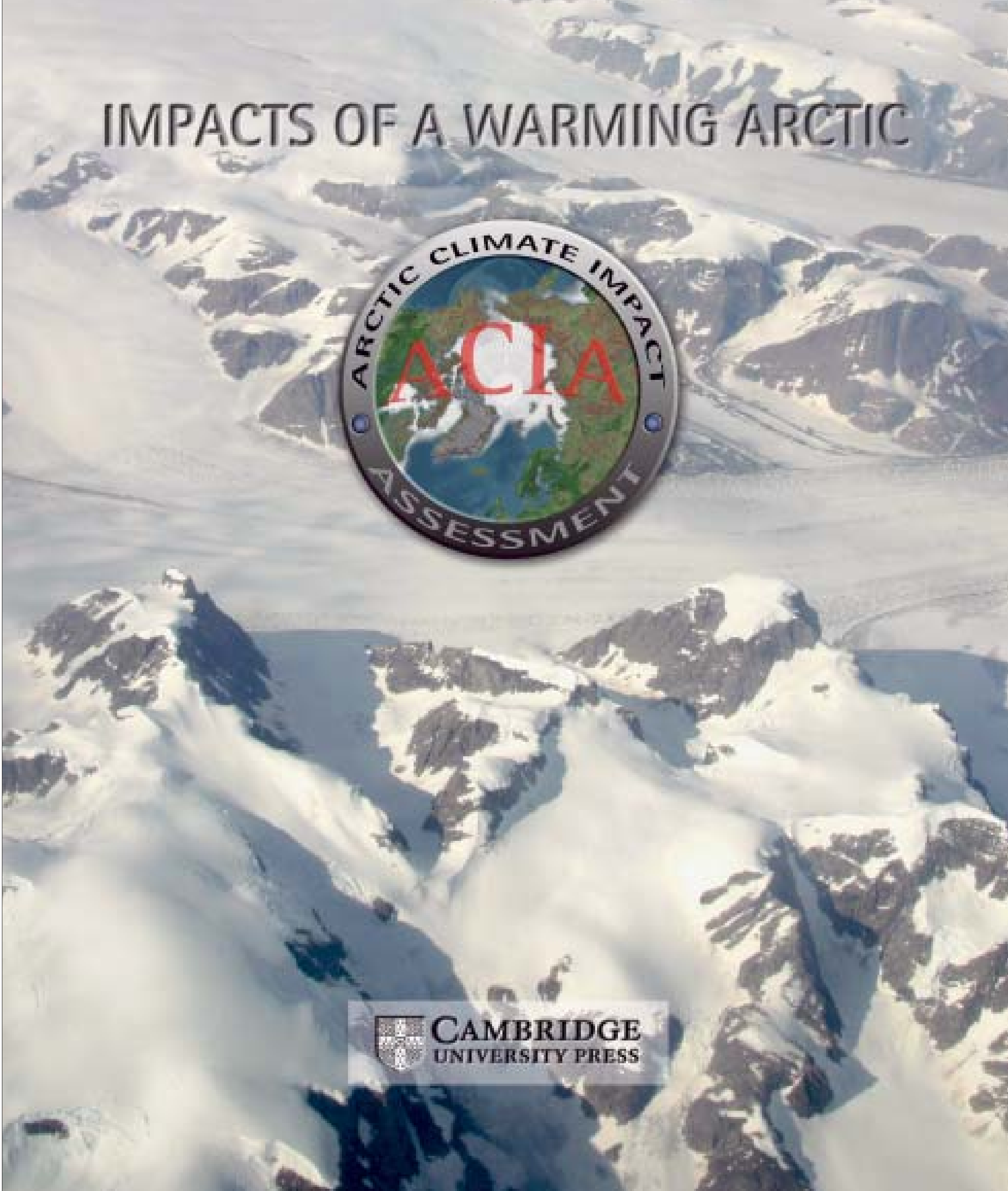
IMPACTS OF A WARMING ARCTIC



ARCTIC CLIMATE IMPACT ASSESSMENT

ACIA

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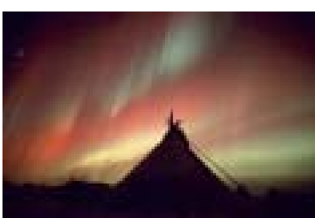
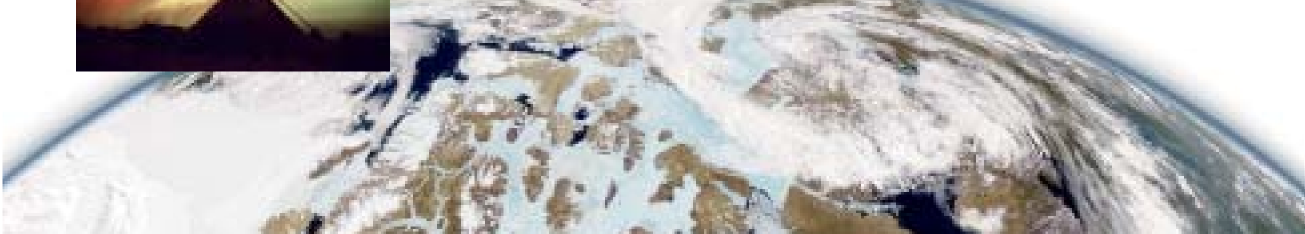
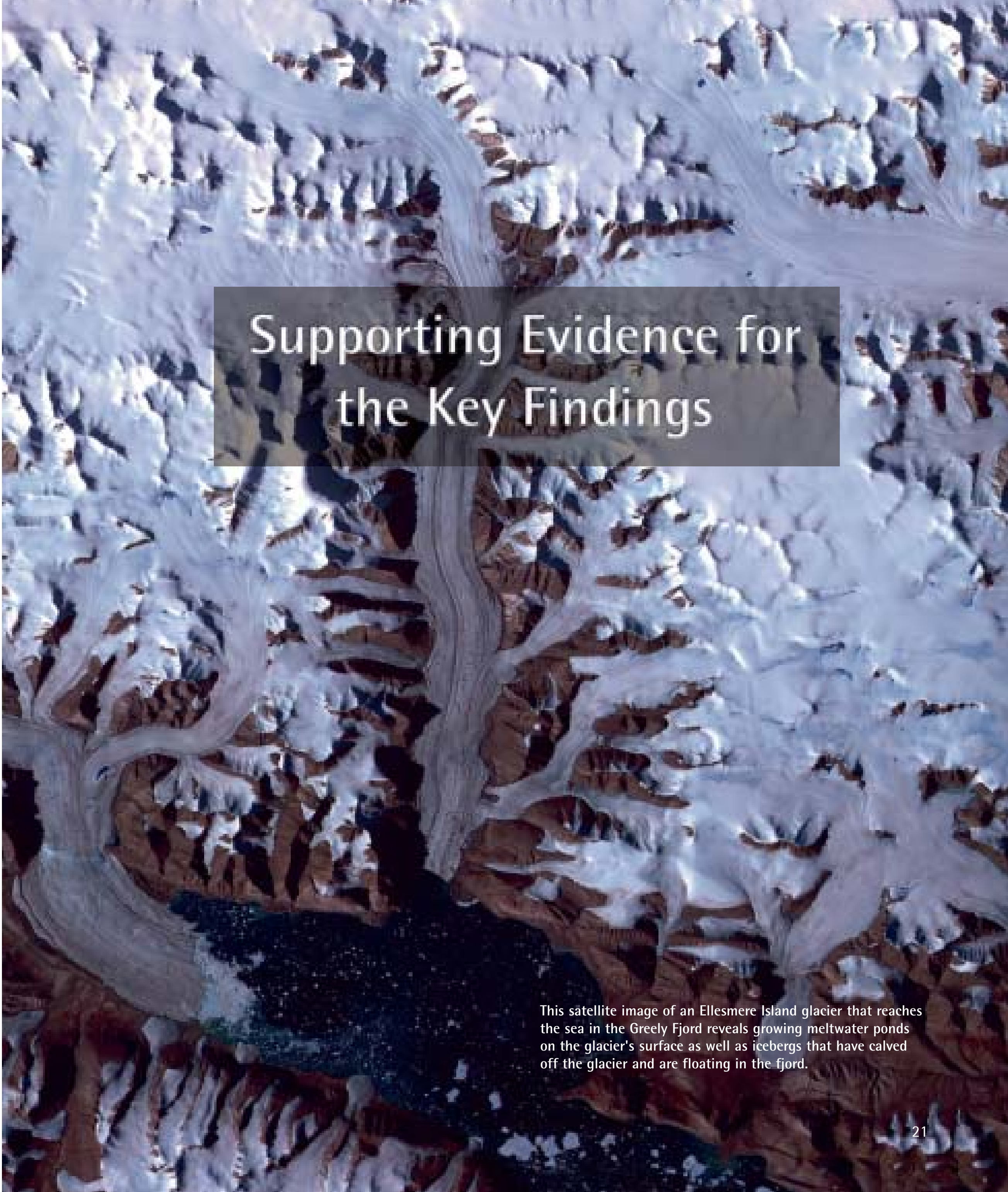




Supporting Evidence for the Key Findings



This satellite image of an Ellesmere Island glacier that reaches the sea in the Greely Fjord reveals growing meltwater ponds on the glacier's surface as well as icebergs that have calved off the glacier and are floating in the fjord.

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

Arctic air temperatures are rising, with the strongest trends in winter and over the last few decades.

Observed Changes in Climate

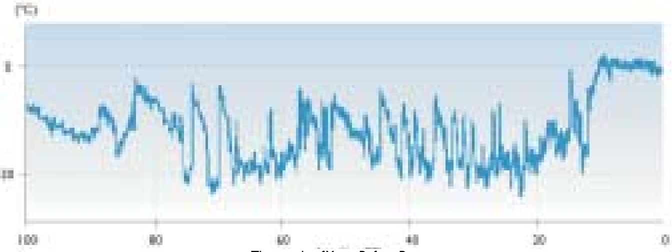
Records of increasing temperatures, melting glaciers, reductions in extent and thickness of sea ice, thawing permafrost, and rising sea level all provide strong evidence of recent warming in the Arctic. There are regional variations due to atmospheric winds and ocean currents, with some areas showing more warming than others and a few areas even showing a slight cooling; but for the Arctic as a whole, there is a clear warming trend. There are also patterns within this overall trend; for example, in most places, temperatures in winter are rising more rapidly than in summer. In Alaska and western Canada, winter temperatures have increased as much as 3-4°C in the past 50 years.

Observations suggest that precipitation has increased by roughly 8% across the Arctic over the past 100 years, although uncertainties in measuring precipitation in the cold arctic environment and the sparseness of data in parts of the region limit confidence in these results. There are regional variations in precipitation across the Arctic, and there will be regional variations in the changes in precipitation as well.

