3 Climate change impacts in the polar regions

> To date, global warming has affected the two polar regions in different ways. While the Arctic is undergoing fundamental changes and is gradually losing its distinctive polar character, the observable changes in the Antarctic are primarily focused on two regions: West Antarctica and the Antarctic Peninsula. East Antarctica, however, is also beginning to respond to the rising temperatures.

The pathways of heat

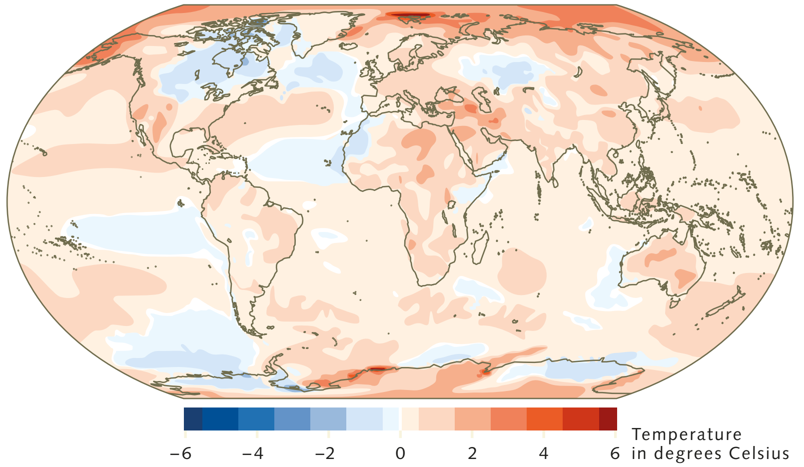
> Climate change produces more visible traces in the polar regions than it does on other parts of the Earth. This is due in part to the special sensitivity to heat of these icy worlds. But another factor is that the warming due to greenhouse gas emissions is more strongly amplified in the Arctic by a number of positive feedback mechanisms, causing temperatures in the northern polar region to rise twice as fast as in the rest of the world.

The new face of the polar regions

In the course of climate change, the polar regions are undergoing a remarkable transformation – more rapidly and more conspicuously than in most other regions of the world. The consequences of the warming so far have been most pronounced in the Arctic, where large areas of the sea ice and snow cover are disappearing, the sea water in many areas is becoming warmer, the permafrost soil is thawing more often and for longer periods, and the glaciers in Alaska, Canada, Greenland, Iceland and Norway are all losing large volumes of ice. In the Antarctic, on the other hand, the trends are distinctively different from one area to another. For example, although researchers have been observing a retreat of the ice shelves and glaciers on the Antarctic Peninsula for decades, as well as diminishing sea ice and rising air temperatures (processes that are in part also influenced by the presence of the ozone hole), the visible signs of change in East Antarctica have only recently begun to take shape in a significant way. In the central region of the continent, however, there has been no evidence of warming thus far. Here, temperatures have remained constant, or have even fallen slightly due to ozone depletion.

The fact that snow, ice, sea, land and atmosphere interact in so many ways with one another complicates the situation for both polar regions, so that it is often impossible to say exactly what is a cause and what is an effect. In the Arctic, for example, it may be reasonable to ask: Is sea ice melting because the ocean has become warmer, or is the water becoming warmer because the insulation provided by the sea ice is no longer present? Presumably both factors play a role, as changes in the polar regions are mutually reinforcing, particularly in the Arctic. Without a doubt, however, the underlying trigger for all of this is a general warming of the Earth that is being caused by massive emissions of greenhouse gases.

3.1 > When icebergs melt at their surface, distinctive features revealing that process are formed. Icicles consisting of re-frozen meltwater are one of these; puddles or pools in which the meltwater collects are another.



3.2 > Greater-than-average warming in the Arctic continues in the year 2018. From February 2018 to January 2019 the average surface temperature in large parts of the northern polar region was as much as five degrees Celsius higher than the average values from 1981 to 2010.

