2 Arctic warming and its consequences have worldwide implications.

Importance of the Arctic to Global Climate

The Arctic exerts a special influence over global climate. Integrated over the year, incoming energy from the sun is greatest near the equator and smallest near the poles. Further, because much of the Arctic is covered with snow and ice, a larger fraction of the incoming solar energy is reflected back to space than at lower latitudes, which absorb most of this energy. If not for the atmosphere and oceans moving energy from the tropics to the poles, the tropics would overheat and the polar regions would be much colder than they are. In the Northern Hemisphere, the Atlantic Ocean is the major carrier of the oceanic component of this energy transfer, and as explained below, arctic processes have the potential to have major impacts on the strength of the Atlantic Ocean's circulation.

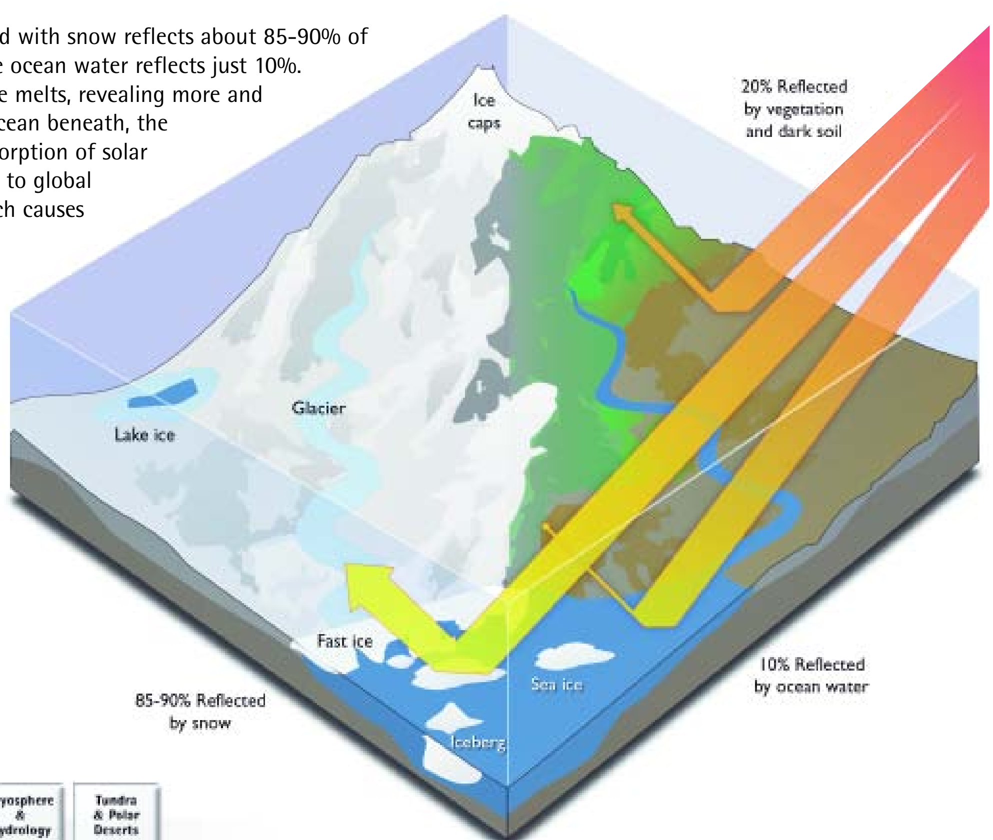
If not for the atmosphere and oceans moving energy from the tropics to the poles, the tropics would overheat and the polar regions would be much colder than they are.

There are three major mechanisms, or so-called "feedbacks", by which arctic processes can cause additional climate change for the planet. One involves changes in the reflectivity of the surface as snow and ice melt and vegetation cover changes, the second involves changes to ocean circulation as arctic ice melts, adding freshwater to the oceans, and the third involves changes in the amounts of greenhouse gases emitted to the atmosphere from the land as warming progresses.

Feedback 1: Surface Reflectivity

The first feedback involves the snow and ice that cover much of the Arctic. Because they are bright white, snow and ice reflect most of the solar energy that reaches the surface back to space. This is one reason why the Arctic remains so cold. As greenhouse gas concentrations rise and warm the lower atmosphere, snow and ice begin to form later in the autumn and melt earlier in the spring. The melting back of the snow and ice reveals the land and water surfaces beneath, which are much darker, and thus absorb more of the

Sea ice covered with snow reflects about 85-90% of sunlight, while ocean water reflects just 10%. Thus, as sea ice melts, revealing more and more of the ocean beneath, the increasing absorption of solar radiation adds to global warming, which causes more melting, which in turn causes more warming, and so on...



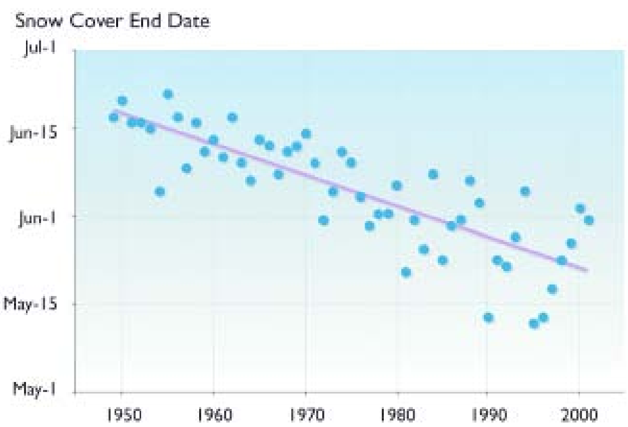
sun's energy. This warms the surface further, causing faster melting, which in turn causes more warming, and so on, creating a self-reinforcing cycle by which global warming feeds on itself, amplifying and accelerating the warming trend. This process is already underway in the Arctic with the widespread retreat of glaciers, snow cover, and sea ice. This is one reason why climate change is more rapid in the Arctic than elsewhere. This regional warming also accelerates warming at the global scale.

Another warming-induced change likely to increase the absorption of solar energy at the earth's surface is that forests are projected to expand northward into areas that are currently tundra. The relatively smooth tundra is much more reflective, especially when covered with snow, than the taller, darker, and more textured forests that are projected to replace it. The reduction in reflectivity that will accompany forest expansion is expected to further increase warming, though more slowly than the snow and ice changes described above. The increased tree growth is expected to absorb more carbon dioxide than the current vegetation, a process that could potentially moderate warming. However, the reduction in reflectivity resulting from forest expansion is likely to exert a larger climatic influence than the carbon uptake effect, thus amplifying warming. Greater vegetation growth also masks snow cover on the ground, further reducing surface reflectivity.

A direct human influence that also decreases reflectivity is that soot is produced when fossil fuels are burned (in addition to the carbon dioxide that is the primary problem). The soot that is carried by the winds and deposited in the Arctic slightly darkens the surface of the otherwise bright white snow and ice, causing them to reflect less of the sun's energy, thus further increasing warming. Soot in the atmosphere also increases solar absorption, further warming the region.

As melting snow and ice reveal darker land and water surfaces, more of the sun's energy is absorbed, further warming the planet.

