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Highlights

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Ice and snow are important components of the Earth's climate system and are particularly sensitive to global warming. Over the last few decades the amount of ice and snow, especially in the Northern Hemisphere, has decreased substantially, mainly due to human-made global warming. Changes in the volumes and extents of ice and snow have both global and local impacts on climate, ecosystems and human well-being.

Snow and the various forms of ice play different roles within the climate system. The two continental **ice sheets** of Antarctica and Greenland actively influence the global climate over time scales of millennia to millions of years, but may also have more rapid effects on, for example, sea level. **Snow** and **sea ice**, with their large areas but relatively small volumes, are connected to key interactions and feedbacks at global scales, including solar reflectivity and ocean circulation. Perennially **frozen ground** (permafrost) influences soil water content and vegetation over continental-scale northern regions and is one of the cryosphere components most sensitive to atmospheric warming trends. As permafrost warms, organic material stored in permafrost may release greenhouse gases into the atmosphere and increase the rate of global warming. **Glaciers and ice caps**, as well as **river and lake ice**, with their smaller areas and volumes, react relatively quickly to climate effects, influencing ecosystems and human activities on a local scale. They are good indicators of climate change.

Photo: Ian Britton/FreeFoto.com

Why are Ice and Snow Changing?

- A main conclusion of the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report of 2007 was that it is very likely that most of the global warming during the last 50 years is due to the increase in human-made greenhouse gases.
- The largest recent increases in annual temperatures for the planet are over the North American Arctic, north central Siberia and on the Antarctic Peninsula.
- The climate system is influenced both by natural variability and external factors such as greenhouse gases and the sun. During the 21st century the most important external influence on snow and ice will be the increase in greenhouse gases.
- Overall Arctic temperatures have been increasing at almost double the global rate. Climate model simulations for the Arctic project further increases in average temperatures plus a trend to warmer high and low temperature extremes.
- In Antarctica the recent warming has not been widespread, but model projections for the end of the 21st century indicate a broader pattern of warmer surface temperatures.
- Ongoing changes to ice and snow have a predominantly positive feedback effect which will result in accelerating rates of change.

Photo: Artis Rams/iStock

Snow

- Mean monthly snow-cover extent in the Northern Hemisphere has declined at a rate of 1.3 per cent per decade over the last 40 years with greatest losses in the spring and summer.
- Major reductions in snow cover are projected for mid-latitudes by the end of this century. Parts of the Canadian Arctic and Siberia are projected to receive increased snow fall.
- Air temperatures are projected to continue increasing in many mountainous regions, which will raise snow lines and cause other changes in mountain snow cover.
- Snow is an important ecological factor. Increased frequency of snow thaw due to rise in air temperatures changes the properties of snow cover, with implications for plants and animals that interact with snow. Projected changes in amount of snow cover will affect the structure of ecosystems.
- Snow cover is a major influence on climate due to its high reflectivity of sunlight and its insulating properties. Decreases in snow-cover extent will act as a positive feedback to global warming by changing the reflectivity of the land surface.
- Changes in snow cover have a dramatic impact on water resources. Snow in mountain regions contributes to water supplies for almost one-sixth of the world's population.
- Changes in snow cover affect human well-being through influences on water resources, agriculture, infrastructure, livelihoods of Arctic indigenous people, environmental hazards and winter recreation.

Photo: Jon Aars/NPI

Ice in the Sea

- In the last three decades there have been declines in the extent of Arctic sea ice of 8.9 per cent per decade in September and 2.5 per cent per decade in March. The retreat of sea ice is particularly noticeable along the Eurasian coast. Sea-ice thickness has declined in parts of the Arctic since the 1950s and both the extent and the thickness of Arctic sea ice are projected to continue to decline with the possibility of a mainly ice-free Arctic Ocean in summer by 2100 or earlier.
- Antarctic sea ice is projected to decline in extent at a similar rate as in the Arctic, but it is not expected to thin as much.
- Declines in the extent of sea ice accelerate the rate of melting because more sunlight is reflected by the bright surface of snow and sea ice than by the dark surface of open water. This is the same feedback process that results from decline of snow-cover extent on land. This feedback process affects climate globally.
- Melting sea ice may influence global patterns of ocean circulation; increasing melting of sea ice in combination with increased freshwater influx from melting glaciers and ice sheets may result in major changes to ocean circulation.
- Sea ice is vital habitat for organisms ranging from tiny bacteria, algae, worms and crustaceans to sea birds, penguins, seals, walrus, polar bears and whales. Some sea-ice dependent animals are already at risk and the predicted declines in sea ice may lead to extinctions.
- Shrinking sea ice is forcing coastal Arctic indigenous people to adopt different methods of travel and to change their harvesting strategies. Further loss of sea ice threatens traditional livelihoods and cultures.
- Increasing extent of open water in polar regions will provide easier access to economic activities such as exploration and exploitation of petroleum resources, and shipborne tourism, with accompanying benefits and risks.
- The Northern Sea Route along Russia's Arctic coast is currently navigable for 20–30 days annually. Predictions are that by 2080 the navigable period will increase to 80–90 days. This, combined with the potential of future opening of the Northwest Passage through Canada's waters, will likely have a major impact on world shipping.