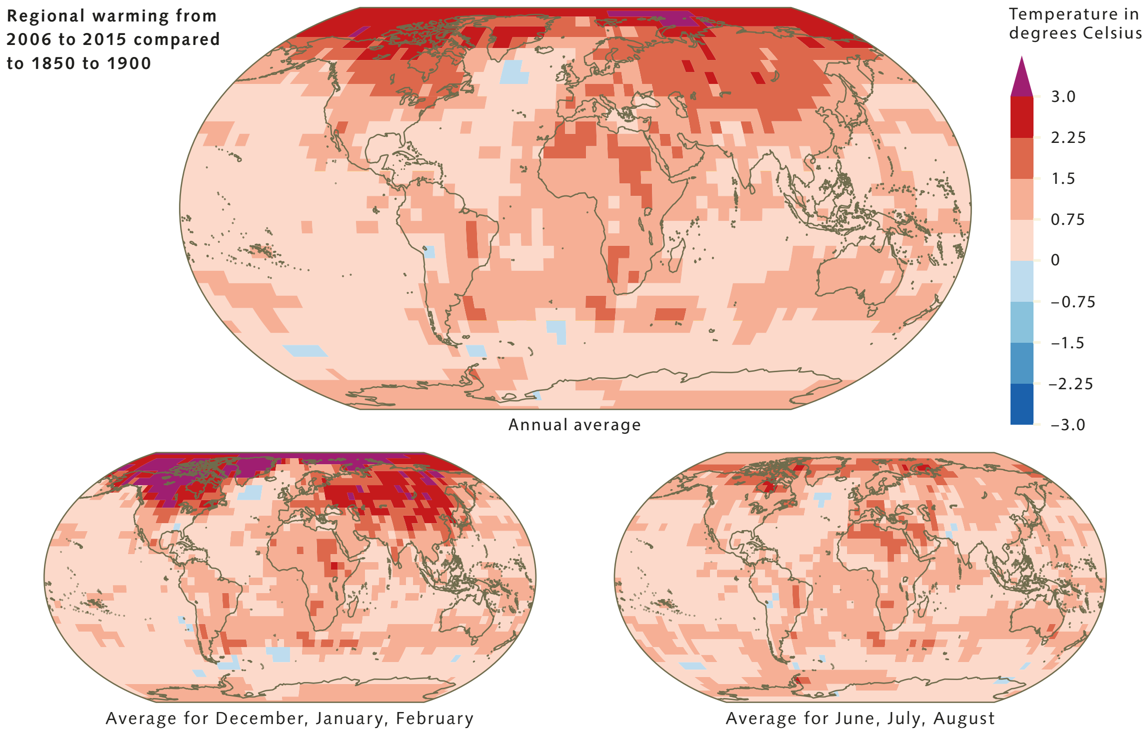
Thawing at the North Pole

The year 2015 drew to a close with a sensational meteorological event in the Arctic. On 29 December, in the middle of the Arctic winter, the surface temperature at the North Pole rose within a single day from minus 26.8 degrees Celsius to minus 0.8 degrees Celsius. It presumably rained at the northernmost point on the Earth on the day before New Year's Eve, based on meteorological measurements in Ny-Ålesund, Spitsbergen, that indicated that a storm had transported warm moist air from the North Atlantic towards the North Pole. Sea-ice buoys drifting at 85 degrees latitude in the Arctic Ocean at the time confirmed these observations. They registered a positive average temperature of 0.7 degrees Celsius. Consequently, on 30 December 2015 it was warmer at the North Pole than it was at the same time in some parts of Central Europe.

Two decades ago, such a remarkable heat incursion into the Arctic would have been an extreme anomaly. Today, however, reports of such exceptional weather events in the high north are becoming more common, especially during the winter. For example, in February 2017, at a temperature of plus two degrees Celsius it rained in Ny-Ålesund, Spitsbergen's northernmost settlement. Instead of icy polar cold, the inhabitants of the research village experienced the dreary weather more typical of northern Germany. One year later, in February 2018, strong offshore winds combined with warmer-than-average air temperatures off the north coast of Greenland led to a first-ever event. The old sea ice frozen to the coast broke off to form a large polynya. On 24 February 2018, when the polynya reached its greatest width, Greenland's northernmost weather station at Cape Morris Jesup recorded a daily high temperature of plus 6.1 degrees Celsius. At Berlin's Tegel Airport the high temperature for that day was only slightly above freezing.