Observed Snow Cover Change Barrow, Alaska



Snow cover extent over arctic land areas has decreased by about 10% over the past 30 years, with the most visible change being an earlier disappearance of snow in spring. One local example is shown in the graph above, for Barrow, Alaska. Over the past 50 years, the snow cover end date has shifted to about one month earlier.

Current Arctic Vegetation

Projected Vegetation, 2090-2100

- Ice
- Polar Desert / Semi-desert
- Tundra
- Boreal Forest
- Temperate Forest
- Grassland

These maps of current and projected vegetation in the Arctic illustrate that forests are projected to overtake tundra and tundra is projected to move into polar deserts. These changes will result in a darker land surface, amplifying warming by absorbing more of the sun's energy and creating a self-reinforcing feedback loop.

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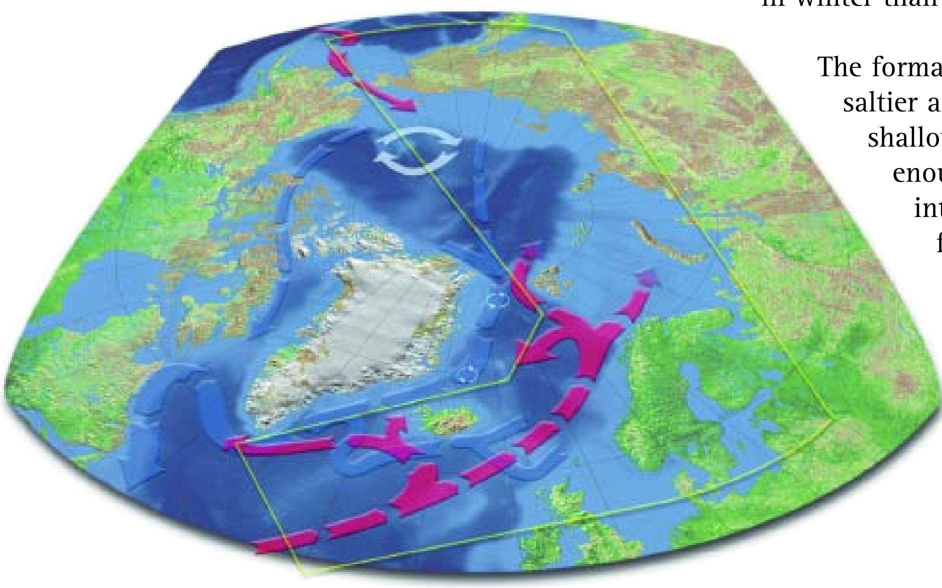
Arctic Thermohaline Circulation

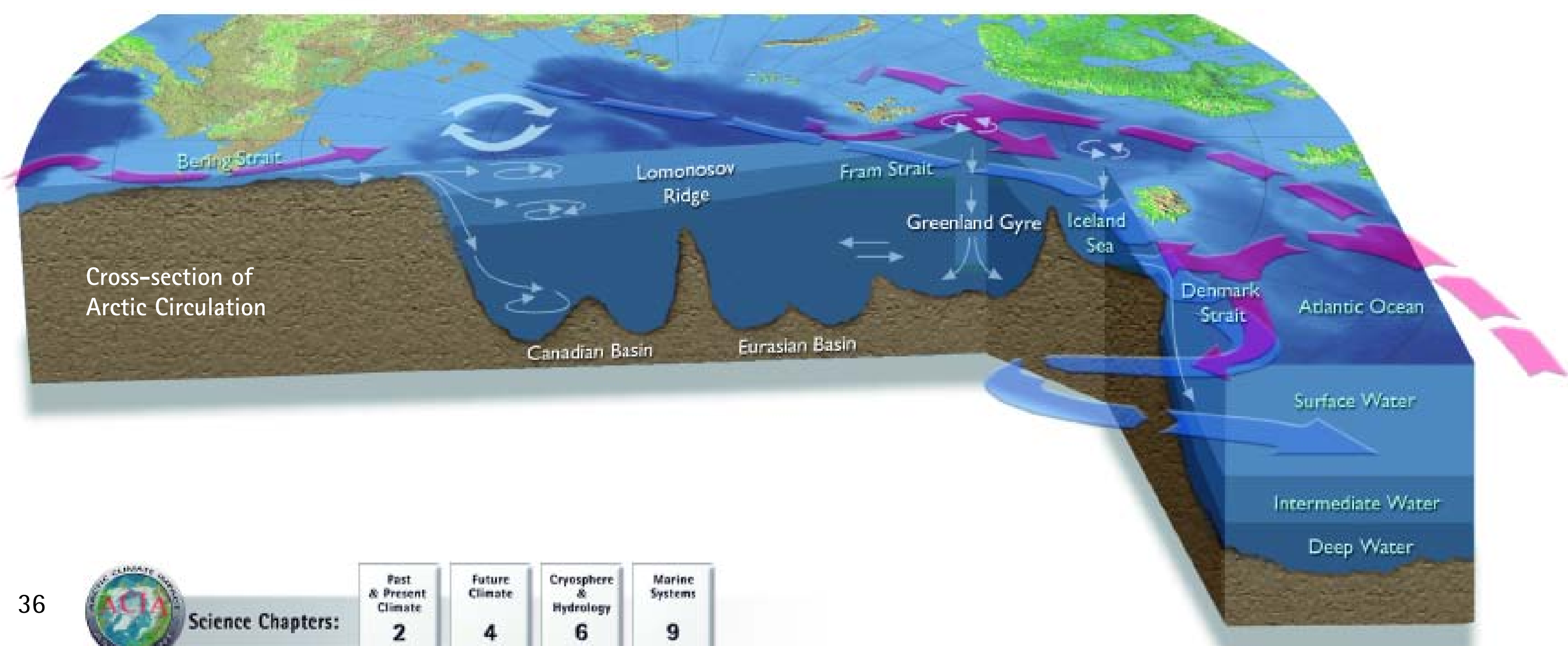
Feedback 2: Ocean Circulation

The second feedback through which arctic processes can amplify changes in global climate is through alterations in ocean circulation patterns. One of the ways the sun's energy is transported from the equator toward the poles is through the globally interconnected movement of ocean waters (see page 32) primarily driven by differences in heat and salt content, known as the thermohaline circulation ("thermo" for heat and "haline" for salt).

At present, the northward extension of the warm Gulf Stream current in the North Atlantic Ocean warms the winds and provides much of the moisture that falls as precipitation over northwestern Europe. As the waters move northward, they become cooler and denser, until they are heavier than the waters below and sink deep into the ocean. This sinking occurs particularly in the seas making up the northern North Atlantic Ocean, and in the Labrador Sea, driving the global thermohaline circulation (sometimes referred to as the "conveyor belt"). This sinking of dense seawater pulls more warm waters northward, helping to provide the heat that keeps Europe warmer in winter than regions of North America that are at the same latitude.