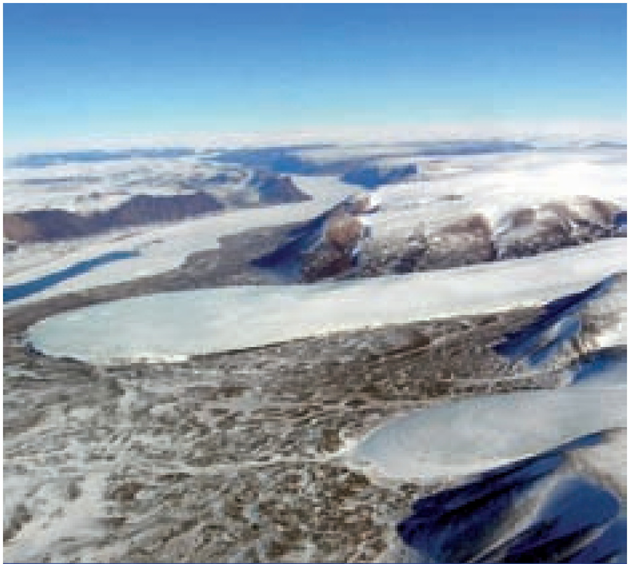

Photo: Konrad Steffen

Ice on the Land

Ice Sheets

- Annual total loss of mass from the Greenland Ice Sheet more than doubled in the last decade of the 20th century and may have doubled again by 2005. This is related to more melting and also to increased discharge of ice from outlet glaciers into the ocean. Warmer Greenland summers are extending the zone and intensity of summer melting to higher elevations. This increases both meltwater runoff into the ocean and meltwater drainage that lubricates glacier sliding and potentially increases ice discharge into the ocean.
- There is uncertainty concerning recent overall changes in ice mass in the Antarctic Ice Sheet but there is probably an overall decline in mass with shrinking in the west and addition in the east due to increased snowfall. Ice shelves are thinning and some are breaking up. Glaciers that feed the ice shelves are observed to accelerate, as much as eight-fold, following ice-shelf break-up.
- Observations made over the past five years make it clear that existing ice-sheet models cannot simulate the widespread rapid glacier thinning that is occurring, and ocean models cannot simulate the changes in the ocean that are probably causing some of the ice thinning. This means that it is not possible now to predict the future of the ice sheets, in either the short or long term, with any confidence.
- The Greenland and Antarctic ice sheets hold about 99 per cent of the world's freshwater ice (the equivalent of 64 m of sea level rise) and changes to them will have dramatic and world-wide impacts, particularly on sea level but also on ocean circulation.

Photo: Igor Smichkov/iStock

Ice on the Land

Glaciers and Ice Caps

- Over the past 100 years, and particularly since the 1980s, there has been worldwide and dramatic shrinkage of glaciers. This shrinking is closely related to global warming.
- Projected increases in global air temperatures will ensure the continuing shrinkage of glaciers and ice caps and may lead to the disappearance of glaciers from many mountain regions over the coming decades.
- Disappearance of glaciers will have major consequences on water resources, especially in regions such as the Himalayas–Hindu Kush, the Andes, Rocky Mountains and European Alps, where many dry-season river flows depend on glacier meltwater.
- Shrinkage of glaciers leads to the deposition of unstable debris, the formation of ice and debris dammed lakes and it increases instability of glacier ice. These conditions pose increased risk of catastrophic flooding, debris flows and ice avalanches.

Photo: Bruce Richmond/USGS

Ice and Sea-level Change

- Sea level is rising at an increasing rate which is associated with global warming. The rate of sea-level rise is now 3.1 mm per year; the average for the 20th century was 1.7 mm per year.
- More than a third of sea-level rise is from meltwater from glaciers and ice sheets with most of the remaining rise being due to thermal expansion of the oceans. The contribution of meltwater to sea-level rise can be expected to continue and accelerate as more land ice melts. Over the long term the ice sheets of Greenland and Antarctica have the potential to make the largest contribution to sea-level rise, but they are also the greatest source of uncertainty.
- For the next few decades, the rate of sea-level rise is partly locked in by past emissions and will not be strongly dependent on 21st century greenhouse gas emissions. However, sea-level projections closer to and beyond 2100 are critically dependent on future greenhouse gas emissions.
- The IPCC Fourth Assessment Report projects a global sea level rise over the 21st century in the range of about 20 to 80 cm. However, the upper bound of this projection is very uncertain.
- Climate change is also projected to increase the frequency and severity of extreme sea-level events such as storm surges. This will exacerbate the impacts of sea-level rise.
- The impacts of sea level rise in any region will depend on many interacting factors, including whether the coastal region is undergoing uplift or subsidence, and to what degree development has altered natural flood protection such as coastal vegetation.
- Rising sea levels will potentially affect many millions of people on small islands and at and near coasts worldwide. A wide range of adaptation and mitigation measures will be required to assist people to cope with the consequences; these will require cooperation among nations as well as among all levels of government, the private sector, researchers, non-government organizations and communities.

