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# Why are Ice and Snow Changing?

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## Summary

Changes in ice and snow are influenced by variability within the climate system itself and by external factors such as greenhouse gases, solar variability, and volcanic dust – factors that act on time scales from months to hundreds of thousands of years. During the 21st century, the most important external influence on high latitude climate and on ice and snow conditions will be the increase in greenhouse gases. Natural climate variability will still impose regional, decadal, and year-to-year differences, and feedbacks will become increasingly important in the climate system. Before 2050 the ice albedo feedback will accelerate the loss of Arctic sea ice. Warmer temperatures will reduce the area of snow cover and produce an earlier melt in snow-covered regions. This reduced snow cover will itself speed up warming.

## Forces that drive the climate system

Atmospheric climate, represented primarily by temperatures, precipitation, and winds, undergoes externally-forced changes as well as natural, internal variations.

External forcing factors include greenhouse gas fluctuations, dust from volcanic eruptions, and variations in the amount of solar radiation reaching the top of the atmosphere. These changes in atmospheric conditions influence the amount of ice and snow cover in a particular region and the regional climate is affected by them in turn. In the 21st century the most significant change in external forcing for high latitude climate, and therefore the largest influence on ice and snow conditions, will be the increase in greenhouse gases. The IPCC 4th Assessment Report[1] notes that it is highly likely (90 per cent confidence) that humans have already contributed to a rise in global temperatures due to an increase in greenhouse gas forcing. Carbon dioxide ($CO_2$), a primary greenhouse gas, is now near 380 ppm (parts per million of the atmosphere) and currently has a greater concentration than during any of the previous interglacial warm periods over the last 500,000 years. $CO_2$ is projected to reach 480 ppm by mid-century.

In addition to external factors, there is a large and natural random aspect to climate change that produces differences from year to year, decade to decade, and place to place. This variability is caused by instabilities in the air flow on the rotating Earth and this effect is greater near the poles than near the equator. Examples of natural variability are the warmer temperatures in the European Arctic in the 1920s and 1930s, and the cooler temperatures in the 1960s.

When the climate trend from future greenhouse gas forcing is added to the natural range of climate variability, the result is a shift during the 21st century to overall warmer temperatures, with many consequences for the cryosphere. The Arctic will experience warmer high and low temperature extremes. The warmer average will lead to a loss of sea ice and to earlier snow melt and river break-up – trends that are observed now. Globally, the freezing level (also called snow line) in mountainous regions will continue to move up mountain slopes and larger proportions of precipitation will fall as rain rather than as snow. In Antarctica, where current warming trends are not widespread, models project that increased warming will affect the central parts of the huge Antarctic ice sheet later in the century.


During the 21st century, the most important external influence on ice and snow conditions will be the increase in greenhouse gases.
*Photo: Ian Britton/FreeFoto.com*

## Learning from the past

The direct influence of variability of the sun's radiation at the Earth's surface is the major influence on the Earth's climate over a scale of hundreds of thousands of years. Long-term variation in temperatures and $CO_2$ are inferred from Antarctic ice cores (see the timeline on the inside back cover). The last 10 000 years have been a warm period in the Earth's history. Before then were the ice ages, each lasting approximately 100 000 years, with interglacial warm periods. The timing of the ice ages is set by changes in solar radiation, amplified by $CO_2$ and water vapour changes and by the position of continents and oceans. These solar changes over glacial time periods are caused by changes in the Earth's orbit, and by the tilt and orientation of the Earth's axis.

Evidence from tree rings and other temperature proxies (Figure 3.1) suggests that during the previous 500 years global temperatures were 1.0ºC cooler than those of the 20th century during a period roughly from 1300 to 1870 – known as the Little Ice Age. While overall temperatures during the Little Ice Age were cooler than now, there was much year-to-year variability and some warm periods[2]. The coldest part of the Little Ice Age, from 1645 to 1715, was also a time of minimum sun spots, referred to as the Maunder minimum. Although there is a correspondence in time, the causal connection between sun variability and Earth climate is a subject of ongoing debate. It is clear, however, that the 20th century was recovering from the average colder temperatures of the 19th century and earlier.

