ANNIKA NILSSON

Abisko, Sweden

Climate change, ozone depletion, and ultraviolet radiation

When the sun returns after the long, dark winter and the snow starts to melt in the Arctic, the local environment changes dramatically. Gradually, the white, reflective snow disappears, revealing dark soil that absorbs the sun's energy. Soon, plants unfold their green leaves to start the new growing season, trying to make the most of the brief Arctic summer.

If the average air temperature during this time of year were consistently a few degrees warmer or a few degrees colder, the consequences could be profound for both plants and animals living along the edge of the receding snow cover. But that would not be the end of the story. Arctic snow is important for the energy balance of the whole globe. An earlier snowmelt might allow Earth to absorb more energy from the sun, affecting far more than a thin band in the far north.

This example illustrates how the Arctic plays a key role in one of the major environmental issues of today: global climate change. This chapter discusses the signs of climate change in the Arctic and the long-term implications for polar people and ecosystems.

In the north, reflective snow is also a key to understanding the effects of another global environmental threat: increased ultraviolet radiation caused by depletion of the ozone layer. This chapter addresses changes in ozone and the implications for the Arctic environment.

Signs of climate change

Concerns about climate change stem from the increasing concentration of greenhouse gases in the atmosphere. These gases keep heat from dissipating into space. According to the Intergovernmental Panel on Climate Change (IPCC), a continued increase at current rates could raise the average global air temperature between 1 and 3.5°C by 2100. The average rate of warming would likely be greater than any seen in the past 10 000 years.

Climate change will not be evenly distributed over the globe. Its effects are likely to be greater in some areas and less significant in others, but current understanding of global climate patterns is insufficient for making reliable regional predictions.

IPCC has drawn some general conclusions about the consequences of an increasing greenhouse effect. These include that sea level will rise somewhere between 15 and 95 centimeters by 2100. Sea-level rise is caused by a combination of melting glaciers and the fact that water expands as it warms. Another prediction is that there will be more extremely warm days and fewer extremely cold days. The probability of both droughts and floods is expected to increase. The largest temperature increases are predicted for winters in the northern part of the northern hemisphere.

High latitude climate is sensitive to changes

The effects of global climate change on Arctic temperatures and precipitation patterns are very difficult to predict, but most studies suggest that the Arctic, as a whole, will warm more than the global mean.

Current understanding is that greenhouse-induced warming will cause substantial decreases in the extent of snow and sea ice and in the thickness of the ice. Such changes can in turn affect local weather patterns, the distribution of clouds, ocean circulation, and climate on a global scale. The consequences of the changes for the climate in different feedback loops are not well understood and represent a major uncertainty in models of climate change.

Sea ice is critical to energy exchange between ocean and atmosphere

Sea ice plays a critical role in the energy budget of the Arctic and thus in the region's climate. Snow-covered ice is highly reflective. If the ice extent decreases, more solar energy will be absorbed by the ocean as less is reflected back to space. Decreasing sea-ice cover can thus enhance a warming trend.

Sea ice is also a physical barrier between the ocean and the atmosphere. For example, it dampens the interaction of winds and water and thus limits exchange of energy.

Less ice and warmer air would allow the air to pick up moisture from the water, which might make the Arctic cloudier. This would probably change regional weather patterns, but no one really knows how it would influence climate on a larger scale. Today, the role of clouds is one of the main uncertainties in climate models.

Sea ice also limits the exchange of carbon dioxide between water and air as well as the penetration of light into the water. Thus changes in sea ice would affect the productivity of algae.

Temperature records point to both warming and cooling

Do observations from the Arctic reveal any signs of changes in climate? The question is difficult to answer for many reasons. Observations are not always completely comparable over time and trends are therefore hard to determine. Moreover, it is almost always impossible to tell whether any observed changes are related to global warming or are part of a natural variation. With these limitations in mind, the following can be said. Surface air temperatures seem to have increased by about 1.5°C per decade over continental Central Siberia and over continental North America. In Fennoscandia, the records do not indicate any significant changes, whereas Baffin Bay has cooled by 1.5°C per decade. North of 70°N, temperature observations are sparse. There are indications, however, of warming around the northern continental rims of central and western North America and central Asia over the past century. For eastern North America through the North Atlantic, there is a cooling trend.

Since 1979, satellites have been used to monitor temperature at different heights in the atmosphere. These measurements show that the lower troposphere, the air mass closest to Earth, has become 0.05°C warmer per decade. This warming in the Arctic troposphere is more pronounced than for the global troposphere as a whole. When greenhouse gases trap heat in the troposphere, the air higher up, in the stratosphere, is expected to get cooler.

Greenhouse gas emissions are global

The sources of greenhouse gases are global. Burning of fossil fuels and deforestation contribute carbon dioxide. Methane adds to warming of the atmosphere with emissions from rice paddies, farm animals, and wetlands. Exploitation of natural gas also contributes methane. Nitrous oxide is a naturally-produced greenhouse gas, but the flux has increased, mainly because of heavy fertilizer use on farmland. CFCs are man-made and highly efficient as greenhouse gases. However, because of their detrimental effect on the ozone layer, their net contribution to global warming is difficult to determine. Other greenhouse gases include ozone and a range of CFC-related compounds.

One type of human emission, sulfur dioxide, seems to reduce warming over industrialized areas, since it forms sulfate aerosols that act as a screen against the sun.

Temperature records for the lower stratosphere in the Arctic reveal dramatic changes since 1979: –1.01°C per decade for the area from 67.5°N to the pole, with the most rapid decreases over Russia. This is the steepest decline on the entire planet.

The Arctic Ocean has warmed slightly in the past decade. In the Nordic Seas, however, there is a cooling trend in the upper 1000 meters, along with a decrease in salinity.

Measuring temperature profiles in permafrost can provide a climate record that goes back hundreds of years at a particular site. Such measurements from Alaska indicate a warming of 2 to 4°C over the past hundred years. This warming has been confirmed by observations that the discontinuous permafrost in Alaska is thawing. Inuit in Barrow, Alaska, have seen their ice cellars, which are dug into the permafrost, drip water for the first time in anyone's memory.