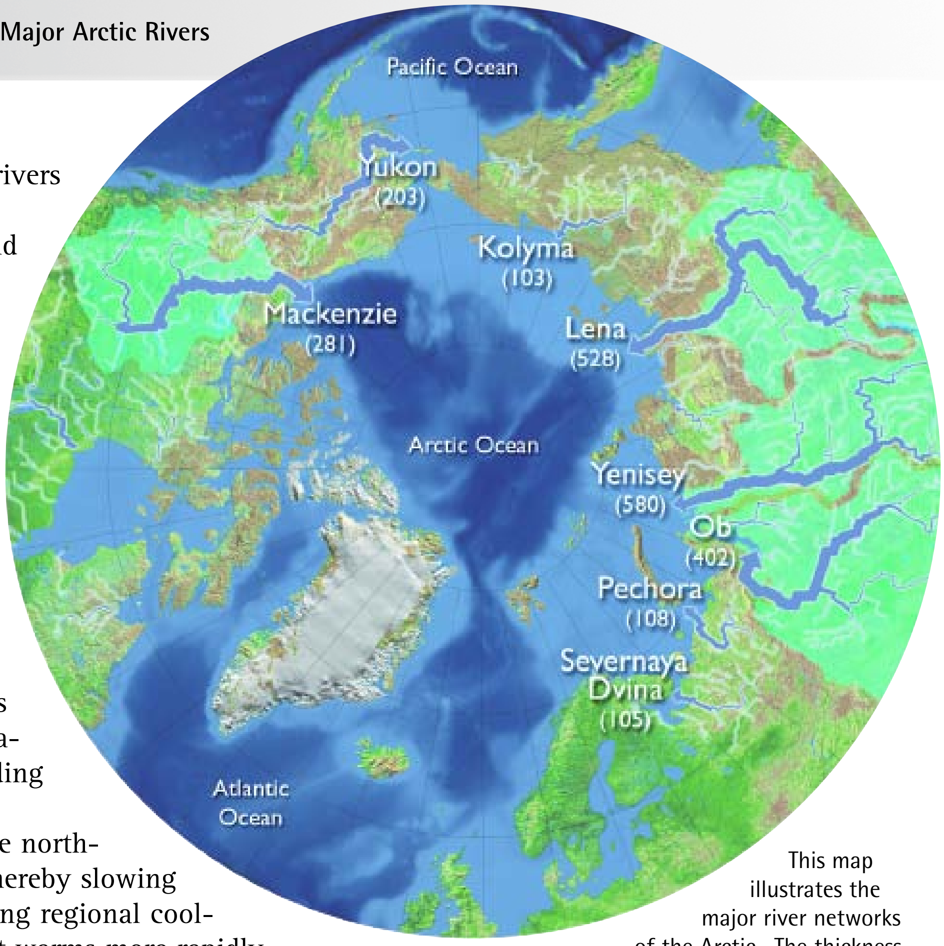


The formation of sea ice also makes the near-surface water saltier and denser as salt is rejected from the ice. In the shallow coastal seas, this water becomes saltier and dense enough to sink. It then flows down the continental shelves into the deep ocean basin, contributing to deep-water formation and the further drawing northward of heat from the tropics. This process is delicately balanced; if the waters are made less salty by an increase in freshwater from runoff and precipitation, or because temperatures are not sufficiently cold to form sea ice, the formation rate of deep water will decrease and less heat from the tropical regions will be pulled northward by the ocean to moderate European winters.



Cross-section of Arctic Circulation

Major Arctic Rivers



This map illustrates the major river networks of the Arctic. The thickness of the blue lines represents the relative river discharge, with the thickest lines indicating the rivers with the largest volume. The numbers on the map are in cubic kilometers per year.

Climate change is projected to influence all of these processes, causing more freshwater to be carried by rivers to the Arctic Ocean due to melting of glaciers and increases in precipitation, and warming the ocean and reducing the rate at which sea-ice formation creates saltier and denser water. As high-latitude waters thus become less salty, they float on top of the saltier waters below, capping them in much the same way as a layer of oil rests above a layer of water. This inhibits vertical mixing, slows the formation of deepwater, and slows the thermohaline circulation.

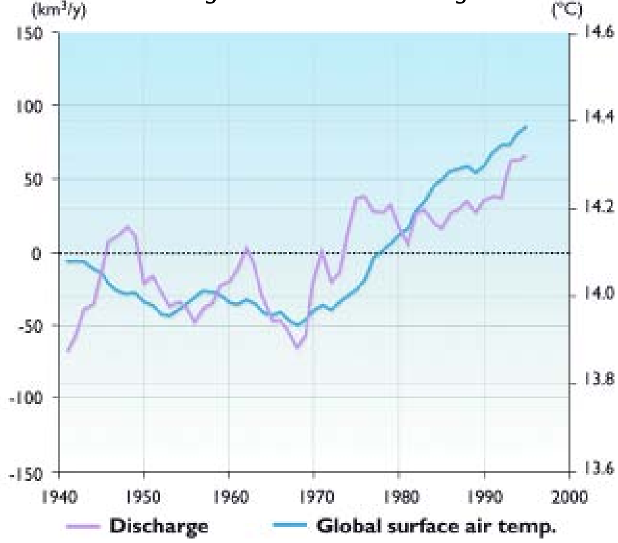
Slowing the thermohaline circulation would have several important global effects. Because the oceanic overturning is an important mechanism for carrying carbon dioxide to the deep ocean, slowing of this circulation would allow the carbon dioxide concentration in the atmosphere to build up more rapidly, leading to more intense and longer-lasting global warming. Slowing of this ocean circulation would also slow the northward transport of heat by Atlantic Ocean currents, thereby slowing the rate of warming in the region, and perhaps causing regional cooling for several decades, even as the rest of the planet warms more rapidly.

Reducing bottom water formation in the Arctic would also reduce the amount of heat and nutrients carried back toward the surface elsewhere in the world by the upward moving components of the thermohaline circulation. This would increase the rate of sea-level rise (due to greater thermal expansion) while reducing the supply of nutrients available to near-surface marine life and the transport of carbon to the deep ocean as carbon-containing living things die and sink. Thus, what happens in the Arctic will have ramifications around the world.

Rising River Flows

The Arctic Ocean is the most river-influenced ocean in the world, receiving 11% of the world's river flow yet containing only 1% of the global volume of seawater. An overall increase has been observed in freshwater flow from rivers to the Arctic Ocean over the past 100 years, with the largest increases taking place in winter and since 1987, in accordance with the largest increases in air temperature. Springtime peak flows are occurring earlier on many rivers. For the next 100 years, models project 10-25% increases in annual river discharge, with greater increases in winter and spring. If summer warming increases losses due to evaporation, it is possible that river levels and flow rates will decrease from present values during summer.

Rising Winter River Discharge



The purple line shows departures from the long-term average of European river discharge in winter (December through March), and the blue line shows changes in global average surface air temperature.