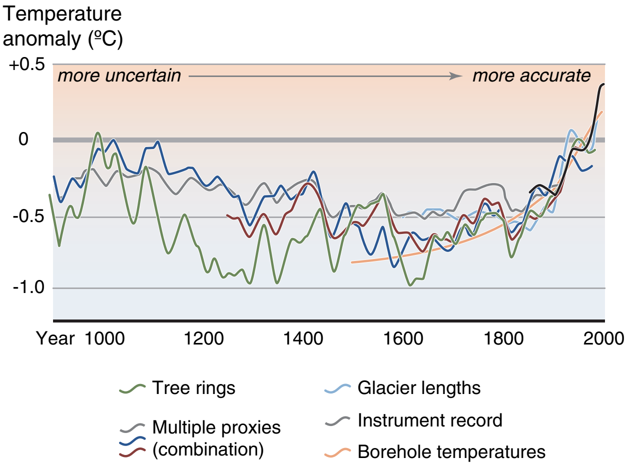



**Figure 3.1: Global mean surface temperatures over previous centuries from various proxy records.** Temperature estimates before 1500 are considered much less reliable.

*Source: based on NRC 2006*[3]

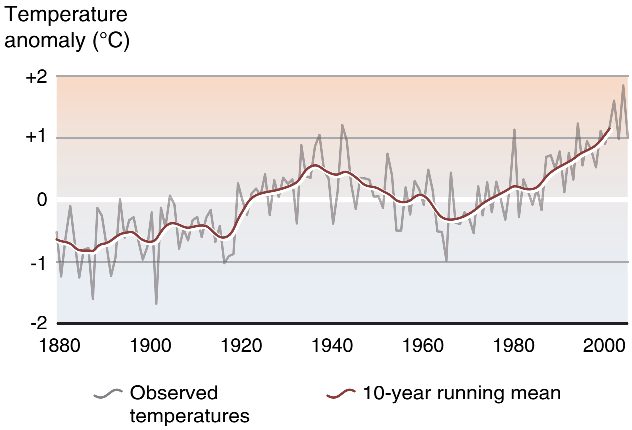



**Figure 3.2: Changes in Arctic mean annual land temperatures from 1880 through 2006.** The zero line represents the average temperature for 1961–1990.

*Source: M. Wang ; data from CRU 2007*[4]

A history of Arctic land temperature anomalies from 1880 through 2006 is shown in Figure 3.2. In the late 1800s the Arctic was relatively cold, although there is some uncertainty around these early temperature estimates. The Arctic warmed by about 0.7°C over the 20th century. There was a warm period in the 1920s to 1940s and cold periods in the early 1900s and in the 1960s. Over the last decade the temperatures were about 1.0°C above the 20th century average.

Figure 3.3 shows that the largest recent gains in annual temperatures for the planet are over the North American Arctic, north central Siberia, and on the Antarctic Peninsula. These recent increases in temperature are confirmed by changes in other features: loss of sea ice, shift of tundra to shrub vegetation, and migration of marine and terrestrial ecosystems to higher latitudes[5].

Natural climate variability is organized into spatial patterns of high and low pressure regions, represented by the Arctic Oscillation (also called the Northern Annular Mode) and North Pacific patterns in the Northern Hemisphere, and the Southern Annular Mode in the Southern Hemisphere. The patterns of surface temperature anomalies when the Arctic Oscillation and Northern Pacific patterns are in their positive extreme are shown in Figure 3.4. When either of the patterns is in its positive extreme, the pattern contributes to an overall Arctic warm period. In recent years (2000–2005), however, the pattern of warm temperature anomalies is circumpolar in distribution and different from either of the two major 20th century climate patterns. We are truly in a new and uncertain climate state for the northern polar region[6,7].