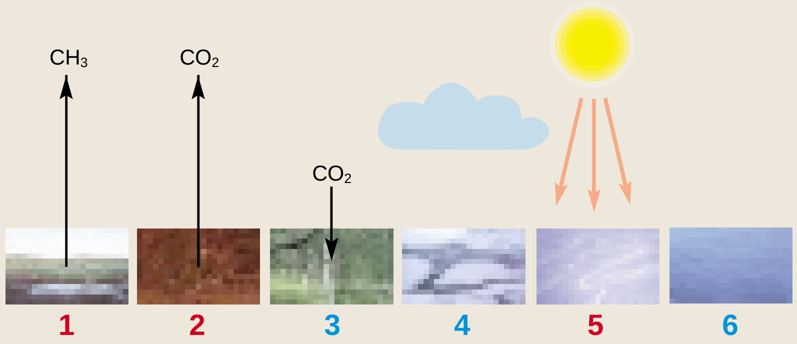
Glaciers leave tell-tale signs of past climate changes by depositing moraines at the limit of their advances. Examining glacier lengths gives indications of global warming that are consistent with, and independent of, other records of global warming for this century. In some cases, however, the interpretation is complicated by the lag time between climate change and the glaciers' response. Moreover, the patterns of change vary geographically, with increased melting in some areas of the Arctic, while other areas show growth because of increased precipitation or no trend at all.

The ice sheets of Greenland and Antarctica hold immense amounts of water. It is very difficult to measure their volumes, but so far they do not seem to be shrinking, and might even be growing slightly. This does not necessarily contradict indications of a warmer climate, since increased snowfall adding more mass to the top of the glacier may compensate for any extra melting and calving of icebergs. These huge ice sheets also respond much more slowly to climate change than do small glaciers.

Precipitation has increased

Precipitation has increased in high latitudes by up to 15 percent during the past 40 years. On the North American tundra, there is a trend toward earlier spring snowmelt. South of the subarctic, the area of land with continuous snow cover during winter, which follows both temperature and precipitation, has retreated by about ten percent during the past 20 years.

Snow plays a key role in protecting plants and animals from cold and dry winter conditions. It is also important for the seasonal water cycle. Changes in snow cover may therefore have a profound impact on plant and animal life in the Arctic. Moreover, a shrinking snow cover is expected to speed up the warming process, since more of the dark, sun-absorbing ground will be exposed, as is further described in the box above.



The Arctic affects the global climate

Global climate change will affect the Arctic, but the opposite is also true – the Arctic environment can have profound effects on global climate. The figure summarizes the mechanisms by which the polar region could enhance or dampen the warming caused by the emission of greenhouse gases.

1. Warming could thaw permafrost under the tundra. If the soil remains waterlogged, microbes in the soil could increase their emissions of the greenhouse gas methane. The warming of permafrost can also release geologically trapped methane to the atmosphere. The potential quantitative impact of this methane release on climate change is unknown, but it could contribute to rising Arctic temperatures, which in turn could lead to further thawing and release of methane, and thus accelerate warming in a feedback loop.
2. Nature's contribution to carbon dioxide emissions is likely to change. For the past 10 000 years, tundra ecosystems have taken carbon dioxide out of the atmosphere and stored it in the soil. The tundra and boreal region hold about 14 percent of the world's soil carbon. A warmer climate could allow microbes to decompose dead plant matter at a higher rate, releasing carbon dioxide. There are indications that at least some parts of the Arctic have switched from being sinks of carbon dioxide to being sources. If all the stored carbon were released, it could increase the atmospheric concentration of carbon dioxide by more than the cumulative contribution from fossil fuels through 1995.
3. Plants, on the other hand, will probably capture carbon dioxide more efficiently, since photosynthesis is more efficient at higher temperatures. Release of nutrients from the soil, which is more efficient in warmer and wetter conditions, may also promote higher plant productivity, but the feedbacks between production and decomposition are complex and uncertain.
4. Polynyas provide a surface of open water at which the ocean and atmosphere can interact. If polynyas become larger and more numerous, more moisture will evaporate, leading to more cloud cover. These clouds can have a significant impact on the amount of solar radiation reaching the Earth, and can effectively counteract the warming. The role of clouds is one of the major uncertainties in current climate models.
5. Snow, on land or ice, has a profound impact on how much energy is reflected back to space without heating the Earth. A receding snow cover could thus enhance the warming process. Less snow cover on land would also allow for faster warming of soil in spring, which would affect both plants and microbes, as described in points 2 and 3.
6. The northern North Atlantic plays a key role in the formation of deep ocean water, a process driven by the cooling of warm surface water as it reaches the Arctic. Higher temperatures and lower salinity are likely to slow this down. Since the formation of deep water serves as a motor for the warm North Atlantic Current, its diminishing efficiency could lead to a colder climate, especially in Scandinavia and northwest Russia. There are some signs that the North Atlantic pump has become weaker in recent years, but it is too early to tell whether this is connected to climate change or simply part of natural variation.

Cores of ice tell of dramatic climate history

Climatic changes are nothing new to the Arctic. Cores of glacier ice have been used to get a picture of the past. Such records reveal gradual changes of a few degrees over centuries, but also abrupt shifts of 6 to 10°C in less than two decades. These dramatic shifts are larger and faster than anyone had previously suspected, and they indicate that the Arctic climate can be very unstable. Thus, the time during which human agriculture and industry has developed in the world seems to be an unusually calm period in climate history.

Plant and animal remains in sediments give another clue about climate in the past. Analysis of sediment cores shows that the timing and magnitude of past climate changes do not follow a uniform pattern around the polar region.

Future impact

The impacts of climate change on the Arctic are difficult to predict because of the intricate interactions between physical and biological factors. The following section describes some of the potential changes that might occur if there is a significant warming of the region.

Melting ice caps and warmer water raise sea level

The shrinking and growth of glaciers are tightly coupled to climate. In the Arctic, many smaller glaciers have been shrinking during the past century and global warming will accelerate their demise. The most immediate effect is that they contribute to a rising sea level. The mass balance of glaciers is controlled not only by temperature but also by snowfall and the physical processes of ice motion. Therefore, changes in glacier size typically lag behind climate changes by years to decades for mountain glaciers and longer for larger ice sheets.

