the Rights of Indigenous Peoples (2007) sets out the individual and collective rights of Indigenous Peoples. It should be used as the foundation for regulations and decision-making processes regarding the use of land, sea and resources.

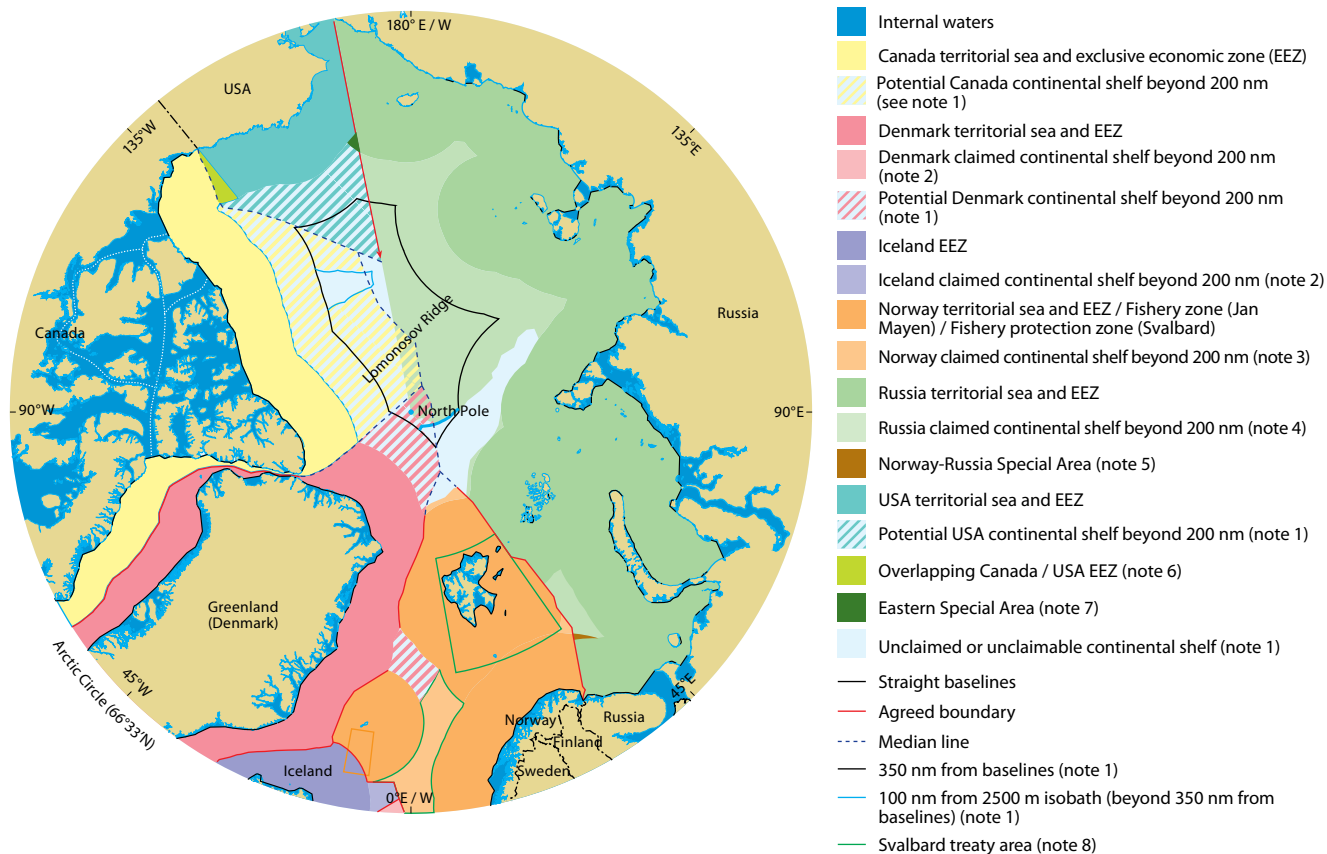


Action to prevent cryospheric change (mitigation)

The main driver of cryospheric change – increasing average temperature – is very likely caused by increasing human greenhouse gas emissions, according to the IPCC. These emissions occur mostly outside the Arctic region. Therefore Arctic communities can play only a limited role in reducing cryospheric change. Nonetheless, policies are needed both within and outside the Arctic to reduce greenhouse gas emissions. Regional mitigation measures include the control of carbon dioxide and other emissions from industry, shipping and the burning of waste.

Scale of action	Actions required
Local	Sustainable management of resources and regulation of key activities; local adaptation to the effects of cryospheric change.
National	Enacting appropriate laws and developing regulatory frameworks, for example to ensure safe working environments and adequate environmental protection; investment in infrastructure, particularly new roads and railways in areas where the ice road season is getting shorter.
International	Global conventions regulating greenhouse gas emissions; setting international standards for activities such as shipping; cooperation to increase Search and Rescue capabilities.