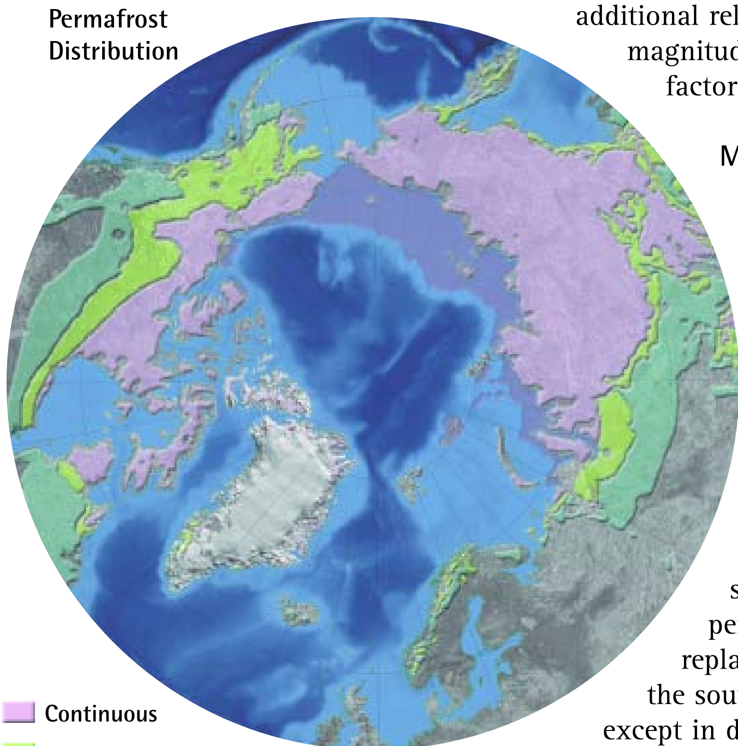
Feedback 3: Greenhouse Gas Emissions

A third feedback through which arctic processes can affect global climate change is by modifying the exchange of greenhouse gases between the atmosphere and arctic soils and sediments, which are likely to be affected as air and water warm.

Methane and Carbon Dioxide from Permafrost

Carbon is currently trapped as organic matter in the permafrost (frozen soil) that underlies much of the Arctic. Large amounts of carbon accumulate particularly in the vast waterlogged peat bogs of Siberia and parts of North America. During the summer, when the surface layer of the permafrost thaws, organic matter in this layer decomposes, releasing methane and carbon dioxide to the atmosphere. Warming increases these releases, and can create an amplifying feedback loop whereby more warming causes additional releases, which would cause more warming, and so on. The potential magnitude of these releases is affected by soil moisture and numerous other factors, and is thus subject to substantial uncertainties.

Permafrost Distribution



Continuous
Discontinuous
Sporadic
Subsea

Subsea permafrost in the Arctic occurs in the wide continental shelf area. Narrow zones of coastal permafrost are probably present along most arctic coasts.

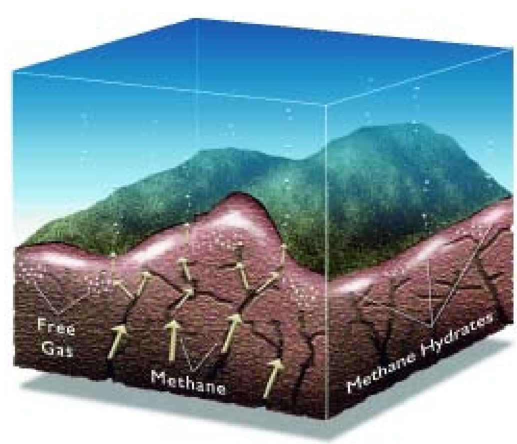
Methane and Carbon Dioxide in Forests and Tundra

The boreal forests and arctic tundra contain some of the world's largest land-based stores of carbon, primarily in the form of plant material in the forests and as soil carbon in the tundra. Methane is about 23 times as potent at trapping heat in the earth's atmosphere as carbon dioxide (by weight, over a 100-year time horizon). Methane is produced by the decomposition of dead plant material in wet soils such as mires and tundra ponds. The release of methane to the atmosphere is generally accelerated by rising temperatures and precipitation, although in areas where drying occurs, methane may be absorbed by forest and tundra soils. Carbon dioxide is released by decomposition in soils in drier areas and by burning of trees in fires. Increasing temperatures will lead to faster decomposition initially, but the likely replacement of arctic vegetation by more productive vegetation from the south would be expected to result in a greater uptake of carbon, except in disturbed and particularly dry areas. It is not known whether the net effect of these changes will be a greater overall carbon uptake as climate change proceeds, though recent studies suggest that over the Arctic as a whole, more productive vegetation will probably increase carbon storage in ecosystems.

Methane Hydrates in the Coastal Arctic Ocean

Vast amounts of methane, in a solid icy form called methane hydrates or clathrates, are trapped in permafrost and at shallow depths in cold ocean sediments. If the temperature of the permafrost or water at the seabed rises a few degrees, it could initiate the decomposition of these hydrates, releasing methane to the atmosphere. The release of methane from this source