Higher water temperatures in the ocean will further increase sea-level rise. This is caused by the fact that water expands when it warms up.

Sea level rise is likely to aggravate erosion and inundate low-lying areas along Arctic coasts. Moreover, the huge amount of freshwater from melting glaciers is likely to affect seawater salinity and thus the mixing of water masses and ocean currents.

Winds and water currents are likely to change

Global warming is likely to affect weather patterns caused by the movement of low-pressure systems, but these changes are not yet well understood. According to some simulations of future climate, global warming could reduce barometric pressure in the Arctic. In combination with a northward push of mid-latitude storm tracks, such a weakening of the Arctic high-pressure system would cause more cyclonic storm systems, especially in winter. We might perceive this change as more day-to-day variability in wind, but it will be very difficult to detect amid the large normal fluctuations already seen. It is uncertain whether there would be any systematic changes in the intensity of the storms or the strength of the winds.

Changes in wind patterns in turn affect temperature and humidity. The winds also influence sea ice and the circulation of water in the ocean.

Higher temperatures could disrupt permafrost

Much of the permafrost in the Arctic is close to 0°C and therefore particularly sensitive to temperature changes. Thawing could thus degrade permafrost. Such changes are likely to allow increased erosion and damage to surface vegetation. Thermokarsts, which are depressions resulting from the thawing of ground ice, could become one of the most important forces acting on the terrestrial environment. Erosion could also expose dark soil surfaces, which are more efficient in absorbing solar energy than the vegetation cover, and thus result in more permafrost thawing and thermokarst.

Any changes in the permafrost will also affect the movement of water over and in the soil. A lower permafrost table would, for example, favor formation of groundwater instead of surface runoff. Most streams and rivers in the Arctic get their water from surface runoff, and permafrost is a major reason that the flow of water in the terrestrial environment changes abruptly with precipitation and snowmelt.

Warmer soils may enhance nutrient cycling

Biological productivity in the soil is highly dependent on temperature and moisture. In addition to permafrost, the cold combined with too much or too little water currently limits decomposition of organic matter. A warmer climate could thus increase decomposition and make more nutrients available for plants. Chemical weathering of the bedrock is also increased at higher temperatures. Moreover, a deeper active layer would allow the roots of some plants to reach mineral horizons in the soil that were previously blocked by the permafrost.

Increased microbial activity in the soil would allow for more nitrogen fixation from the air. Some projections point to a 65 to 85 percent increase, which would minimize nitrogen limitations on plant growth in the projected climates. But one should be cautious with predictions. Enhanced release of nutrients does not necessarily lead to increased uptake in plants.

Plant productivity is difficult to predict, since it depends on a combination of factors of which climate is only one. Higher temperatures along with higher carbon dioxide concentrations would probably increase productivity, but only if other factors such as nutrient or moisture availability are not limiting.

Southern invaders might out-compete native species

Many Arctic plants are compact and grow slowly. They are extremely frugal with the limited nutrients available. Those plants that are stressed by the harsh environment will do better in a warmer climate. However, plants that are best adapted to the extremes might be outcompeted by other species in a warmer, more nutritive climate. In fact, such competition may be a greater threat to Arctic flora than the changes in the physical environment. A special threat is when thermokarst disrupts the plant cover. This opens up new ground for colonization, which might favor immigrant species.

The migration of southern species will probably be slower than one would predict from the temperature increase, which suggests that a warming of 2°C would result in a 400 to 500 kilometers northward shift of vegetation types by the year 2020. Eventually, the predicted climate change might allow the taiga forest to completely displace tundra on the Eurasian mainland.

Any long-term shift in forest productivity or the area covered by commercially valuable trees will affect the forest industry, which is economically very important in several Arctic countries.

Animals are sensitive to changing food supplies

Arctic animals are ultimately dependent on plants for energy and nutrients. However, the effects of climate on primary productivity are uncertain. Migratory mammals and birds can probably adjust to changes in the quantity and quality of plants and prey, but some grazing animals, both vertebrates and invertebrates, may face problems if the quality of the food becomes poorer. Extreme events, such as droughts and ice layers over winter forage, will also play a role.

Non-migratory animals could be severely affected by direct changes in their environment, such as changing snow conditions in the winter, which could make it hard to find food, water, and shelter.

Invertebrates with short generation times may be able to take advantage of the changing climate. This would be especially true for insects whose eggs are sensitive to low temperatures during the winter. One example is winter moth larvae that sometimes defoliate large parts of the Fennoscandian subarctic birch forest. Warmer winters could lead to increased populations and greater defoliation. Other organisms that cause damage or carry diseases may also find their way into the Arctic if the climate becomes milder.

Lakes and ponds will have a longer growing season

Lakes and ponds in the High Arctic are particularly sensitive to changes in climate. Today, their biological productivity is limited to a period as short as a few weeks because snow-covered ice limits the penetration of solar rays into the water. With a longer ice- and snow-free season, the water will also get warmer. Moreover, unfrozen ground around the lake and more microbial activity in the soil would allow a higher input of nutrients. These changes would probably lead to higher productivity for the existing life in the water. A longer growing season and higher productivity might also allow for more complex food webs.

For some shallow lakes and ponds, a warmer climate could have dramatic effects. If evaporation increases more than precipitation, or if there is not enough runoff to supply the lakes with water, they could simply dry up and disappear. Inland lakes with salt water are rare but extremely sensitive to even slight changes in the balance between evaporation and precipitation.

Higher air temperatures, increased precipitation, and increased groundwater flow will change the environment in rivers and streams. Glacier-fed rivers will probably become colder while small streams might become warmer. Some streams may become more suitable for migrating fish than they are today, which could benefit freshwater and salmon fisheries.

Northern fisheries will benefit from warmer seawater

Ocean fisheries in northern seas have always been sensitive to changes in climate. In Norway, where the fishing industry is very important economically, past experience shows that a warming of the sea can drastically change both productivity and species composition. Unless greenhouse warming is counteracted by other factors, North Sea fish, such as cod and herring, are likely to move northward out of the North Sea. Under the various climate change scenarios predicted for the next 40 years, the Norwegian commercial catch in the Barents and Norwegian Seas may triple. In the North Sea, overall productivity would probably remain similar to today, but a change in species composition would make the catches less valuable. Changes in productivity and species composition would also have a dramatic influence on other regions that are economically dependent on fishing and the fish industry.