In addition to the overall increase, changes in the characteristics of precipitation have also been observed. Much of the precipitation increase appears to be coming as rain, mostly in winter, and to a lesser extent in autumn and spring. The increasing winter rains, which fall on top of existing snow, cause faster snowmelt and, when the rainfall is intense, can result in flash flooding in some areas. Rain-on-snow events have increased significantly across much of the Arctic, for example, by 50% over the past 50 years in western Russia.

In order to assess whether recent changes in arctic climate are unusual, that is, outside the range of natural variability, it is helpful to compare recent observations to records of how climate has behaved in the past. Data on past

100 000 Years of Temperature Variation in Greenland

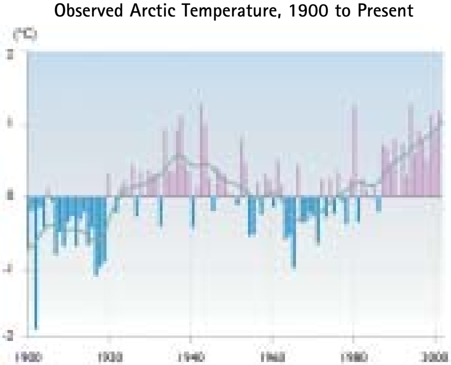


This record of temperature change (departures from present conditions) has been reconstructed from a Greenland ice core. The record demonstrates the high variability of the climate over the past 100 000 years. It also suggests that the climate of the past 10 000 years or so, which was the time during which human civilization developed, has been unusually stable. There is concern that the rapid warming caused by the increasing concentrations of greenhouse gases due to human activities could destabilize this state.

climate come from ice cores and other sources that provide reasonable representations of what climate was like in the distant past. Examining the record of past climatic conditions indicates that the amount, speed, and pattern of warming experienced in recent decades are indeed unusual and are characteristic of the human-caused increase in greenhouse gases.