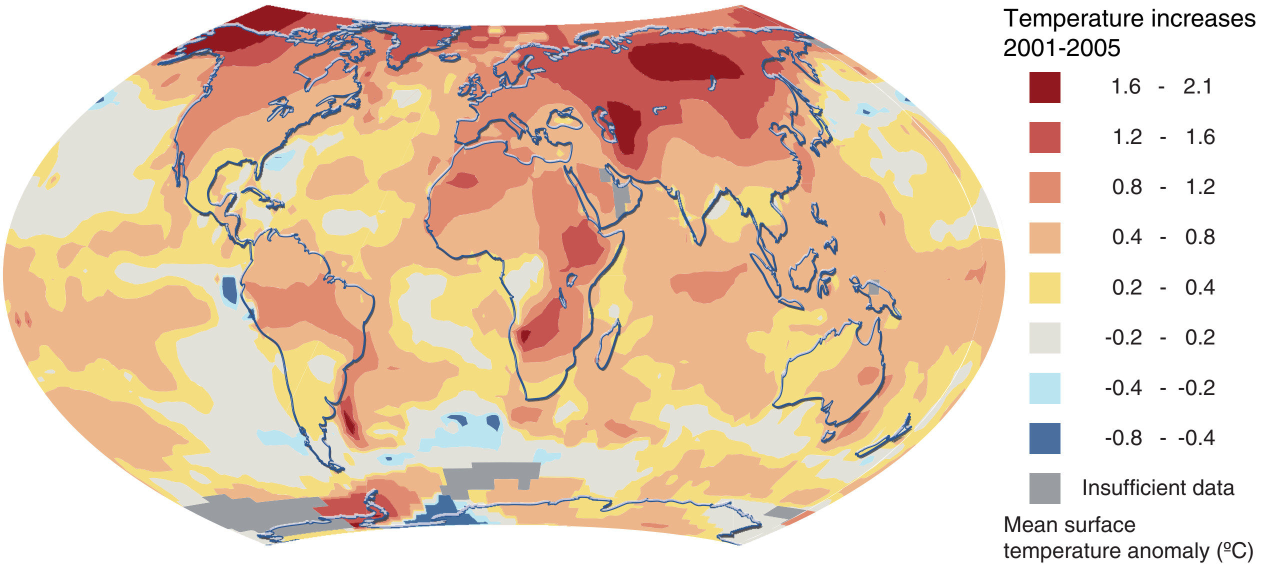



**Figure 3.3: Increases in annual temperatures for a recent five-year period relative to 1951–1980.** Warming is widespread, generally greater over land than over oceans, and greatest at high latitudes in the Northern Hemisphere.