People depend on stable climate

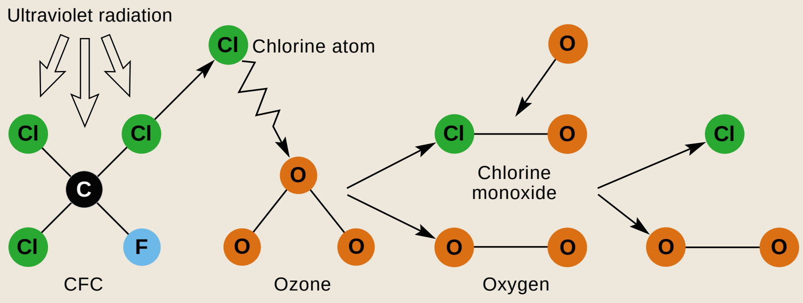
The survival of Arctic peoples has always been intricately linked to climate. Arctic settlements are typically located close to food, water, and shelter, all of which are affected by climate. To the extent that people continue to harvest plants and animals and live permanently or seasonally on coastal spits or along river banks and lake shores, climate change will directly impact their lives. Even if modern resources can mitigate some effects, climate change is likely to disrupt culturally important hunting and fishing activities.

Coastal erosion has already forced native communities in Alaska to relocate. A rise in sea level would threaten many more communities, especially in Russia and Alaska where they are often located on low-lying coastal plains and on river deltas. Coastal erosion would also cause great changes to the geography of river deltas.

Temperature and humidity changes will probably affect the local physical environment. A decrease in snowfall or rain could reduce water supplies for villages and towns. On large areas of the coastal plains and wet tundra, an increase in precipitation could make land unusable. It might also shift the migration patterns of terrestrial mammals and alter the breeding and molting areas of birds.

Changes in snow cover would alter traveling conditions over the tundra, making it potentially more difficult for hunters to reach inland locations in spring and fall. A change in either direction would also affect the abundance and distribution of freshwater and anadromous fish.

For communities on the coast, changes in sea ice might have dramatic impacts by shifting the migration routes of marine mammals. Even if animal life seems abundant, it is often made up of seasonal migrants on their way to specific feeding grounds where food production is intense but brief. The population density of seals, for example, is correlated with the distribution of coastal sea ice. The separate and combined effects of the warming of land and water will most assuredly affect ice formation and thereby the distribution and breeding of animals hunted for food and materials.



Chlorine plays a key role in ozone destruction

The chlorine responsible for ozone destruction comes from man-made compounds that are extremely stable and can spread all around the globe. When they reach the stratosphere, the energy from ultraviolet radiation in sunlight splits off the chlorine atoms (Cl). The chlorine, which is very reactive, proceeds to attack ozone (O_3), splitting off one of its oxygens (O). The reaction leads to the formation of chlorine monoxide (ClO) and ordinary oxygen gas (O_2).

Chlorine monoxide is not stable, and the chlorine atom will soon be free to attack another ozone molecule. The only way to stop the destruction is for the chlorine to form some stable reservoir molecule, which, at mid-latitudes, eventually happens. In the polar regions, ice crystals in polar stratospheric clouds can make it impossible for the reservoir molecules to hold on to the chlorine. When the sun returns in spring, the free chlorine can again attack ozone molecules. Inside the polar vortex, the high concentration of active chlorine in spring sets up the severe destruction that can lead to an ozone hole.

Aerosols in the stratosphere can serve the same function as the ice in polar stratospheric clouds. In 1991, the Mount Pinatubo eruption emitted enough such aerosols to speed up ozone depletion for several years.

In Fennoscandia and Eurasia, domestic reindeer herding is a source of employment and food, as well as a foundation of cultural heritage among indigenous people. Changes in temperature, precipitation, and the carbon dioxide concentration in the atmosphere could affect the growth and spread of plants that the reindeer depend on for fodder, but it is difficult to foresee the overall effect on reindeer herding as a livelihood.

People in the Arctic have had to adapt to changing climates in the past, sometimes successfully, sometimes not. The demise of the Norse settlement in Greenland in the Middle Ages may be an example of the inability to adapt to a drop in temperature. The Norse, who were dependent on sheep farming, may not have been unable to survive the longer winters. Inuit in the same area continued to thrive because they were able to shift their economic base toward seal hunting.