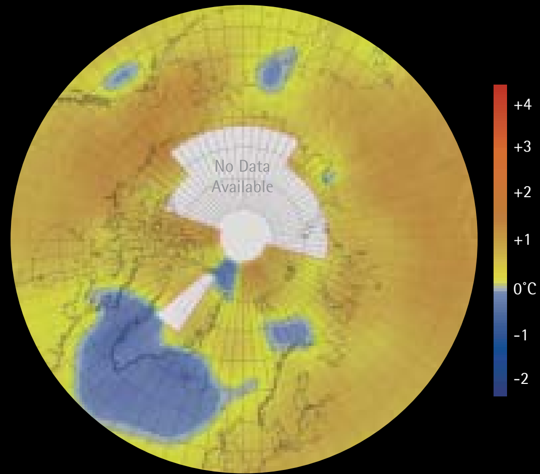
Both natural and human-caused factors can influence the climate. Among the natural factors that can have significant effects lasting years to decades are variations in solar output, major volcanic eruptions, and natural, sometimes cyclic, interactions between the atmosphere and oceans. Several important natural modes of variability that especially affect the Arctic have been identified, including the Arctic Oscillation, the Pacific Decadal Oscillation, and the North Atlantic Oscillation. Each of these can affect the regional patterns of such features as the intensity and tracks of storm systems, the direction of the prevailing winds, the amount of snow, and the extent of sea ice. In addition to changing long-term average climatic conditions, human-induced changes in the climate may also affect the intensity, patterns, and features of these natural variations.

Observed Arctic Temperature, 1900 to Present



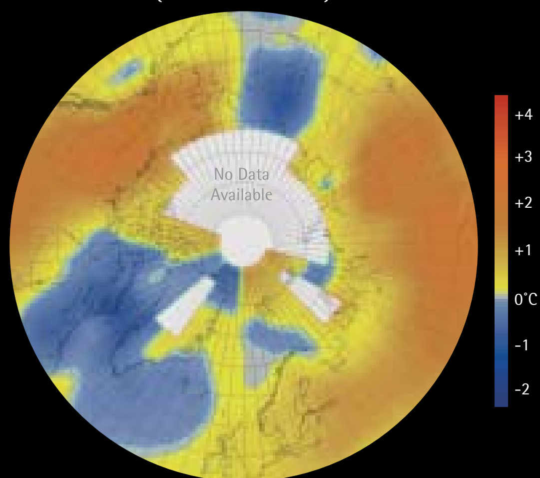
Annual average change in near surface air temperature from stations on land relative to the average for 1961-1990, for the region from 60 to 90°N.

Observed Surface Air Temperature Changes: 1954 - 2003
(ANNUAL, °C)



The colors indicate the change in temperature from 1954 to 2003. The map above indicates annual average temperature change, which ranges from a 2-3°C warming in Alaska and Siberia to a cooling of up to 1°C in southern Greenland.

Observed Surface Air Temperature Changes: 1954 - 2003
(WINTER: Dec-Feb in °C)



The map directly above indicates the temperature change during the winter months, ranging from a warming of up to 4°C in Siberia and Northwest Canada to a cooling of 1°C over southern Greenland.

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

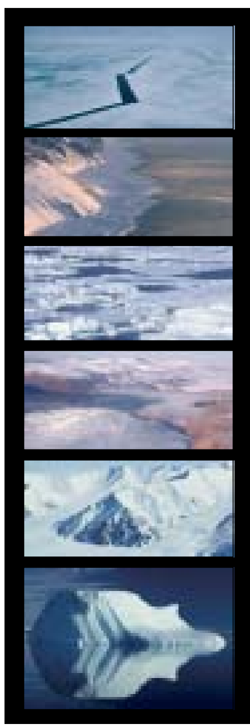
Changes in Sea Ice: A Key Climate Change Indicator

"Climate" refers to much more than just temperature and precipitation. In addition to long-term average weather conditions, climate also includes extreme events, as well as aspects of the system such as snow, ice, and circulation patterns in the atmosphere and oceans. In the Arctic, sea ice is one of the most important climatic variables. It is a key indicator and agent of climate change, affecting surface reflectivity, cloudiness, humidity, exchanges of heat and moisture at the ocean surface, and ocean currents. And as illustrated later in this report, changes in sea ice have enormous environmental, economic, and societal implications.

Just as miners once had canaries to warn of rising concentrations of noxious gases, researchers working on climate change rely on arctic sea ice as an early warning system. The sea ice presently covering the Arctic Ocean and neighboring seas is highly sensitive to temperature changes in the air above and the ocean below. Over recent decades, Arctic watchers detected a slow shrinkage of the ice pack, suggestive of the initial influences of global warming. In recent years, the rate of retreat has accelerated, indicating that the "canary" is in trouble.

"Ice is a supporter of life. It brings the sea animals from the north into our area and in the fall it also becomes an extension of our land. When it freezes along the shore, we go out on the ice to fish, to hunt marine mammals, and to travel... When it starts disintegrating and disappearing faster, it affects our lives dramatically."
Caleb Pungowiyi
Nome, Alaska

AN ICE PRIMER



Sea ice is formed as seawater freezes. Because sea ice is less dense than seawater, it floats on top of the ocean. As sea ice forms, it rejects the majority of its salt to the ocean, making the ice even lighter. Because sea ice is formed from existing sea water, its melting does not raise sea level.

Fast ice is sea ice that grows from the coast into the sea, remaining attached to the coast or grounded to a shallow sea floor. It is important as a resting, hunting, and migration platform for species such as polar bears and walrus.

Pack ice refers to a large area of floating sea ice fragments that are packed together.

Ice caps and **glaciers** are land-based ice, with ice caps "capping" hills and mountains and glaciers usually referring to the ice filling the valleys, although the term glacier is often used to refer to ice caps as well.

An **ice sheet** is a collection of ice caps and glaciers, such as currently found on Greenland and on Antarctica. When ice caps, glaciers, and ice sheets melt, they cause sea level to rise by adding to the amount of water in the oceans.