*Source: based on Hansen and others 2006[8]*

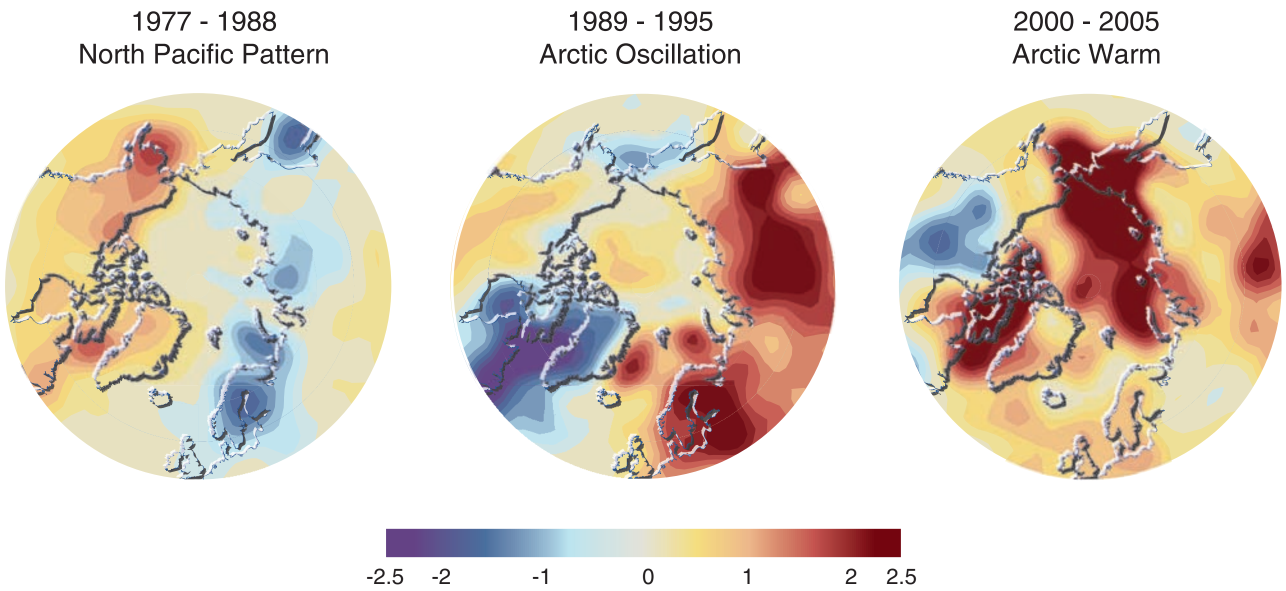



**Figure 3.4: Recent Northern Hemisphere surface temperature anomalies averaged over periods with different types of dominating pattern of natural variability.** The Northern Pacific pattern was dominant in the Arctic from 1977 to 1988, while the Arctic Oscillation dominated the region from 1989 to 1995. In spring 2000 to 2005 neither of these alternate states is evident – the recent warm period in the Arctic represents a new and uncertain climate pattern.

*Source: J.E. Overland; data from NOAA/ESRL 2007*[9]

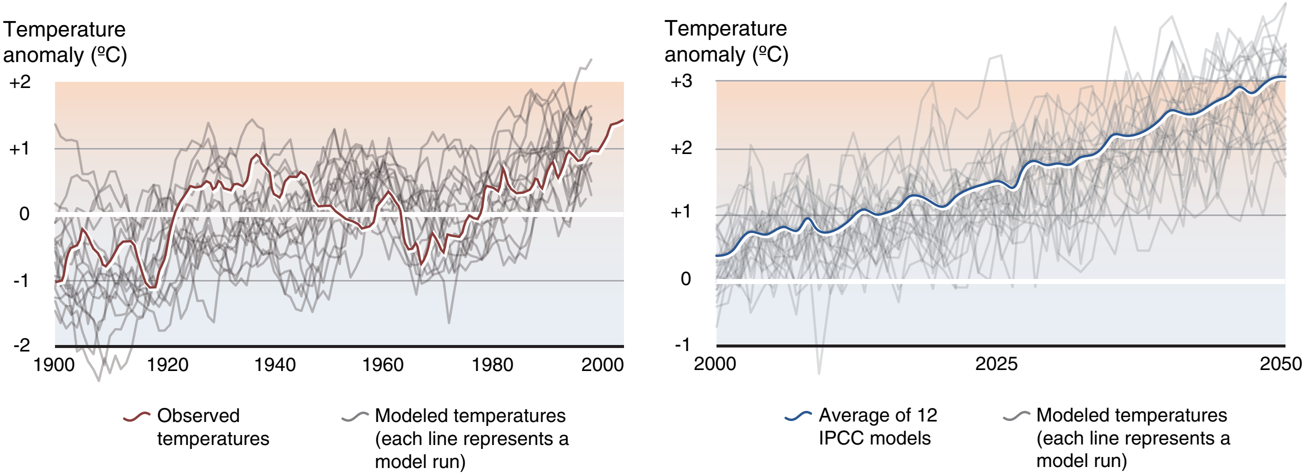
## Using climate models to examine the 20th century and to look ahead

We can understand the relative influence of external forcing from greenhouse gases and internal natural variability of the climate system for the 20th and 21st centuries through the use of atmosphere-ocean coupled climate models. To enable comparisons of the climate model runs for the Intergovernmental Panel on Climate Change Fourth Assessment Report[1], the World Climate Research Programme (WCRP) established an archive containing model results from over 20 national climate centres around the world, for the recent past and for the future. These models were run several times, starting with slightly different conditions but with the same external forcing, to simulate the effects of natural variability.