Marine jurisdiction in the Arctic



International Boundaries Research Unit, Durham University. Briefing notes referred to in the key are available at <https://www.dur.ac.uk/ibru/resources/arctic/>

6.2 THE BIG UNKNOWNNS

There remains a great deal of uncertainty about what will happen in the Arctic and how this will affect the rest of the world. We know changes are happening that have never been seen before. But we do not know what the ultimate effects or impacts of these changes will be, or exactly how fast changes will occur.

The biggest unanswered questions identified during the SWIPA project are:



What will happen to the Arctic Ocean and its ecosystems as freshwater is added?

Freshwater in the Arctic Ocean forms a layer between the sea ice and heavier, warmer, saltier water below. This system has been stable for a long time, but now two things are changing. First, more freshwater is being added as land-based ice melts. Second, the sea ice is melting, exposing the ocean's surface to the wind and the sun. It is not known how the Arctic Ocean will respond to these changes.



How quickly could the Greenland Ice Sheet melt?

Instead of reducing uncertainty about how much ice is being lost from the Greenland Ice Sheet, new measurements from satellites have revealed how little we understand about the dynamics of large ice sheets. The biggest changes in mass seem to be at the edges, where melting ice meets the sea. Close monitoring of the Greenland Ice Sheet on the ground is really important now, coupled with further development of climate models that can describe the local conditions around Greenland and how they might respond to the changing shape of the ice sheet.



How will changes in the Arctic cryosphere affect the global climate?

Over 30 feedback effects between the Arctic cryosphere and the overall climate system have now been identified. Many have the potential to affect global climate change. Some could greatly accelerate change and the impacts of change, in unpredictable ways. More work is needed to quantify the magnitude of individual feedbacks, as we do not yet know when feedbacks will happen or what the overall effects of feedbacks will be.



How will the changes affect Arctic societies and economies?

To date there has been much more research on the physical changes to the cryosphere and ecosystems of the Arctic and how they might change in future, than there has been on how these changes will affect society. The potential socio-economic impacts of changing ice, water and ecosystems now need to be analyzed in the short, medium and long-terms. Such knowledge is needed to allow Arctic communities and Arctic-based institutions to make appropriate forward-looking decisions.

The need for consistent ground-based observation

Satellite imagery and other remote sensing have greatly improved our capacity to observe changes in the Arctic over large scales. But some features of the cryosphere need to be observed at ground level. These are things that are difficult to measure accurately from space, like the depth of snow, the amount of rain and snowfall, and the amount of ice cover on rivers and lakes.

Ground-based measuring networks are sparse and unevenly distributed in the Arctic. Systematic observations of ice conditions on lakes and rivers have declined, not improved, since the 1980s, while measurements of snow depth are biased towards coastal areas of the North American Arctic. In both cases, changes in methods over time have made it difficult to assess long-term change.

An evenly distributed network of measuring stations across the entire Arctic, all making observations in the same way, would provide invaluable data now and in the future.

There is also a wealth of historical data, going back 50 to 100 years, which is not used to its full extent. Russia, for example, has daily observations of permafrost going back to the 19th century at some sites. Translating these data into a format accessible to the international scientific community is detailed work and can be expensive. Such data rescue efforts would enhance our understanding of current cryospheric change by providing more historical context.