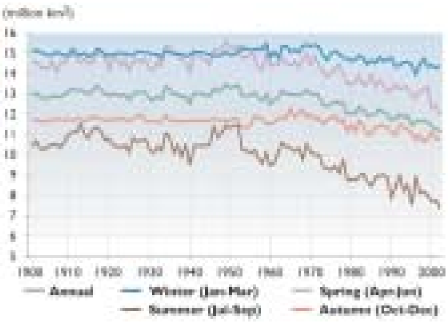
An **iceberg** is a chunk of ice that calves off a glacier or ice sheet and floats at the ocean surface.

Over the past 30 years, the annual average sea-ice extent has decreased by about 8%, or nearly one million square kilometers, an area larger than all of Norway, Sweden, and Denmark combined, and the melting trend is accelerating. Sea-ice extent in summer has declined more dramatically than the annual average, with a loss of 15-20% of the late-summer ice coverage. There is also significant variability from year to year. September 2002 had the smallest extent of arctic sea-ice cover on record, and September 2003 was very nearly as low.

Sea ice has also become thinner in recent decades, with arctic-wide average thickness reductions estimated at 10-15%, and with particular areas showing reductions of up to 40% between the 1960s and late 1990s. Impacts of a decline in sea ice are discussed throughout this report and include increased air temperature, decreased salinity of the ocean's surface layer, and increased coastal erosion.

Just as miners once had canaries to warn of rising concentrations of noxious gases, researchers working on climate change rely on arctic sea ice as an early warning system.

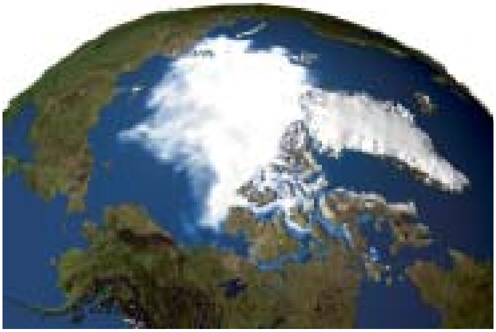
Observed seasonal Arctic sea-ice extent (1900-2003)



Annual average extent of arctic sea ice from 1900 to 2003. A decline in sea-ice extent began about 50 years ago and this decline sharpened in recent decades, corresponding with the arctic warming trend. The decrease in sea-ice extent during summer is the most dramatic of the trends.

Observed sea ice September 1979

Observed sea ice September 2003



These two images, constructed from satellite data, compare arctic sea ice concentrations in September of 1979 and 2003. September is the month in which sea ice is at its yearly minimum and 1979 marks the first year that data of this kind became available in meaningful form. The lowest concentration of sea ice on record was in September 2002.

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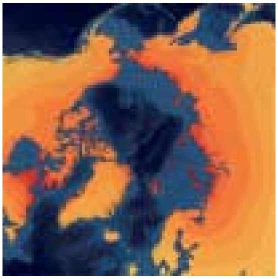


Even using the lowest emissions scenario, and the model that generates the least warming in response to changes in atmospheric composition, leads to a projection that the earth will warm more than twice as much in this century as it warmed over the past century.

Projecting Future Climate

This assessment has drawn information from a variety of approaches for documenting past and present climatic conditions and projecting future climatic conditions, including: observed data (such as data from instruments like thermometers, and past climate records from tree rings, ice cores, and sediments); field experiments; computer-based climate models; and indigenous knowledge. When information from several methods converges, it offers greater confidence in the results. Still, there will always be uncertainties and surprises in projecting future changes in climate.

Projecting future climate change and its potential impacts is undertaken in a systematic manner. Two major factors determine how human activities will cause the climate to change in the future:

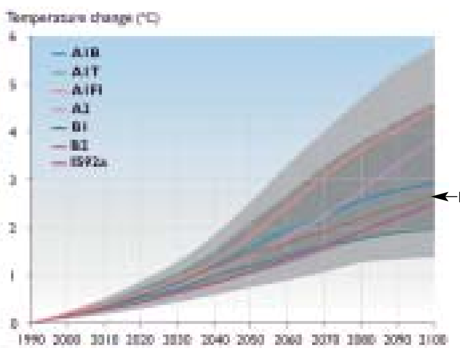
- the level of future global emissions of greenhouse gases, and
- the response of the climate system to these emissions.

Research over recent decades has contributed a great deal of information regarding each of these factors.

Projecting the level of future emissions is carried out by developing plausible scenarios for future changes in population, economic growth, technological and political change, and other aspects of future human society that are difficult to fully anticipate. The IPCC produced a Special Report on Emissions Scenarios (SRES) to grapple with these issues. Their scenarios encompass a range of possible futures based on how societies, economies, and energy technologies are likely to evolve, and can be used to estimate the likely range of future emissions that affect the climate.

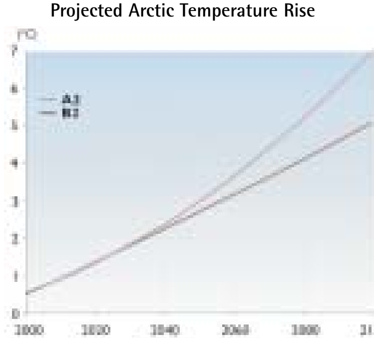
Regarding the response of the climate system, computer models developed by research centers from around the world represent aspects of the climate system (such as how clouds and ice cover might be expected to change, and ultimately how climate and sea level might be influenced) somewhat differently, resulting in differences in the degree of warming projected.

Projected Global Temperature Rise



Projections of global temperature change (shown as departures from the 1990 temperature) from 1990 to 2100 for seven illustrative emissions scenarios. The brown line shows the projection of the B2 emissions scenario, the primary scenario used in this assessment, and the scenario on which the maps in this report showing projected climate changes are based. The pink line shows the A2 emissions scenario, used to a lesser degree in this assessment. The dark gray band shows the range of results for all the SRES emissions scenarios with one average model while the light gray band shows the full range of scenarios using various climate models.

Projected Arctic Temperature Rise



Increases in arctic temperature (for 60°-90°N) projected by an average of ACIA models for the A2 and B2 emissions scenarios, relative to 1981-2000.