Subsea Methane Hydrates

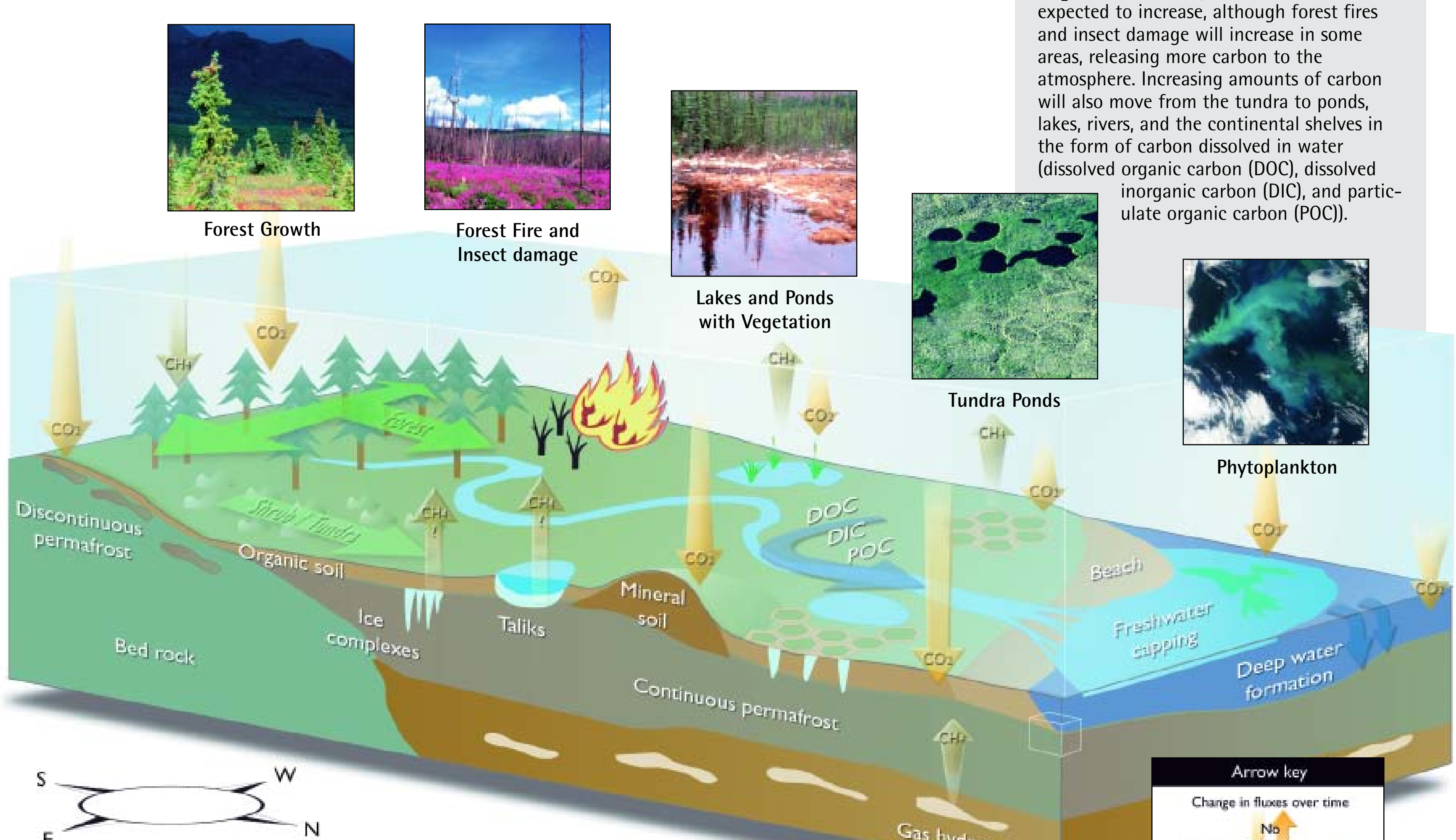


is a less certain outcome of climate change than the other emissions discussed here because it would probably require greater warming and take longer to occur. If such releases did occur, however, the climate impacts could be very large.

Carbon Uptake in the Oceans

To date, the Arctic Ocean has not played a very large part in the global carbon budget because absorption of carbon dioxide from the air has been limited by the sizeable ice cover and because uptake to support biological productivity under perennial sea ice has not been very significant compared to elsewhere in the world's oceans. Under warmer climate conditions, however, it is possible that the amount of carbon taken up by the Arctic Ocean could increase significantly. With less sea ice, more carbon dioxide is likely to be absorbed by the very cold waters, and, as dense water is formed during the seasonal formation of sea ice, the additional carbon dioxide could be carried downward. In addition, increased biological productivity in the open waters could lead to more carbon being carried down as living things die and sink, especially if increased runoff adds to the amount of available nutrients. While these changes are likely to be important regionally, the total area is not large enough to significantly reduce global atmospheric carbon dioxide concentrations.

This schematic illustrates changes in the cycling of carbon in the Arctic as climate warms. For example, beginning at the left of the figure, the boreal forest absorbs CO_2 from the atmosphere and this is expected to increase, although forest fires and insect damage will increase in some areas, releasing more carbon to the atmosphere. Increasing amounts of carbon will also move from the tundra to ponds, lakes, rivers, and the continental shelves in the form of carbon dissolved in water (dissolved organic carbon (DOC), dissolved inorganic carbon (DIC), and particulate organic carbon (POC)).



Note: The arrows are not drawn proportional to the size of the carbon flows. This representation is for the near future only. In the longer term, continued warming would be expected to dry out many lakes and ponds and soil moisture could become too great or too little to support forest expansion, resulting in large releases of carbon to the atmosphere.

Melting Glaciers Contribute to Global Sea-level Rise

The total volume of land-based ice in the Arctic has been estimated to be about 3 100 000 cubic kilometers, which corresponds to a sea-level equivalent of about eight meters. Most arctic glaciers and ice caps have been in decline since the early 1960s, with this trend speeding up in the 1990s. A small number of glaciers, especially in Scandinavia, have gained mass as increased precipitation outpaced the increase in melting in a few areas.

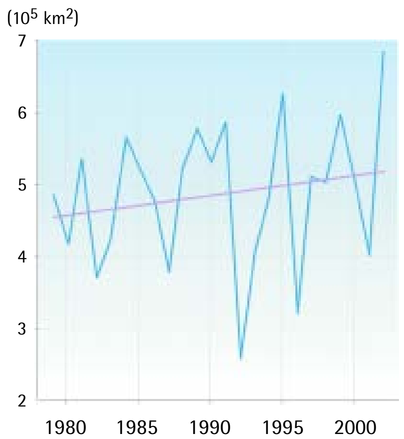
The Greenland Ice Sheet dominates land ice in the Arctic. Maximum surface-melt area on the ice sheet increased on average by 16% from 1979 to 2002, an area roughly the size of Sweden, with considerable variation from year to year. The total area of surface melt on the Greenland Ice Sheet broke all records in 2002, with extreme melting reaching up to a record 2000 meters in elevation. Satellite data show an increasing trend in melt extent since 1979. This trend was interrupted in 1992, following the eruption of Mt. Pinatubo, which created a short-term global cooling as particles spewed from the volcano reduced the amount of sunlight that reached the earth.

Recent studies of glaciers in Alaska indicate an accelerated rate of melting. The associated sea-level rise is nearly double the estimated contribution from the Greenland Ice Sheet during the past 15 years. This rapid retreat of Alaska's glaciers represents about

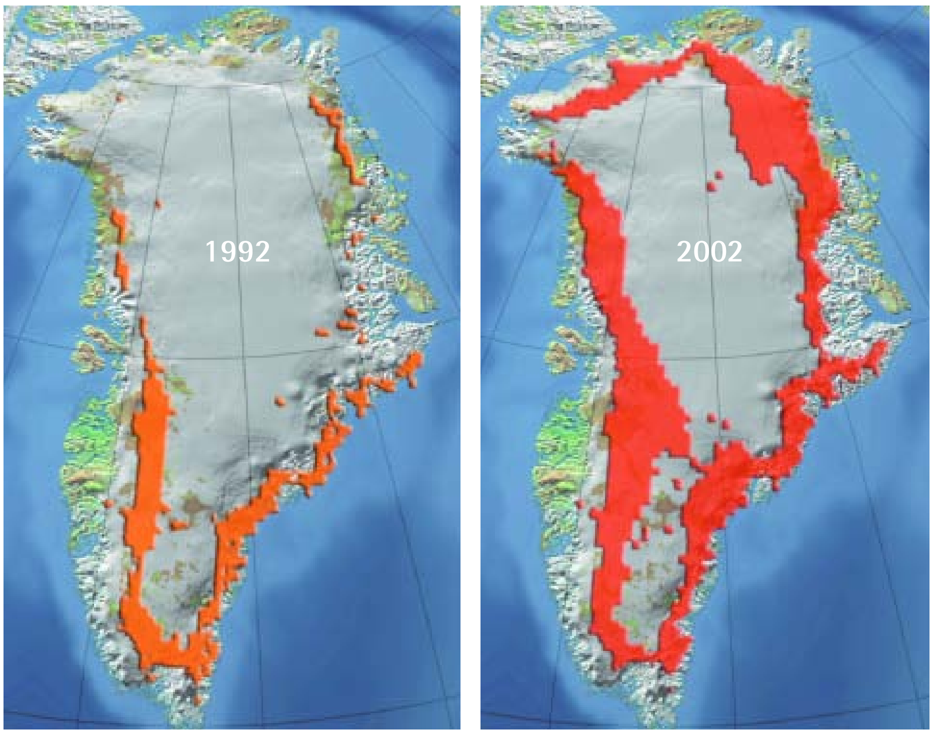
"That year [2002] the melt was so early and so intense – it really jumped out at me. I'd never seen the seasonal melt occur that high on the ice sheet before, and it had never started so early in the spring."