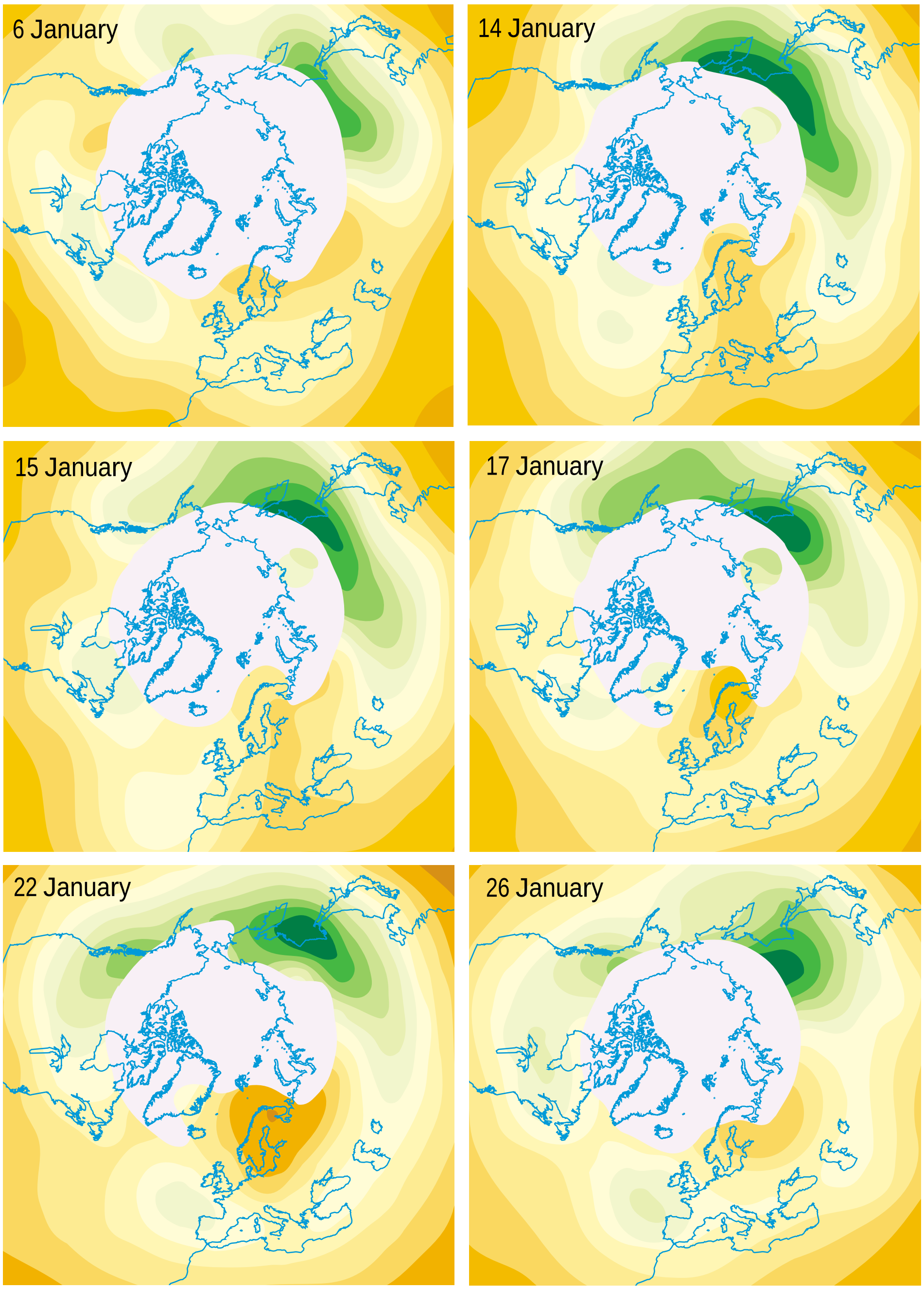
The thinning ozone layer

Ozone is a gas in the atmosphere, which plays a critical role in blocking harmful ultraviolet (UV) radiation from reaching the Earth. The highest concentration of ozone is in the stratosphere, 25 to 40 kilometers above Earth's surface. The amount of ozone in the stratosphere is currently decreasing, especially in the polar regions, which has raised concern that plants and animals will be damaged by increased ultraviolet radiation. Moreover, a decrease in ozone also affects the temperature structure of the atmosphere and therefore has implications for climate. Also, climate change may enhance ozone depletion by cooling the stratosphere and by changing circulation patterns in a way that brings low-ozone air into the Arctic.

The major emissions responsible for depletion of the ozone layer are chlorofluorocarbons (CFCs), but there are several other man-made compounds that also contribute. The use and production of such substances are controlled by the Montreal Protocol on Substances that Deplete the Ozone Layer.

Several severe ozone depletions have occurred in the Arctic

The ozone-depleting chemicals are spread globally in the atmosphere, but ozone depletion is much more severe in the polar areas than closer to the equator. The extreme case is the Antarctic ozone hole, which appears every spring over an area that includes the southern



This ozone hole in January, 1996 evolved in just a few days and was primarily caused by the dynamic atmospheric circulation and then augmented by chemical reactions.
January 6: normal Arctic ozone pattern as measured in Dobson units showing higher ozone values in green. Light grey area indicates no data.
January 14-15: influx of low-ozone air from lower latitudes after which this air starts to be pinched off by the strong winds of the developing polar vortex.
January 17: The polar vortex isolates the low-ozone air over northern Fennoscandia and Kola, forming an ozone hole.
January 22: Chemical reactions enhance ozone depletion in the isolated hole.
January 26: The ozone hole dissipates.

end of South America. The stratospheric chemistry over Antarctica has been studied extensively, and one of the contributing factors to the hole is the extremely low temperatures inside the polar airmass, which is insulated from other air by a strong polar vortex.

The Arctic, while similar in general climate, does not exhibit the same sort of distinct yearly ozone hole. The major reason is instability of the northern polar vortex, which usually does not allow temperatures to drop far enough for the very special chemistry that occurs in the Antarctic atmosphere.

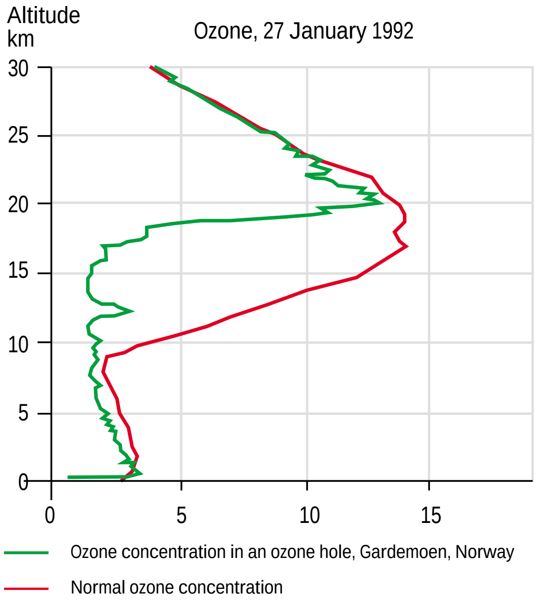
The most common form of Arctic ozone depletion can better be described as a Swiss cheese, where smaller holes occur from time to time, especially during the late winter and early spring. The ozone depletion in these holes can be severe, up to 40 percent, but they normally cover only a few hundred kilometers in diameter and last only a few days.

Chemistry and air movement provide two explanations

It has been possible to distinguish two different types of Arctic ozone holes. One type is primarily caused by the same chemical mechanisms as in Antarctica and the other primarily by changes in circulation patterns in the atmosphere; see the maps above.

Chlorine monoxide is a reactive, intermediate chemical that can be used as a signal for chemically-induced ozone holes; see the box on the opposite page. In 1995, a cold polar vortex formed over the European Arctic in which stratospheric clouds and chlorine monoxide were present. The ozone loss in the vortex was up to 60 percent in certain layers of the atmosphere. Several other chemically-induced ozone lows have been recorded, for example in February and March of 1993.