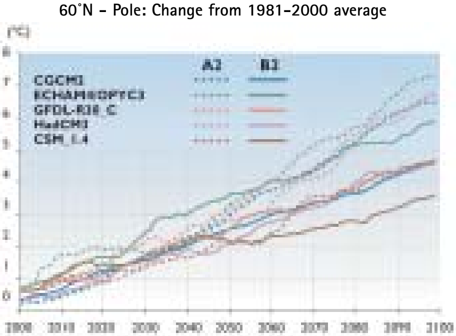
Regardless of the emissions scenario or computer model selected, every model simulation projects significant global warming over the next 100 years. Even using the lowest emissions scenario, and the model that generates the least warming in response to changes in atmospheric composition, leads to a projection that the earth will warm more than twice as much in this century as it warmed over the past century. Model simulations further indicate that the warming in the Arctic will be substantially greater than the global average (in some regions, more than double). While the models differ in their projections of some of the features of climate change, they are all in agreement that the world will warm significantly as a result of human activities and that the Arctic is likely to experience noticeable warming particularly early and intensely.

The climate models and emissions scenarios reviewed by the IPCC generate a range of possible conditions for the future. To provide an indication of the types of impacts that are likely to occur, ACIA drew upon the results of five climate models from leading climate research centers and one moderate emissions scenario (known as B2, see Appendix 1 for more information) to be the primary basis for its assessment of the impacts of future climate conditions. The maps of projected climate conditions in this report are based on this B2 emissions scenario. A second emissions scenario (called A2) was added to some analyses to explore another possible future. The focus on these two scenarios here reflects a number of practical limits to conducting this assessment, and is not a judgment that these are the most likely outcomes.

When viewing the model results in this report, it is important to remember that these are not worst-case or best-case scenarios, but rather fall slightly below the middle of the range of temperature rise projected by global climate models. It is also important to note that for many of the impacts summarized in this report, information was also drawn from additional sources, including observed changes in climate, observed impacts, extrapolation of current trends, and laboratory and field experiments published in the peer-reviewed scientific literature.

When viewing the model results in this report, it is important to remember that these are not worst-case or best-case scenarios, but rather fall slightly below the middle of the range of temperature rise projected by global climate models.

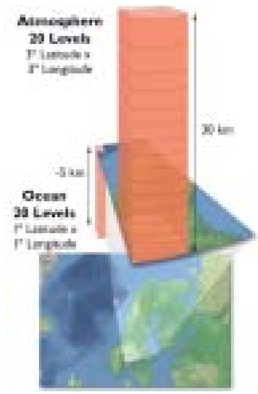
Projected Arctic Surface Air Temperatures 2000–2100
60°N – Pole: Change from 1981–2000 average



The ten lines show air temperatures for the region from 60°N to the pole as projected by each of the five ACIA global climate models using two different emissions scenarios. The projections remain similar through about 2040, showing about a 2°C temperature rise, but then diverge, showing increases from around 4° to over 7°C by 2100. The full range of models and scenarios reviewed by the IPCC cover a wider range of possible futures. Those used in this assessment fall roughly in the middle of this range, and thus represent neither best- nor worst-case scenarios.

Note: The full names of these models and a description of the A2 and B2 emissions scenarios can be found in Appendix 1, on pages 128 - 129.

Global Climate Model



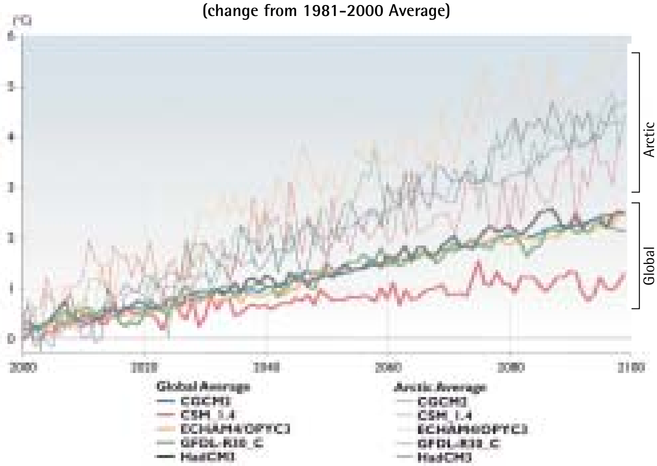
Global climate models are computer simulations based on physical laws represented by mathematical equations that are solved using a three-dimensional grid over the globe. The models include the major components of the climate system including the atmosphere, oceans, land surface, snow and ice, living things, and the processes that go on within and between them. As illustrated in the figure, the resolution (grid size) of the global models is fairly coarse, meaning that there is generally higher confidence in larger scale projections and greater uncertainty at increasingly small scales.

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

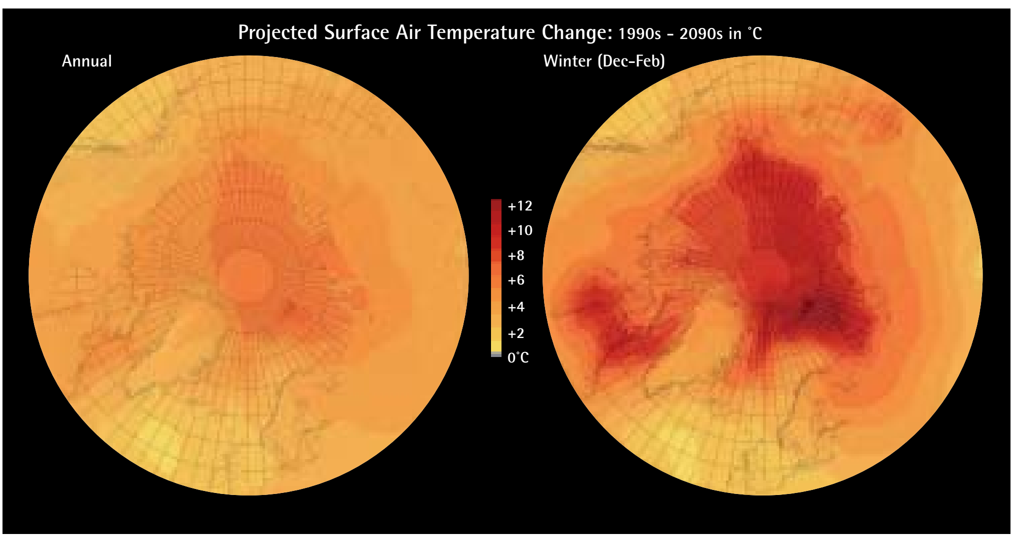
Projected Changes in Arctic Temperature

The maps below show projected changes in arctic temperature as an annual average, and for the winter (December, January, and February). They show the projected temperature change from the 1990s to the 2090s, based on the average change calculated by the five ACIA climate models using the B2 emissions scenario (resulting in a temperature rise slightly below the middle of the range of IPCC scenarios). Under this scenario, by the latter part of this century, annual average temperatures are projected to rise across the entire Arctic, with increases of roughly 3-5°C over the land areas and up to 7°C over the oceans. Winter temperatures are projected to rise significantly more, with increases of 4-7°C over the land areas and 7-10°C over the oceans. Some of the strongest warming is projected for land areas, such as northern Russia, which are adjacent to oceans in which sea ice is projected to decline sharply.