Photo: V. Romanovsky

Frozen Ground

- Permafrost temperatures have increased during the last 20–30 years in almost all areas of the Northern Hemisphere. Warming of permafrost is also reported from areas of mountain permafrost. This warming has not yet resulted in widespread permafrost thawing.
- Climate changes are projected to result in permafrost thawing across the subarctic by the end of this century, with the most significant thawing occurring in North America.
- Permafrost stores a lot of carbon, with upper permafrost layers estimated to contain more organic carbon than is currently contained in the atmosphere. Permafrost thawing results in the release of this carbon in the form of greenhouse gases which will have a positive feedback effect to global warming.
- Thawing of ice-rich permafrost results in the formation of thermokarst, land forms in which parts of the ground surface have subsided. Thermokarst affects ecosystems and infrastructure and can accelerate permafrost thawing.
- The construction and everyday use of existing infrastructure can result in permafrost thawing, with subsequent effects on infrastructure. Increases in air temperatures may accelerate this ongoing permafrost degradation associated with infrastructure.
- Thawing of permafrost has significant impacts on ecosystems, with the potential to completely change habitats, for example, from boreal forest to wetlands.
- In mountainous areas thawing permafrost may increase slope instability, raising the risk of natural hazards such as landslides and rock falls.

Photo: Esko Kuusisto

River and Lake Ice

- Changes that have largely mirrored rising air temperatures are affecting river and lake ice, mainly seen as earlier spring break up and, to a lesser extent, later autumn freeze up.
- The trend to longer ice-free periods is projected to continue. Details are uncertain but strong regional variation is expected, with the amount of change depending on the degree of warming that is forecast.
- Ice formation on rivers and lakes is a key factor controlling biological production and changes in the length and timing of ice cover have ecosystem effects.
- In remote areas frozen rivers and lakes are used as transport corridors and longer ice-free periods mean reduced or more expensive access to communities and industrial developments. Many northern indigenous people depend on frozen lakes and rivers for access to traditional hunting, fishing, reindeer herding or trapping areas.
- Spring break up often causes damming of rivers by ice, resulting in costly flooding. Lowered temperature gradients along north-flowing rivers in the Northern Hemisphere may lead to reductions in ice-jam flooding. This has potential negative ecological consequences for deltas where annual flooding is needed to maintain ponds and wetlands.

Photo: Christian Lambrechts

Policy and Perspectives

Changes in ice and snow raise policy issues at global, regional and local scales.

Global

- Ice, snow and climate change are closely linked. Mitigating climate change by reducing greenhouse gases emissions is the main global policy response to mitigate changes in ice and snow.
- The IPCC Fourth Assessment Report concluded that, to avoid further and accelerated global warming with major negative consequences, greenhouse gases must stop increasing and start decreasing no later than 15 to 25 years from now. Economic assessments indicate that this is achievable without significant welfare losses.

Regional

- Adaptation policy must be tailored to regions and requires regional scientific knowledge and assessment of impacts of climate change.
- In the Arctic, key policy issues centre on the prospect of retreating sea ice and the implications for shipping and exploitation of oil and gas reserves. This raises issues of jurisdiction and of regulatory regimes in the Arctic marine environment.
- In Antarctica, the projected decrease in sea-ice extent is likely to contribute to an already rapid expansion of the tourism industry with potential impacts on the environment and on the value of Antarctica in research. This points to the need for a regulatory framework for Antarctic tourism.
- In the Himalayas–Hindu Kush region, projected changes in snowfall and glacier melt are expected to increase risks of both floods and water shortages, potentially affecting hundreds of millions of people. Strategies for water management and land-use planning are needed to reduce vulnerability to the impacts of global warming.

Local

- Impacts of changes in ice and snow are already major concerns in many Arctic communities. Examples of local impacts are damage to coastal infrastructure from thawing permafrost and increased storm surges, and loss of access to subsistence resources for indigenous people. Expansion of shipping and oil and gas development will bring both local opportunities and potential for negative economic and social effects. Most individual communities currently lack the capacity to cope effectively with these stresses. Responses to these challenges are likely to reflect differences in political and legal systems among Arctic states.