GLOSSARY



- High Arctic
- Low Arctic
- Subarctic
- Treeline

Adaptation	The process of finding ways to cope with, moderate or take advantage of change. Adapting to cryospheric change in the Arctic could involve relocating coastal villages, or developing open-water fishing techniques, for example.
Active layer	The layer (usually of soil) above the permafrost that freezes and thaws each year, rather than being permanently frozen.
Arctic	There are many different definitions of 'the Arctic', based on physical-geographical characteristics or on political and administrative considerations within different countries. To establish a geographical context for its assessments AMAP has defined a regional extent based on a compromise among various definitions. The 'AMAP area' essentially includes the terrestrial and marine areas north of the Arctic Circle (66°32'N), and north of 62°N in Asia and 60°N in North America, modified to include the marine areas north of the Aleutian chain, Hudson Bay, and parts of the North Atlantic Ocean including the Labrador Sea.
Arctic Rapid Change Pattern	A previously unseen weather pattern observed over the Arctic since 2006, in which low air pressure develops during winter off the north Russian coast and higher pressure develops on the opposite side of the Arctic Ocean, over Greenland and north of Canada. These conditions create winds that blow across the North Pole from Greenland towards Russia. Also called a 'dipole anomaly'.
Black carbon	Particles of incompletely combusted carbon also known as soot. Black carbon is released from fires, vehicles and industrial activities and transported to the Arctic by the atmosphere.
Carbon dioxide	One of the main greenhouse gases (chemical symbol CO ₂). This gas is released to the atmosphere during combustion (of fossil fuels for example) and decomposition. It is absorbed by plants and algae and stored as carbon as they grow.
Calving	The process of ice breaking from ice sheets or glaciers as solid chunks (icebergs), which float out to sea.
Cryosphere	Scientific term for the part of Earth's surface that is frozen. The cryosphere includes snow, permanently frozen ground, ice on rivers and lakes, glaciers, ice caps and sea ice.
Feedback	A feedback is when a change in one part of a system drives a change in another part and the second part's response changes the first part. In the climate-cryosphere system, there are many potential feedback mechanisms when a change in one aspect of climate drives a change in the cryosphere and the cryosphere's response changes that aspect of the climate. An example is the loss of sea ice creating further warming of the ocean water and air (a positive feedback).
First-year ice	Sea ice that grows through the winter and then melts completely during summer. First-year ice (FYI) is relatively thin, making it more sensitive to changes in winds and air temperature.
Gigatonne	One gigatonne (1 Gt) is 1 billion tonnes, or 1000 000 000 tonnes. A gigatonne of ice is slightly larger than a cubic kilometre (1.1 km ³). 1 gigatonne of water is enough to supply the daily water consumption of between 5 and 9 million city-dwellers. 360 gigatonnes of melted ice is equivalent to 1 mm of global sea-level rise.

Glacier	A body of ice whose shape and size is controlled by bedrock – the ice is bounded by the edges of a valley, for example.
Greenhouse gases (GHGs)	Gases in the atmosphere that absorb and emit solar radiation in the thermal infrared range. This process is the fundamental cause of the ‘greenhouse effect’, which warms the Earth. The main greenhouse gases emitted by human activities are carbon dioxide, methane and nitrous oxide.
High Arctic	The High Arctic, the most northern region of the Arctic, has a growing season which lasts only 1–2.5 months and mean July temperatures of 4–8 °C. Fewer flora and fauna are supported under these extreme conditions than in the Low Arctic (see map).
Iceberg	Chunk of ice released from glaciers or ice sheets by calving.
Ice cap	A dome-shaped body of ice that entirely submerges the underlying rock and takes on its own shape.
Ice sheet	A very large ice cap. There is only one ice sheet in the Arctic, the Greenland Ice Sheet.
IPCC	Intergovernmental Panel on Climate Change, the leading international body for the assessment of climate change. www.ipcc.ch
Land-fast sea ice	Sea ice that has frozen along coasts.
Low Arctic	The Low Arctic or tundra growing season ranges from 3–4 months, with mean July temperatures of 4–11 °C. This region supports more than 600 vascular plant species and has 80–100% plant cover (see map).
Methane	One of the main greenhouse gases (chemical symbol CH ₄). This gas is released to the atmosphere when organic matter decomposes in the absence of oxygen. Methane is 25 times more effective at warming the planet than carbon dioxide (over a 100 year time scale).
Mitigation	In the context of climate change, mitigation is action to decrease concentrations of greenhouse gases in the atmosphere, either by reducing emissions or enhancing storage.
Multi-year ice	Sea ice that has survived at least one melt season. Multi-year ice (MYI) becomes thicker each year as new ice forms underneath it.
Negative feedback	In the climate-cryosphere system, negative feedback is when warming causes a change that creates cooling, or cooling causes a change that creates warming. Negative feedbacks slow or inhibit change.
Permafrost	Soil, rock or sediment that remains below 0 °C for two or more consecutive years.
Persistent Organic Pollutants (POPs)	Organic compounds that are resistant to being broken down by biological and chemical processes or by exposure to light and ultra-violet radiation. POPs remain in the environment for long periods of time and can be transported long distances, either in the air or in water. They include industrial chemicals such as PCBs (polychlorinated biphenyls) and organic pesticides including DDT (dichlorodiphenyltrichloroethane) and lindane (hexachlorocyclohexane or HCH).
Phytoplankton	Tiny plant-like creatures (algae) living in the sea. They are known as primary producers, because they convert sunlight into sugars, absorbing carbon dioxide from the air in the process.
Positive feedback	In the climate-cryosphere system, positive feedback is when warming causes a change that creates further warming, or cooling causes a change that creates further cooling. Positive feedbacks magnify or amplify change.
Snow-cover duration	Number of days in which at least 50% of the visible land surface is continuously covered with snow.
Snow-cover extent	The area of land covered by snow at a given time.
Thermohaline circulation	Large-scale density-driven circulation in the ocean, caused by differences in temperature and salinity.
Thermokarst	A type of landscape that forms when parts of the ground collapse because underground ice has melted.
Zooplankton	Tiny animals in the sea, including crustaceans, and the larvae of fish, molluscs and other groups.

SWIPA 2011 Overview Report

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