Many of the Arctic ozone holes have occurred outside the polar vortex, where chemical destruction is unlikely to play a direct role. One example is a hole that moved eastward over the European Arctic in January 1992. Studies of air movement suggested that this ozone-poor airmass came from the subtropics, leaving a latitude of 20°N four days before reaching Gardemoen in southern Norway.



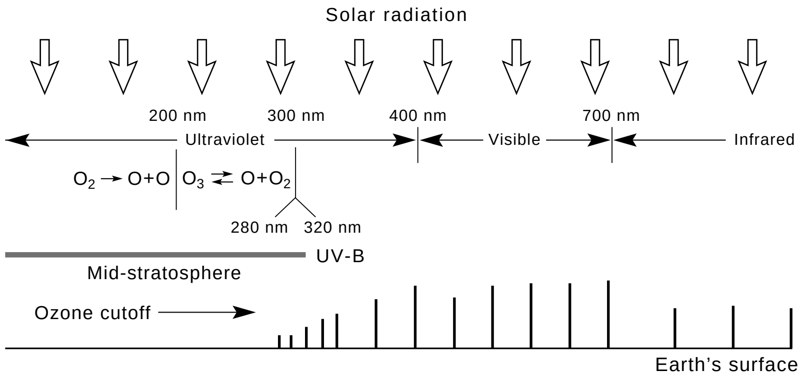
Ozone measurements from Gardemoen, southern Norway, when ozone-poor air was passing over the area. The loss occurred at lower altitudes than is typical for a chemically-induced ozone hole and below the altitudes where low temperatures are typically observed.

The depletion was also at a lower altitude than is typical of chemically-induced ozone loss; see graph above.

A number of other ozone anomalies in recent years have also been connected to warm temperatures. In fact, most ‘holes’ in the ozone layer over the European Arctic can probably be explained by the dynamic movement of ozone-poor airmasses, rather than the chemical mechanisms typical of Antarctica. The incidence of such ozone holes could be connected to changing patterns of atmospheric circulation, but there are as yet no clear explanations.

Downward trend has led to increasing ultraviolet radiation

Ozone depletion does not occur only in occasional holes in the sky. There is also a general downward trend in the Arctic greater than 8 percent per decade in winter and spring. In the early 1990s, the average yearly values for the Arctic were 10 percent lower than in the late 1970s, according to surface monitoring of ozone.



Earth’s atmosphere absorb sunlight, in particular wavelengths shorter than 320 nanometers. Losses in ozone open up the atmospheric window for shorter wavelengths to reach the Earth’s surface.

Ozone is particularly effective in blocking out the most damaging ultraviolet radiation; see the diagram below left. The downward trend in ozone therefore raises questions about how the light environment in the Arctic is changing and how this in turn may affect the health of people and ecosystems.

UV monitoring sites in the Arctic.

Location	Coordinates	Established
Tromsø, Norway	70°N, 19°E	1987
Ny-Ålesund, Norway	79°N, 12°E	1990
Longyearbyen, Norway	78°N, 16°E	1991
Barrow, Alaska	71°N, 156°W	1990
Resolute, Canada	75°N, 95°W	1992
Alert, Canada	82°N, 62°W	1992
Eureka, Canada	80°N, 86°W	1993
Thule, Greenland	76°N, 69°W	1994
Søndrestrøm, Greenland	67°N, 51°W	1990
Abisko, Sweden	68°N, 19°E	
Kiruna, Sweden	67°N, 21°E	1989
Sodankylä, Finland	67°N, 27°E	1989
Varrio, Finland	67°N, 30°E	1995

Based on a general understanding of the effects of ultraviolet radiation, it is clear that the increase in biological damage can be greater than the percent decrease in ozone. However, each biological system is unique in its response to ultraviolet radiation, and any damage is the result of a combination of factors. A particular risk in the Arctic is reflected light.

Snow cover will increase the ultraviolet dose

One of the most striking ways in which the Arctic light environment differs from other parts of the world is that the sun never reaches very high in the sky, even in summer. The rays therefore have to travel much farther through the atmosphere than if the sun was directly overhead. If these direct-but-low rays were the only source of ultraviolet radiation, the atmospheric filter would lower the ultraviolet dose enough that it would not be a major concern for the health of people and animals.

However, snow cover changes the situation drastically. New snow can reflect as much as 90 percent of all the incoming ultraviolet radiation. Moreover, a thin cloud cover can cause ultraviolet rays to bounce back and forth between the snow and the clouds, increasing the ultraviolet dose in all directions.

Unfortunately, some of the protective adaptations people have against the sun do not shield us very effectively from the horizontal rays. Our eyebrows mostly shield the light coming from above. Also, we usually turn our faces toward the ground rather than toward the sky. But reflected light will reach a human face from all sides, which explains how the low polar sun can cause snow blindness and how one can get a sunburn in the Arctic; see the graph right.

Reflected light is especially important when the terrain is open. The snow-covered tundra in spring is thus an extreme light environment compared with many other situations. In fact, snow cover can double UV-exposure. The graph bottom right illustrates the effect of snow on the capacity of the sun to make skin turn red with sunburn during different parts of the year. Reflected light is more important when the skies are covered by thin clouds than on a clear day. Heavy clouds, on the other hand, can shield ultraviolet radiation very effectively.

Calculations of increased risk for some skin cancers also emphasize how intense reflected light can be. For each one percent decrease in ozone, the risk for squamous cell carcinoma in a white population would increase by about 2.5 percent if the exposure was only to a flat, horizontal surface, such as a sunbather or a bald head. By adding the effect of reflected light to a vertical surface, such as the face of a standing person, the increase in risk jumps to 3.2 percent. The effects of ultraviolet radiation on people are further discussed in the chapter *Pollution and Human Health*.