Konrad Steffan
University of Colorado, USA

Greenland Ice Sheet Melt Extent
(Maximum melt extent 1979 - 2002)



Greenland Ice Sheet Melt Extent



Seasonal surface melt extent on the Greenland Ice Sheet has been observed by satellite since 1979 and shows an increasing trend. The melt zone, where summer warmth turns snow and ice around the edges of the ice sheet into slush and ponds of meltwater, has been expanding inland and to record high elevations in recent years. When the meltwater seeps down through cracks in the ice sheet, it may accelerate melting and, in some areas, allow the ice to slide more easily over the bedrock below, speeding its movement to the sea. In addition to contributing to global sea-level rise, this process adds freshwater to the ocean, with potential impacts on ocean circulation and thus regional climate.

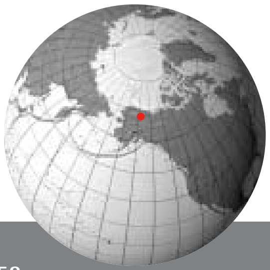
half of the estimated loss of mass by glaciers worldwide, and the largest contribution by glacial melt to rising sea level yet measured.

Projections from global climate models suggest that the contribution of arctic glaciers to global sea-level rise will accelerate over the next 100 years, amounting to roughly four to six centimeters by 2100. Recent research suggests that this estimate should be higher due to the increase in arctic glacial melt during the past two decades.

Over the longer term, the arctic contribution to global sea-level rise is projected to be much greater as ice sheets continue to respond to climate change and to contribute to sea-level rise for thousands of years. Climate models indicate that the local warming over Greenland is likely to be one to three times the global average. Ice sheet models project that local warming of that magnitude would eventually lead to a virtually complete melting of the Greenland Ice Sheet, with a resulting sea-level rise of about seven meters.

"Glaciers are very notably receding and the place names are no longer consistent with the appearance of the land. For example, Sermiarsuussuaq ('the Smaller Large Glacier'), which previously stretched out to the sea, no longer exists."

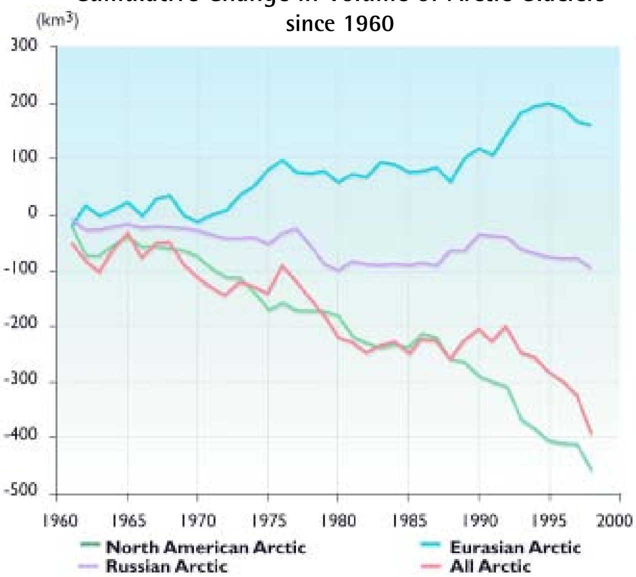
Uusaqqak Qujaukitsoq
Qaanaaq, Greenland



McCall Glacier Retreat
Brooks Range, Alaska

1958 — 2003

Cumulative Change in Volume of Arctic Glaciers since 1960



For the Arctic as a whole, there was a substantial loss in glacial volume from 1961 to 1998. Glaciers in the North American Arctic lost the most mass (about 450 km^3), with increased loss since the late 1980s. Glaciers in the Russian Arctic have also had large losses (about 100 km^3). Glaciers in the European Arctic show an increase in volume because increased precipitation in Scandinavia and Iceland added more to glacial mass than melting removed over that period.

2 Arctic warming and its consequences have worldwide implications.

Sea-level rise is projected to have serious implications for coastal communities and industries, islands, river deltas, harbors, and the large fraction of humanity living in coastal areas worldwide.

Impacts of Global Sea-level Rise

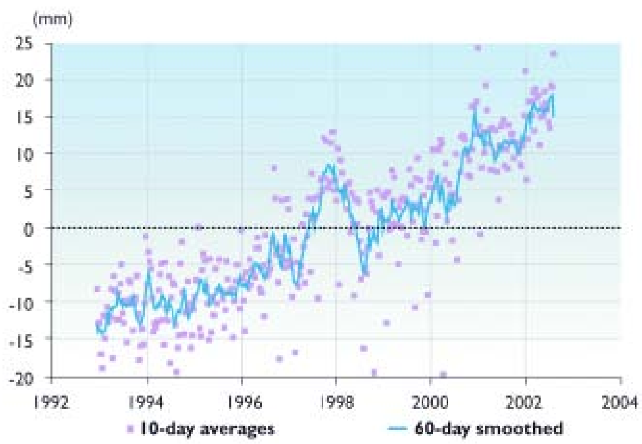
Sea-level rise has the potential for significant impacts on societies and ecosystems around the world. Climate change causes sea level to rise by affecting both the density and the amount of water in the oceans. First and most significantly, water expands as it warms, and less-dense water takes up more space. This "thermal expansion" is projected to be the largest component of sea-level rise over the next 100 years and will persist for many centuries. Secondly, warming increases melting of glaciers and ice caps (land-based ice), adding to the amount of water flowing into the oceans.

Global average sea level rose almost three millimeters per year during the 1990s, up from about two millimeters per year in the several decades prior to that. This rate is, in turn, 10 to 20 times faster than the estimated rate of rise over the past few thousand years. The primary factors contributing to this rise are thermal expansion due to ocean warming and melting of land-based ice that increases the total amount of water in the ocean.

Global average sea level is projected to rise 10 to 90 centimeters during this century, with the rate of rise accelerating as the century progresses. Over the longer term, much larger increases in sea level are projected. Sea-level rise is expected to vary around the globe, with the largest increases projected to occur in the Arctic, in part due to the projected increase in freshwater input to the Arctic Ocean and the resulting decrease in salinity and thus density.

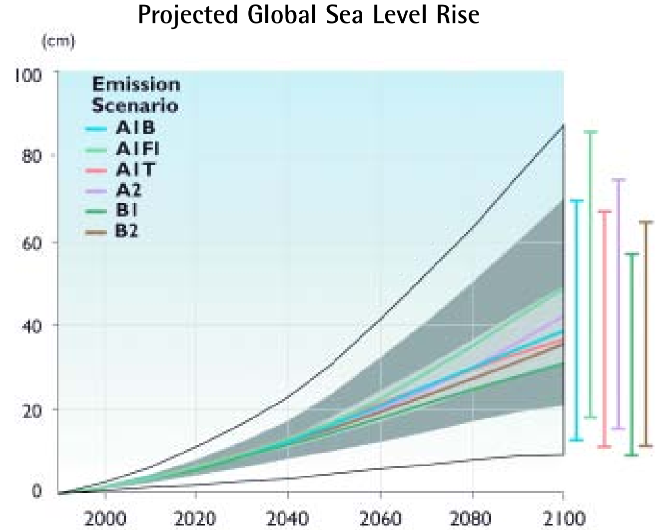
Sea-level rise is projected to have serious implications for coastal communities and industries, islands, river deltas, harbors, and the large fraction of humanity living in coastal areas worldwide. Sea-level rise will increase the salinity of bays and estuaries. It will increase coastal erosion, especially where coastal lands are soft rather than rocky.