### Arctic

Figure 3.5(a) shows model runs for a subset of models, recreating the Arctic winter land temperatures of the 20th century. By the end of the century virtually all model runs arrive at temperatures that are above the 20th century mean, implying the importance of greenhouse gas forc-

**Figure 3.5: 20th century (a) and 21st century (b) Arctic land temperatures: results from IPCC models**




**(a)** Observed Arctic winter land temperatures and model recreations for the 20th century. Note that although these model runs are able to capture the range of Arctic warm and cold periods, the timing of the peaks varies, suggesting that the early 20th century warming was due to random causes, while the increases at the end of the century shown by all the models supports $CO_2$ as an external forcing of the Arctic climate system.

*Source: based on Wang and others 2007*[10]

**(b)** Projected Arctic annual land temperature increases for the first half of the 21st century relative to the average temperature for 1980–99. The average of the models (the blue line) shows an increase of 3°C by 2050. The averages of the runs from each of the 12 models show increases from 2–4°C, the range of uncertainty in these model projections.

*Source: based on Wang and others 2007*[10]

ing in raising Arctic temperatures in recent decades. Earlier in the 20th century, observed temperature extremes are similar to those generated by the models, but the timing is different. This difference in timing indicates that the warm period in the early 20th century was a result of natural variability of the Arctic climate system, and that the late warm period of the 20th century had contributions both from an anthropogenic, forced trend due to greenhouse gases and from natural variability. There is no evidence from the internal atmospheric structure of these early and late 20th century warm events that would indicate that they are both part of a simple climate oscillation.

Looking forward, we can project that 21st century climate will have contributions from both greenhouse gas forcing and internal natural variability. Figure 3.5(b) shows projected annual land temperature increases for the Arctic. The average of all the model simulations shows an increase in Arctic annual mean temperatures of 3.0°C by 2050, with the various models showing increases ranging from 2.0–4.0°C. The individual model runs show a trend towards warmer high and low temperature extremes. Differences between models reflect the uncertainty around representations of climate physics. Models appear to be less reliable in projecting climate variables other than temperature – such as precipitation or wind conditions[11].

## Antarctica

The temperature trends for Antarctica show that late 20th century warming was primarily along the Antarctic Peninsula without significant warming trends elsewhere on the continent. The proximate cause for the warming on the Peninsula was the increase in the magnitude of the Southern Annular Mode during the period from 1960 to 2001, a change that implies stronger winds, reduced sea ice, and warmer temperatures upwind of the Peninsula, which contributed to the local warming. There are indications of warming higher up in the atmosphere over Antarctica over the last 30 years, but causes cannot be assessed[12].

Model experiments for the end of the 21st century do show broader patterns of warm surface temperatures throughout Antarctica. The delay in the response is thought to be the result of the large thermal inertia of the Southern Ocean[13] or details of the internal physics of the Southern Annular Mode[14], but uncertainties are large.

# Feedbacks and interactions

Feedback refers to the modification of a process by changes resulting from the process itself. Positive feedbacks accelerate the process, while negative feedbacks slow it down. Part of the uncertainty around future climates relates to important feedbacks between different parts of the climate system: air temperatures, ice and snow albedo (reflection of the sun's rays), and clouds.

An important positive feedback is the ice and snow albedo feedback (see also Chapters 2, 4 and 5). Sea ice and snow have high albedo. This means that they reflect most of the solar radiation. With warmer polar temperatures, the area of sea ice and snow cover decreases, exposing new expanses of ocean and land surfaces that absorb an increased amount of solar radiation. This increase of total absorbed solar radiation contributes to continued and accelerated warming. Many IPCC climate models suggest a major loss in sea ice cover by the mid 21st century caused by albedo feedback from shrinking snow cover and increased open water areas in summer[15].

A second feedback is negative: the cloud-radiative feedback. Its future impact is important but uncertain. Increased cloud cover, an expected result of global warming, increases the reflection of solar radiation away from the Earth's surface, but it also increases the net long-wave radiation emitted downward from the same clouds back to the surface[16]. The net effect of increased cloudiness is expected to be a small decrease in radiation received by the Earth's surface.