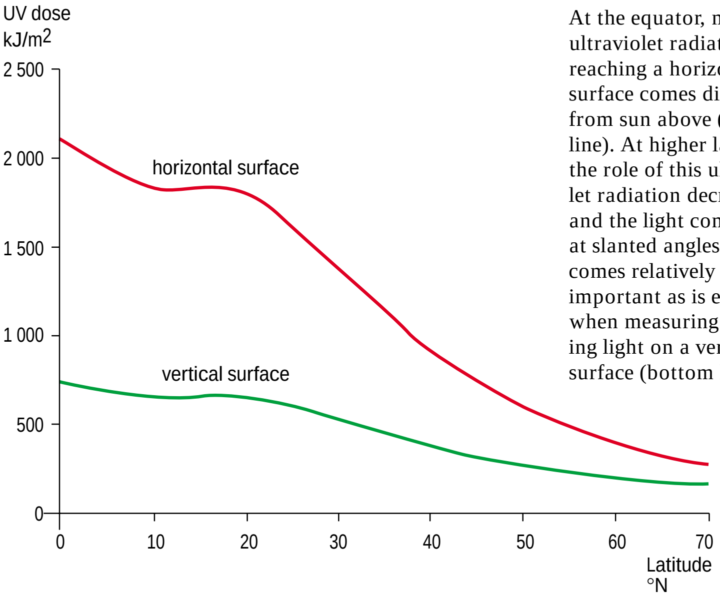
UV models emphasize the role of clouds and aerosols

Understanding future changes of ultraviolet radiation in the Arctic requires integrating a number of different factors. A model looking at the combined role of ozone depletion and clouds shows that stratus clouds provide a substantial shield against UV exposure. Stratospheric aerosols have a similar shielding effect, but at low solar elevations, they might increase the dose because of their ability to bounce snow-reflected light back down to the ground. Tropospheric aerosols (Arctic haze) shield against UV exposure, even when reflection is taken into account.

Effects of increased ultraviolet radiation

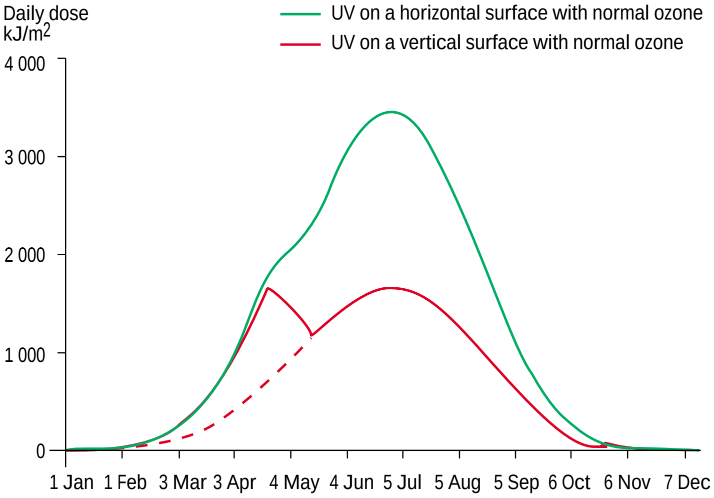
That ultraviolet radiation can damage living cells is well known. One of the most striking examples is how direct and reflected sunlight on a bright spring day can cause a painful inflammation of the surface of the eyeball and snowblindness.

One of the primary targets for UV damage is the hereditary material, the DNA, in all living cells. Other sensitive molecules include proteins that function as building blocks or as chemical helpers in the cells, for example, the photosynthetic machinery that makes it possible for plants and phytoplankton to capture solar energy and grow. Ultraviolet radiation can also damage cell membranes and affect the ability of cells to take up nutrients.



At the equator, most ultraviolet radiation reaching a horizontal surface comes directly from sun above (top line). At higher latitudes, the role of this ultraviolet radiation decreases and the light coming in at slanted angles becomes relatively more important as is evident when measuring incoming light on a vertical surface (bottom line).

Ultraviolet radiation has always been a stressor in the environment, and some organisms have developed various strategies to protect themselves. For example, many plants and animals can produce their own sunscreen in the form of protective pigments, and most cells also have some ability to repair UV damage. Rather than looking at the immediate impact of ultraviolet radiation on isolated cells or organisms, research on effects of ultraviolet radiation has therefore put increasing emphasis on ecological studies, where various adaptations are implicitly taken into account.



The amount of energy from ultraviolet radiation reaching a horizontal surface peaks around midsummer. The amount of energy from ultraviolet radiation reaching a vertical surface peaks in the early spring, in part because the snow reflects light very efficiently. An ozone depletion at this time could increase the energy from ultraviolet radiation to a vertical surface by a factor of two. The dashed red line shows the situation if there were no snow in the Arctic.

Cold climate and low sun make polar life extra vulnerable

Several factors might make Arctic ecosystems especially vulnerable to changes in the light environment. Because the sun is low, ultraviolet exposure has never been very high and the increase in damaging radiation becomes proportionally greater than at southern latitudes. There are several examples showing that plants and plankton in polar areas are adapted to low light conditions, including only low doses of ultraviolet radiation. They also seem to have less protective pigment than organisms from other regions.

Temperature is another factor. Low temperatures make repair mechanisms sluggish. UV damage, on the other hand, is not temperature dependent.

Shrubs grow more slowly

Knowledge about UV effects on terrestrial ecosystems comes from controlling the light reaching plants or by illuminating with extra light. Such studies show that some species of low subarctic brush will react. The leaves of an evergreen bush became thicker while the deciduous leaves of dwarf shrubs grew thinner. The growth of shoots also seemed to be slower, at least after several years of increased exposure. Some mosses thrived under extra ultraviolet radiation, but only as long as they also got extra water. Other mosses did not fare well.

One conclusion from these studies is that the responses of subarctic plants to ultraviolet radiation are subtle and sometimes surprising. They also vary from species to species. Therefore, the most likely long-term consequence is a change in the composition of the plant community as the UV-tolerant species get a new competitive edge.

Another conclusion is that the decomposition of plant litter worked less efficiently after UV exposure, because the UV changed the chemical content of the plants, making them richer in hard-to-decompose tannins. Moreover, some fungi that are responsible for decomposition also seem to be UV-sensitive. Increased ultraviolet radiation could thus slow nutrient cycling, which is already a limiting factor for plant growth in the Arctic.