Observed Global Sea Level Rise



These data, from a satellite launched in 1992, show the rise in global average sea level over the past decade.

Projected Global Sea Level Rise



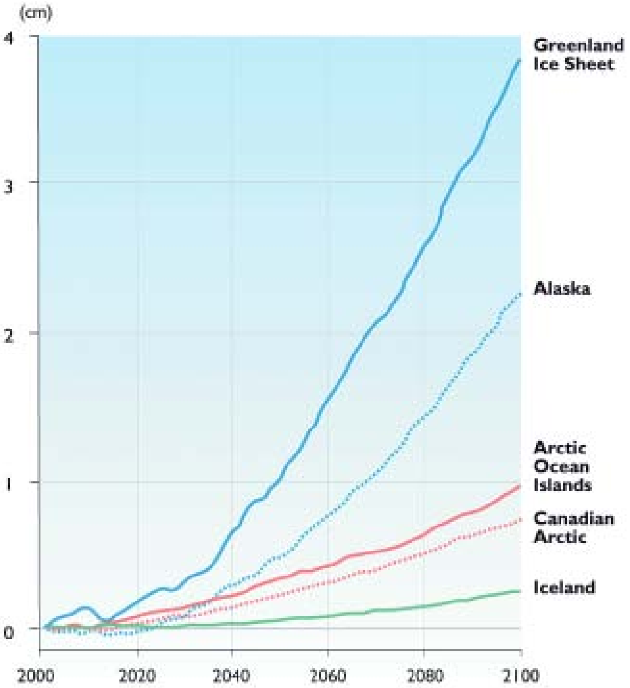
The graph shows future increases in global average sea level in meters as projected by a suite of climate models using six IPCC emissions scenarios. The bars at right show the range projected by a group of models for the designated emissions scenarios.

Extensive coastal lowlands and delta areas contain important ecosystems that will be affected by rising sea levels. Wetlands will be forced farther inland, and the incidence of coastal floods will increase.

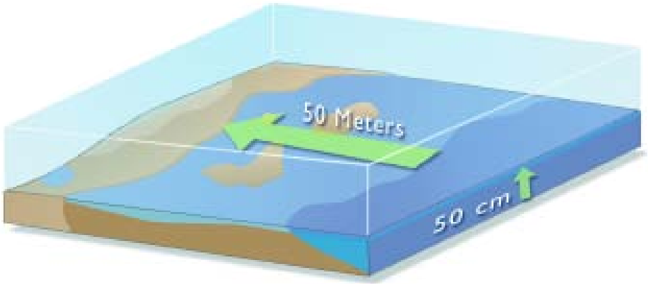
The impacts of sea-level rise are likely to be most severe along gently sloping coastal lands, inland areas bordering estuaries, and coastlines that are subsiding due to tectonic forces, sedimentation, or extraction of oil or groundwater. Low-lying islands in the Pacific Ocean (Marshall, Kiribati, Tuvalu, Tonga, Line, Micronesia, Cook), Atlantic Ocean (Antigua, Nevis), and Indian Ocean (Maldives), are very likely to be severely affected.

In Bangladesh, about 17 million people live less than one meter above sea level and are already vulnerable to flooding. In Southeast Asia, a number of very large cities including Bangkok, Bombay, Calcutta, Dhaka, and Manila (each with populations greater than five million), are located on coastal lowlands or on river deltas. In the United States, Florida and Louisiana are particularly susceptible to impacts of future sea-level rise.

Projected Contribution of Arctic Land Ice to Sea-level Change

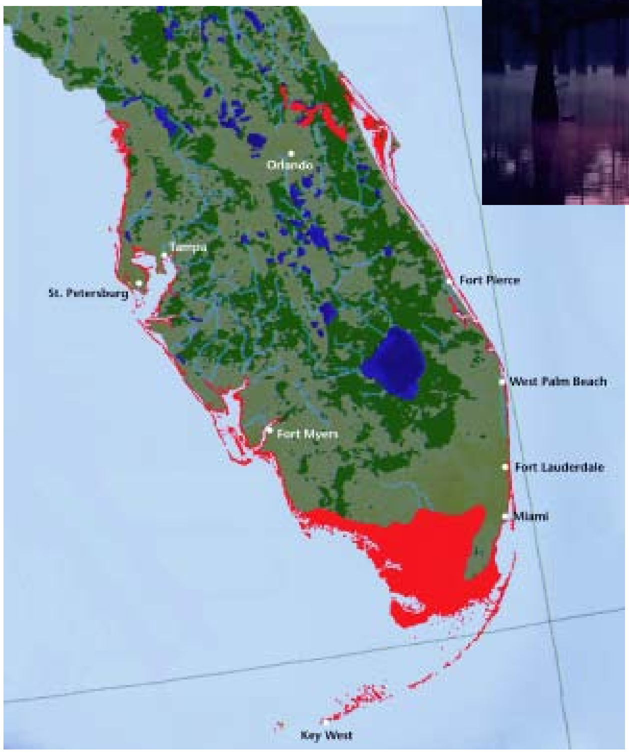


This chart compares the projected contributions to sea-level change due to melting of land-based ice in various parts of the Arctic. The Greenland Ice Sheet is projected to make the largest contribution because of its size. Although Alaska's glaciers cover a much smaller area, they are also projected to make a large contribution. The total contribution of melting land-based ice in the Arctic to global sea-level rise is projected to be about 10 cm by 2100. The primary driver of sea-level rise is thermal expansion due to ocean warming, and that is not included in this chart.



A 50-cm rise in sea level will typically cause a shoreward retreat of coastline of 50 meters if the land is relatively flat (like most coastal plains), causing substantial economic, social, and environmental impacts.

Areas in Florida Subject to Inundation with 100 Centimeter Sea Level Rise



2 Arctic warming and its consequences have worldwide implications.

Access to Arctic Resources Will Change

The Arctic provides natural resources to the world, and climate change will affect these resources in a variety of ways that are examined in more detail throughout this report. Arctic resources have economic value in trade; whales, seals, birds, and fish have long been sold in more southerly markets. Arctic seas contain some of the world's oldest and most productive commercial fishing grounds, which provide significant harvests for many arctic countries, as well as for the rest of the world. For example, Norway is one of the world's largest exporters of fish.