One of the great challenges of climate change science is to understand the net effect of these rather complex interactions (Figure 3.6). This is not just a question of understanding the physics of climate systems – many of these interactions and feedbacks also involve the living world. For example, the increase in shrub growth in tundra regions due to high-latitude warming leads to a decrease in albedo in summer, but  an increase in snow retention in winter over large areas of land. Another feedback comes from melting permafrost that releases methane, a powerful greenhouse gas, into the atmosphere, which then amplifies the greenhouse effect. The need to understand these interactions has led to an increase in interdisciplinary studies in recent years and is a focus of research being conducted through the International Polar Year 2007–2008.

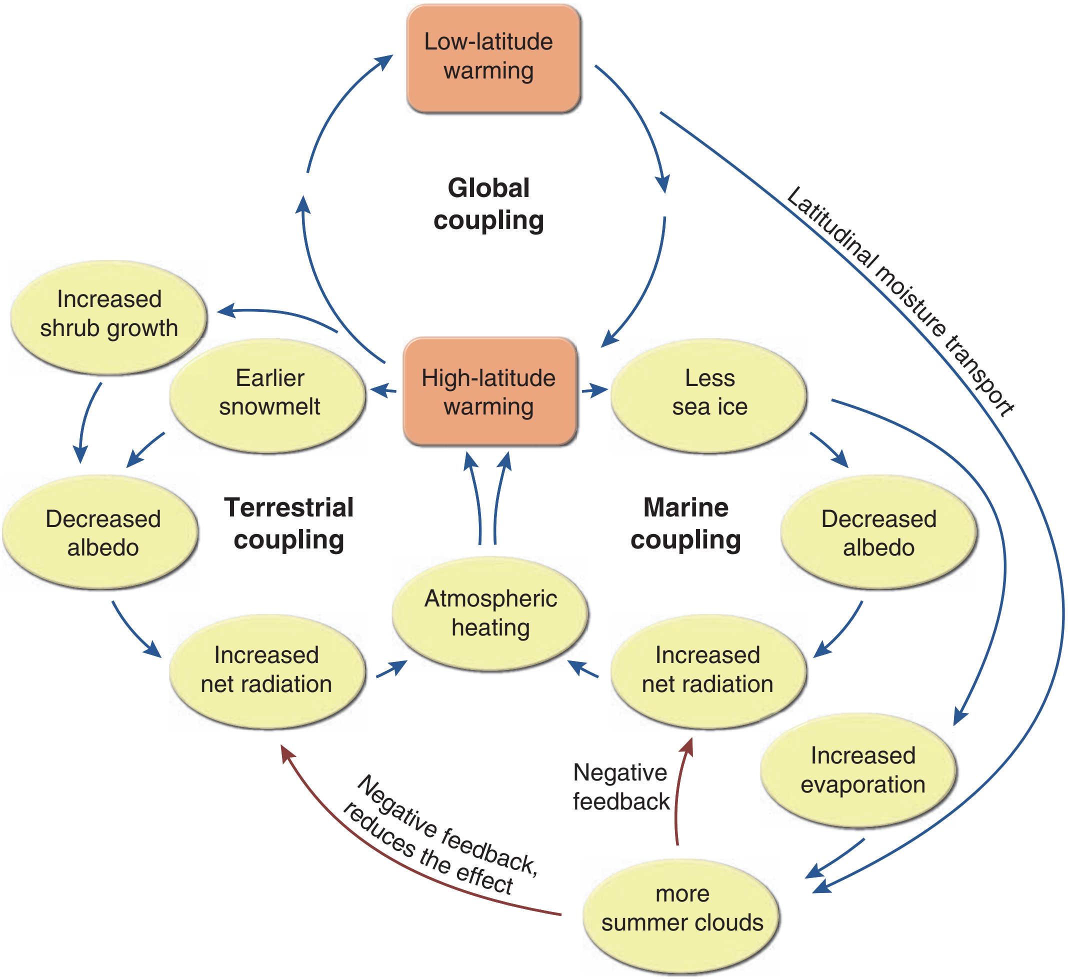



**Figure 3.6: Feedbacks.** This conceptual diagram illustrates the connectivity of the positive ice/snow albedo feedback, terrestrial snow and vegetation feedbacks and the negative cloud/radiation feedback.

*Source: based on Chapin III and others 2005*[17]

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