Projected Surface Air Temperature Change
(change from 1981-2000 Average)



This graph shows average temperatures projected by the five ACIA climate models for the B2 emissions scenario. The heavy lines at the bottom are projected average **global** temperature increases and the thinner lines above are the projected **arctic** temperature increase. As the results show, the temperature increases are projected to be much greater in the Arctic than for the world as a whole. It is also apparent that the year-to-year variability is greater in the Arctic.

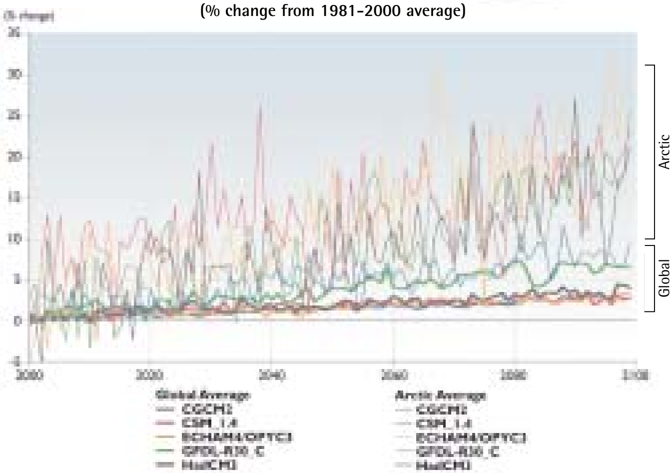


These maps show the projected temperature change from the 1990s to the 2090s, based on the average change calculated by the five ACIA climate models using the lower of the two emissions scenarios (B2) considered in this assessment. On these maps, orange indicates that an area is projected to warm by about 6°C from the 1990s to the 2090s.

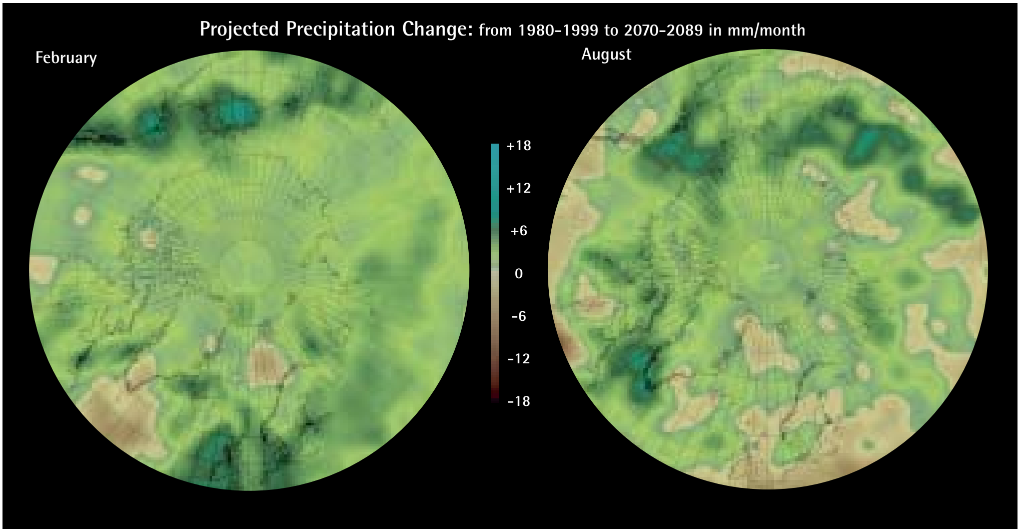
Projected Changes in Arctic Precipitation

Global warming will lead to increased evaporation and in turn to increased precipitation (this is already occurring). Over the Arctic as a whole, annual total precipitation is projected to increase by roughly 20% by the end of this century, with most of the increase coming as rain. During the summer, precipitation over northern North America and Chukotka, Russia is projected to increase, while summer rainfall in Scandinavia is projected to decrease. During winter, precipitation for virtually all land areas (except southern Greenland) is projected to increase. The increase in arctic precipitation is projected to be most concentrated over coastal regions and in the winter and autumn; increases during these seasons are projected to exceed 30%.

Projected Precipitation Change
(% change from 1981-2000 average)



This graph shows percentage changes in average precipitation projected by the five ACIA climate models for the B2 emissions scenario. The heavy lines at the bottom are projected average **global** precipitation changes and the thinner lines above are projected **arctic** precipitation changes. As the results show, the precipitation increases are projected to be much greater in the Arctic than for the world as a whole. It is also apparent that the year-to-year variability is much greater in the Arctic.

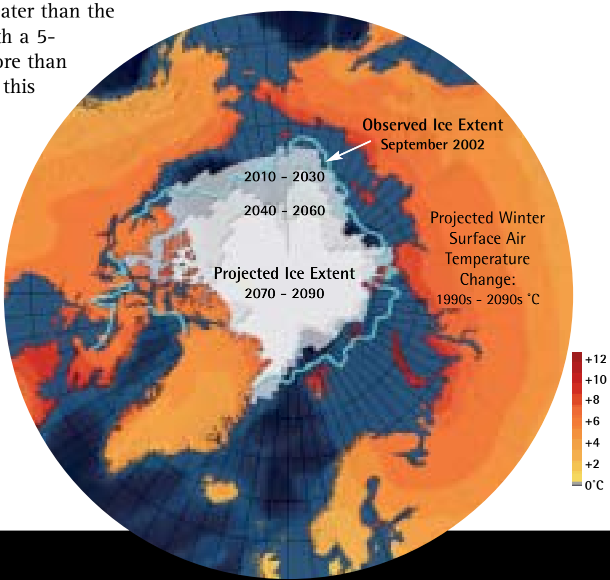


These maps show the projected precipitation change in mm per month, calculated by the ACIA climate models. On these maps, dark green indicates that precipitation is projected to increase by about six mm per month from the 1990s to the 2090s.