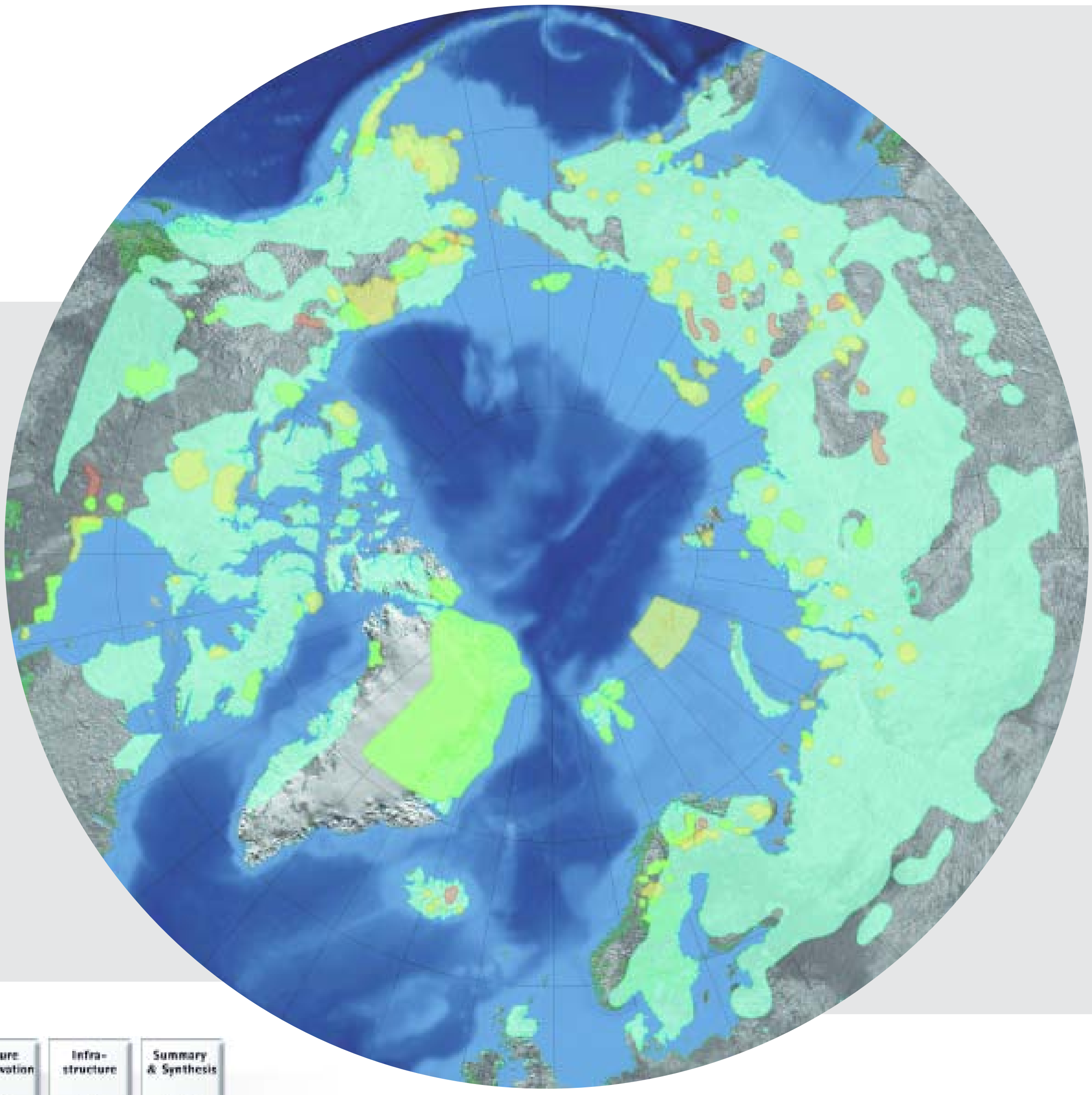
The Arctic has significant oil and gas reserves, most of them located in Russia, with additional fields in Canada, Alaska, Greenland, and Norway. The Arctic also holds large stores of minerals, ranging from gemstones to fertilizers. Russia extracts the largest quantities of minerals, with Canada and Alaska also having significant extraction industries, providing raw materials to the world's economy. Marine access to oil, gas, and minerals is likely to be enhanced in many places in a warmer Arctic, with positive impacts for some and negative impacts for others. Access to resources by land is likely to be hampered in many places due to a shortening of the season during which the ground is sufficiently frozen for travel.

Marine access to oil, gas, and minerals is likely to be enhanced in many places in a warmer Arctic.

Arctic Protected Areas

Strategies for conserving arctic biodiversity by establishing protected areas are important for defending natural habitats against direct human development, but they do not protect against a changing climate. This map indicates how climate change will affect currently protected areas, putting at risk the living resources these areas were designed to protect.

- Strict Nature Reserve / Wilderness Area National Park
- Natural Monument Habitat / Species Management Area
- Protected Landscape / Seascape Managed Resource Protected Area
- Areas with Predicted Future Changes in Vegetation



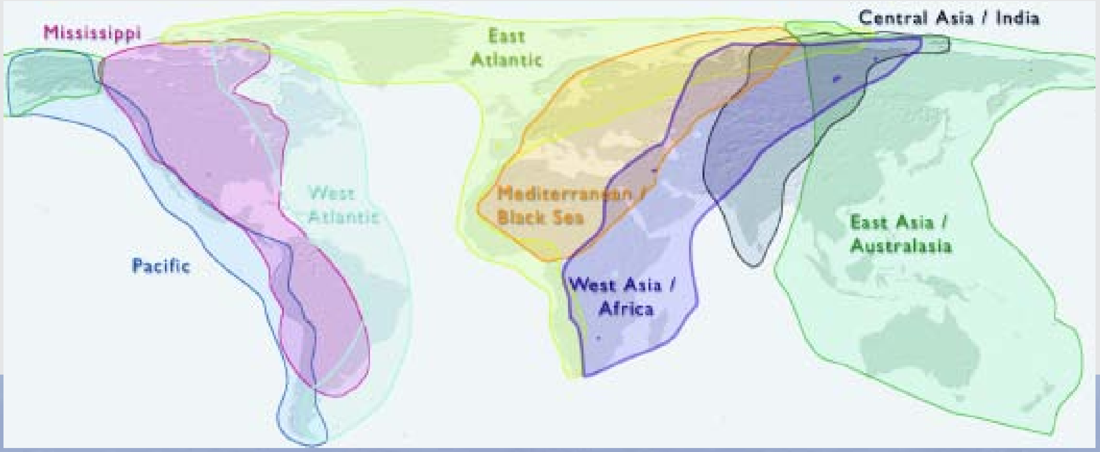
Arctic Ecosystem Changes Will Reverberate Globally

Climate-related changes in arctic ecosystems will not just have consequences for local people and other living things that depend on these systems for food, habitat, and other goods and services, but will have impacts at the global level because of the many linkages between the Arctic and regions further south. Many species from around the world depend on summer breeding and feeding grounds in the Arctic, and climate change will alter some of these habitats significantly.

For example, several hundred million birds migrate to the Arctic each summer and their success in the Arctic determines their populations at lower latitudes. Important breeding and nesting areas are projected to decrease sharply as treeline advances northward, encroaching on tundra, and because the timing of bird arrival in the Arctic might no longer coincide with the availability of their insect food sources. At the same time, sea-level rise will erode tundra extent from the north in many areas, further shrinking important habitat for many living things. A number of bird species, including several globally endangered seabird species, are projected to lose more than 50% of their breeding area during this century.

Many species from around the world depend on summer breeding and feeding grounds in the Arctic, and climate change will alter some of these habitats significantly.

Migratory Bird Flyways



Key Finding #2