Lake life is often stressed by high UV

In some freshwater ecosystems, ultraviolet radiation already seems to be an important stress factor for plankton. A further increase could therefore be detrimental, especially in clear, shallow lakes, where organisms have no protection from the light. Studies from Norway and Canada show that ultraviolet radiation affects the flagella of certain plankton, which are important for movement, as well as the uptake of phosphorous and the growth rate and structure of the cell wall. The changes in the cell wall also seem to make the phytoplankton less digestible for the zooplankton that normally eat them.

Marine plants are inhibited by extra radiation

Numerous studies have shown that the algae at the base of the marine food web are sensitive to ultraviolet radiation. For example, the ozone hole in Antarctica reduces their ability to sequester carbon dioxide from the atmosphere. But sensitivity seems to vary, both in time and among different plankton communities. With current knowledge, it is therefore difficult to predict any overall effects on algae productivity in the Arctic Ocean.

In the shelf areas, sea grasses and macroalgae also play an important role and account for more that 50 percent of primary productivity. Moreover, they are known to produce compounds that might be important in the trace-gas chemistry of the atmosphere. But again, it is impossible to estimate how large an impact ozone depletion could have on these plants, even if ultraviolet radiation is known to inhibit their growth and productivity.

Sunlight can damage zooplankton and fish

Zooplankton, as well as their eggs and the drifting nauplii, can be very sensitive to sunlight. In experiments with short-term exposures, even normal levels of ultraviolet radiation can kill some species. However, some of the zooplankton will probably be able to adapt to increases in ultraviolet radiation by using protective pigments, by avoiding the surface water, or by better repair mechanisms. The most likely change in the marine ecosystem is therefore that sensitive species will decrease in abundance, which could change the food webs.

Fish are also vulnerable. The most threatened species would be those that have eggs or larvae in shallow waters in the early spring or pelagic eggs floating close to the sea surface. This includes many commercially important fish such as herring, pollock, cod, and salmon. The solar rays can also damage the adult fish by causing lesions on the skin and gills.

For higher animals, whether terrestrial or marine, the effects of ultraviolet radiation have hardly been studied. One of the major concerns would probably be damage to the eyes and any skin that is not protected by fur or feathers.

Cycling of carbon may change

Organic matter that gives water a brown color is very efficient in absorbing ultraviolet radiation. Sunlight might therefore play a key role in the cycling of carbon in aquatic ecosystems by breaking down complex molecules to smaller ones. The small organic compounds are important food for bacteria in the water, and making them more abundant could stimulate the bacteria that use them as fuel. This has led to some speculation about ozone depletion worsening the greenhouse effect. The dissolved organic matter in the oceans is one of the largest global carbon reservoirs. If ultraviolet radiation really limits the rate of carbon cycling in this process, an increase in UV could lead to greater production of carbon dioxide in lakes, wetlands, rivers, and marine waters. This might amount to a significant increase in atmospheric carbon dioxide concentration, and thus a reinforcement of the greenhouse effect.

The dissolved organic matter also affects the balance of many micronutrients in the water, such as iron, manganese, copper, and aluminum.

Plastics will degrade faster

Many building materials degrade under sunlight. Plastics, for example, get yellow and brittle with age, mostly as a result of ultraviolet radiation. Currently, different additives are used to stabilize the material. Within limits, similar technology should be able to compensate for increases in ultraviolet radiation, but for existing structures one can expect shorter technical lifetimes.

Research and monitoring needs

AMAP has been asked to assess the need for research and monitoring of climate change, ozone depletion, and ultraviolet radiation in the Arctic. Despite the particular sensitivity of the Arctic to climate change and ultraviolet radiation, the effects of these changes have not been given adequate attention. Some particularly high priority areas have been identified.

In regard to the assessment of climate change, stratospheric ozone depletion, and ultraviolet radiation, many international fora have emphasized the importance of the Arctic in understanding these processes. Moreover, these global atmospheric changes are likely to be most pronounced in the polar regions. This emphasis on the Arctic needs to be reinforced, especially considering the current lack of information about Arctic processes. For instance, there are, at present, no international programs focusing on the development and application of climate models for predicting future changes in the Arctic. Research and modeling are also needed to improve our understanding of complex feedback interactions involving terrestrial and marine systems as well as snow and ice.

Monitoring of changes in the Arctic is also a high priority. This should include intensive studies of particular sites or systems as well as extensive observations throughout the circumpolar area. Detection of permafrost by remote sensing and ground networks is critically needed, along with studies of sea-ice extent and thickness. Several other issues need to be more adequately addressed. These include hydrological and trace gas cycles, mechanisms responsible for recently-documented ozone anomalies, spatial resolution of UV measurements, and integrated assessment of the effects of increased UV radiation and other stressors on ecosystems and humans in the Arctic. Examining the direct effects of UV radiation requires immediate attention, particularly with respect to eye damage, immunosuppression, and skin disorders in humans. Assessments are needed of the potential redistributions of pollutants that may result from climate-change-induced alterations of atmospheric and ocean currents, sea-level rise, and frequent extreme climatic events.

Summary

Climate change is likely to be more pronounced in the Arctic than in other areas of the world. Feedback mechanisms that can enhance the warming caused by greenhouse gases also make the Arctic important for understanding global climate change.

Observations from snow cover, and permafrost cores suggest that some warming is already taking place in the Arctic, while temperature records show warming in some areas but cooling in others. Glacial melting, along with warmer water temperatures, has raised sea level globally and this sea-level rise is expected to continue.

The polar environment is sensitive to changes in temperature and precipitation. This is especially true for marine areas governed by sea ice and terrestrial environments governed by permafrost. Effects on animals include changes in migration routes and changes in species composition. Arctic peoples are directly dependent on climate for access to game animals, fishing and hunting grounds, and suitable places for settlement.

Ozone depletion has been more severe in the polar regions than elsewhere in the world. However, Arctic ozone depletion is poorly understood at present, making it difficult to estimate the risk of future ozone holes.

Ozone depletion leads to increases in ultraviolet radiation that is damaging to living cells. This increase is accentuated in the Arctic because of the reflective snow cover. The most important long-term effect on Arctic ecosystems may be changes in species composition. Effects on humans are discussed in the chapter *Pollution and Human Health*.

In regard to climate change, stratospheric ozone depletion, and ultraviolet radiation, there is a clear need for more basic research and monitoring to better understand processes and effects in the Arctic.