The projected reductions in sea ice will increase regional and global warming by reducing the reflectivity of the ocean surface.

Projected Changes in Sea Ice

As noted earlier, sea ice has already declined considerably over the past half century. Additional declines of roughly 10-50% in annual average sea-ice extent are projected by 2100. Loss of sea ice during summer is projected to be considerably greater than the annual average decrease, with a 5-model average projecting more than a 50% decline by the end of this century, and some models showing near-complete disappearance of summer sea ice. The projected reductions in sea ice will increase regional and global warming by reducing the reflectivity of the ocean surface. Additional impacts of the projected sea-ice decline on natural systems and communities in the Arctic and around the world are discussed throughout this report.



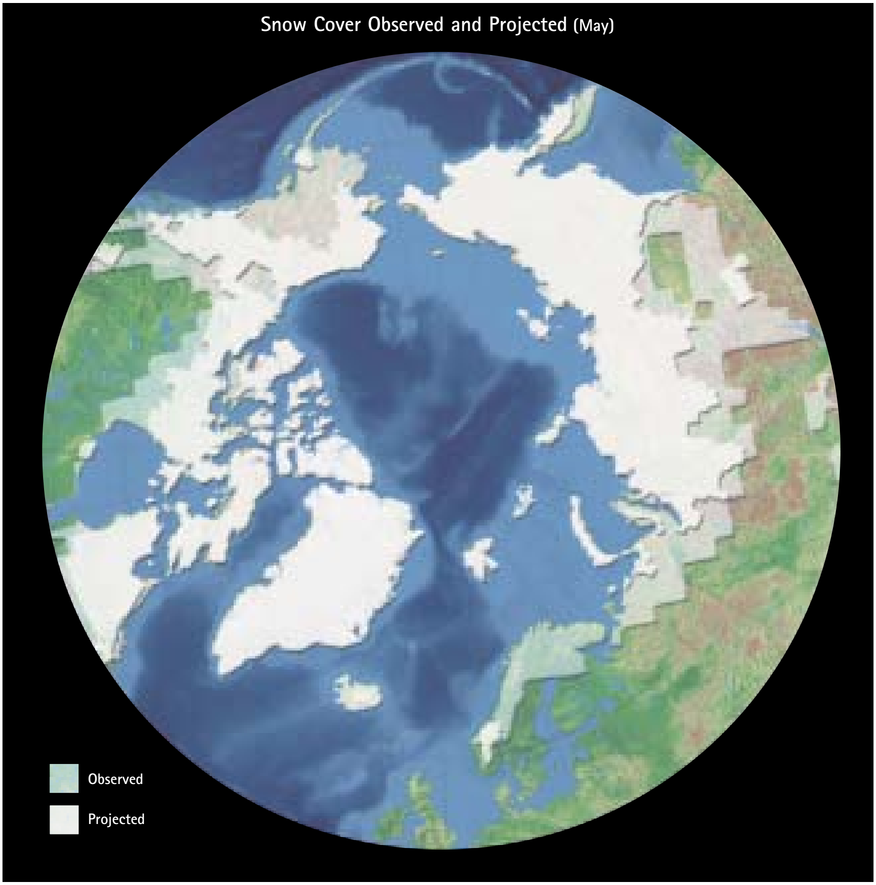
Projected Ice Extent (5-model average for September)

September sea-ice extent, already declining markedly, is projected to decline even more rapidly in the future. The three images above show the average of the projections from five climate models for three future time periods. As the century progresses, sea ice moves further and further from the coasts of arctic land masses, retreating to the central Arctic Ocean. Some models project the nearly complete loss of summer sea ice in this century.

Projected Changes in Snow Cover

Snow cover extent over arctic land areas has declined by about 10% over the past 30 years, and model projections suggest that it will decrease an additional 10-20% before the end of this century. The decreases in snow-covered area are projected to be greatest in spring (April and May), suggesting a further shortening of the snow season and an earlier pulse of river runoff to the Arctic Ocean and coastal seas. Important snow quality changes are also projected, such as an increase in thawing and freezing in winter that leads to ice layer formation that in turn restricts the access of land animals to food and nesting sites. Some impacts of the projected changes will include a reduction in the beneficial insulating effect of snow cover for vegetation and other living things and the ability of animals to forage. Flows of freshwater across the land to the ocean, and transfers of moisture and heat from the land to the atmosphere and marine systems will also be affected by the changes. Additional impacts of the snow cover decline are discussed throughout this report.

The decreases in snow-covered area are projected to be greatest in spring (April and May), suggesting a further shortening of the snow season and an earlier pulse of river runoff to the Arctic Ocean and coastal seas.



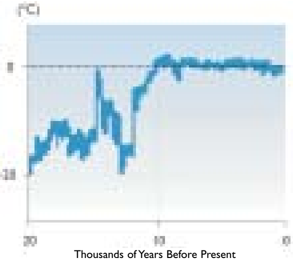
May snow cover is projected to decrease substantially throughout the Arctic. The gray area in the figure shows the current extent of May snow cover. The white area is the projected area of May snow cover in the 2070 to 2090 time period based on ACIA model projections. The large-scale pattern of projected snow cover retreat in spring is apparent.

Abrupt Change

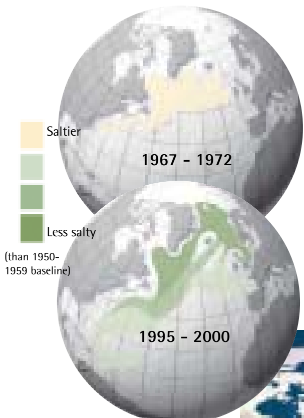
While most analyses of climate impacts in this and other assessments focus on scenarios of steady warming of the climate, there is also the possibility that gradual warming could trigger an abrupt change in climate. Such abrupt change could result from non-linear processes in the climate system. An example would be if a critical threshold (such as the freezing point) were crossed. Once a threshold is passed, the system could shift abruptly from one state to another. There is evidence that alternative stable states exist for components of the climate system, and for natural systems as well, though less is known about what triggers system shifts from one state to another. The mechanisms of abrupt change are thus not adequately represented in current climate models, leaving open the possibility of surprises. The idea that abrupt changes are plausible outcomes is also suggested by the relatively high natural variability of arctic climate as compared to conditions in the rest of the world. Records of past climate indicate, for example, that very large shifts in arctic climate patterns have apparently occurred over short timescales in the past.

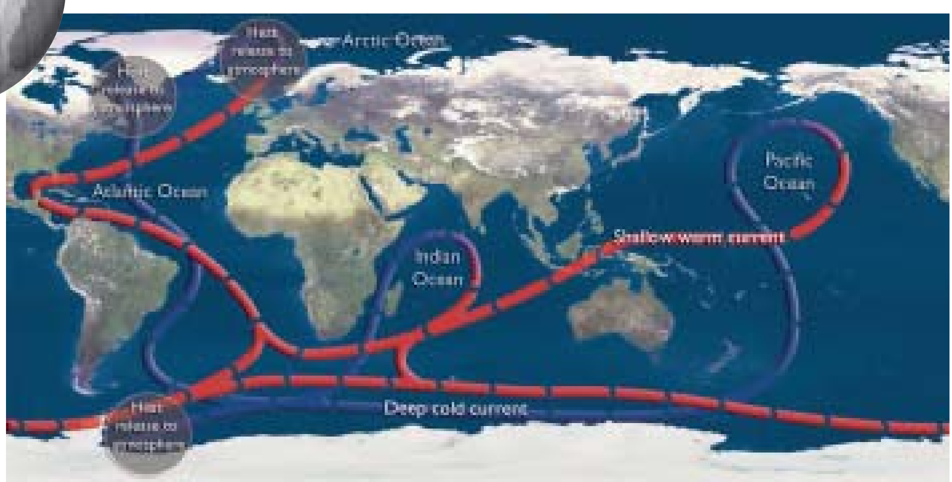
For example, ice core records indicate that temperatures over Greenland dropped by as much as 5°C within a few years during the period of warming that followed the last ice age, before abruptly warming again. This relatively sudden and then persistent change in the weather over Greenland was apparently driven by the crossing of a threshold involving ocean salinity that led to a sharp reduction in the ocean circulation that brings warmth to Europe and the Arctic. This oceanic change most likely prompted a shift in atmospheric circulation that lasted several centuries and caused large climatic changes over land areas surrounding the North Atlantic and beyond. Persistent, although smaller shifts in atmospheric circulation patterns (such as occur during the phase changes of the North Atlantic and Arctic Oscillations) occurred during the 20th century. These shifts apparently caused changes in the prevailing weather of arctic countries, contributing, for example, to warm decades, such as the 1930s and 1940s, and cool decades, such as the 1950s and 1960s.

20 000 Years of Temperature Variation in Greenland



Reduced Salinity of North Atlantic Waters





Changes in global ocean circulation can lead to abrupt climate change. Such change can be initiated by increases in arctic precipitation and river runoff, and the melting of arctic snow and ice, because these lead to reduced salinity of ocean waters in the North Atlantic, evidence of which is shown above. Further discussion of this issue is found on pages 36-37.

The Importance of Thresholds

There are many thresholds in the arctic environment, which if crossed, could lead to significant consequences for the region and the world. As human-induced warming continues, the potential exists for various arctic systems to shift to new or unusual states. Such changes might be initiated when a temperature or precipitation threshold is crossed. Records of ancient arctic climate suggest that such changes in some cases occurred abruptly (over a few years) and in other cases more gradually (over several decades or more). Such shifts have the potential to cause the relatively rapid onset of various types of impacts. For example, unusually warm and wet conditions might accelerate outbreaks of pests or infectious diseases.

The onset of the long-term melting of the Greenland Ice Sheet is an example of a threshold that is likely to be crossed during this century. Climate models project that local warming in Greenland will exceed 3˚C during this century. Ice sheet models project that a warming of that magnitude would initiate the long-term melting of the Greenland Ice Sheet. Even if climatic conditions then stabilized, an increase of this magnitude is projected to lead eventually (over centuries) to a virtually complete melting of the Greenland Ice Sheet, resulting in a global sea level rise of about seven meters. The tentative indication from the North Atlantic of an initial slowing of the deep ocean circulation is another example of a possible threshold that might be crossed. If present trends continue, leading to a significant slowdown, the northward oceanic transport of tropical warmth that now moderates European winters could be significantly diminished.

There are also thresholds that can be crossed in the world of living things. For example, nearly half of all white spruce trees at treeline in Alaska show a marked decrease in growth when average July temperature measured at a nearby station exceeds 16˚C. The observed relationship between this temperature threshold and reduced growth suggests that growth of these trees would cease entirely under the amount of warming projected to occur during this century, thus eliminating this population. Similar population crashes in some animal species can result if critical thresholds are passed.

Sudden or unexpected changes pose great challenges for scientists to project as well as for the ability of societies to adapt, and can thus increase vulnerability to significant impacts. While there is still much uncertainty about which of these thresholds will be crossed and exactly when this might occur, records of the past suggest that the possibilities for abrupt changes and new extremes are real.

Rates of Change

The rate at which a change occurs can be as important or more important than the amount of change. When examining impacts of climate change, rates of change must be considered in relation to factors that are important to human society. For example, if thawing of permafrost or increasing coastal erosion were to occur very slowly, people might be able to replace buildings, roads and the like as part of the normal replacement cycle for infrastructure. But if the changes occur rapidly, then the costs of replacement can be high.

The rate of change is also critical to the discussion of abrupt climate change. Evidence from past climates suggests that abrupt changes are most likely to occur when earth's climate is changing rapidly. Since abrupt changes are often most difficult to adapt to, the rate of climate change is clearly a major concern.

Climate models project that local warming in Greenland will exceed 3˚C during this century. Ice sheet models project that a warming of that magnitude would initiate the long-term melting of the Greenland Ice Sheet.

Projected Annual Temperature Change 2070-2090