This capricious weather matches a pattern that meteorologists at the polar research station called AWIPEV (French-German Arctic Research Base operated by the Alfred Wegener Institute for Polar and Marine Research [AWI] and the Polar Institute Paul-Émile Victor [IPEV]) at Ny-Ålesund, Spitsbergen, have identified through long-term observations. Over the past 35 years the air above Spitsbergen has warmed significantly, not only near the ground but also at higher altitudes. The warming of the Atlantic sector of the Arctic has been especially prominent in the winter months. During recent cold seasons, the temperatures on Spitsbergen have averaged 3.1 degrees Celsius warmer than those of ten years ago. Summers, on the other hand, have warmed less markedly, with an increase in air temperature in Ny-Ålesund of 1.4 degrees Celsius per decade, calculated throughout the year.

There are similar reports from almost all other parts of the Arctic, and their central message is clear: The northern polar region has been warming more than twice as fast as the rest of the world over the past 50 years, and the trend is continuing. Researchers have observed the largest temperature increases during the winter. For example, in



3.3 > Warming of the Earth due to climate change is not uniform geographically. During the period from 2006 to 2015, for example, temperatures in the Arctic rose twice as fast as those in the rest of the world, whereby the warmer temperatures in the northern polar region were primarily recorded during the winter months. The average temperature was more than three degrees Celsius higher than the average for the period from 1850 to 1900.

January and February of 2016 the temperature north of 66 degrees latitude was five degrees Celsius above the average monthly value for the years 1981 to 2010. From October 2017 to September 2018 it was 1.7 degrees Celsius warmer all across the Arctic than in the reference period from 1981 to 2010.

Greenhouse gases are warming planet Earth

The warming of the Earth is human-induced and is a result of the unchecked emission of greenhouse gases such as carbon dioxide, methane and nitrous oxide. Since the onset of industrialization, humankind has discharged an estimated 2220 billion tonnes of carbon dioxide into the atmosphere (from 1876 to the end of 2017). This very persistent greenhouse gas is produced primarily by the burning of fossil fuels such as coal, petroleum and natural gas. But it is also released in cement production, the draining of wetlands, and in the deforestation of wooded areas for agricultural and livestock use. As a result of these activities, the concentration of this gas in the Earth's atmosphere has risen by a factor of 1.5 in recent centuries. In 1750 the value was 277 parts per million (ppm), while present concentrations are around 410 ppm.

The planet's self-cooling mechanisms are disrupted by the enrichment of carbon dioxide, methane and laughing gas in the atmosphere. This means that the Earth's surface can no longer simply radiate large portions of the incoming solar energy back into space as long-wave heat radiation, and a kind of heat congestion occurs close to the ground. This has been disturbing the Earth's climate system at least since 1970, because since that time the planet has been absorbing more radiation than it can release. The average radiation balance value since then has been calculated at around plus 0.4 watts of solar energy per square metre.

In recent centuries around 93 per cent of this additional radiative energy has been absorbed by the oceans and distributed through their depths. The remaining energy has contributed to warming of the air and the continents, so that the global average surface temperature has risen by about one degree Celsius over the past 120 to 170 years. The greenhouse gas carbon dioxide alone is responsible for around 50 per cent of this warming. Methane contributes 29 per cent and laughing gas around five per cent. The remaining 16 per cent is attributed to other substances such as carbon monoxide, halogenated and fluorochlorinated hydrocarbons, and soot particles.

However, the whole Earth has not warmed uniformly. This is due to the distribution patterns of land and sea areas. The sun heats land surfaces and the overlying air layers more rapidly than it does the large seas. At the same time, however, the ground stores less energy than sea water, and so it also cools down again faster. The oceans are therefore significantly slower in reacting to climatic changes than the atmosphere. The cooling effect of the Antarctic ice masses also plays an important role. Their far-reaching influence on the climate of the southern hemisphere may be one reason why the effects of climate change became apparent earlier and more prominently in the more land-dominated northern hemisphere than in the sea-dominated southern hemisphere. While the first signs of warming appeared in the Arctic as early as the 1830s, for example, the temperatures in Australia and South America remained steady through the turn of the century. In the Antarctic region, it was not until the 1950s that meteorologists began to report rising temperatures on the Antarctic Peninsula and in the West Antarctic.

However, slightly higher local temperatures are not necessarily indicative of general climate change. Scientists can only speak in these terms when a clear and sustained temperature curve – over a period of at least 30 years – exceeds the boundaries that were previously defined by naturally occurring climatic fluctuations. In the Arctic this became clear as early as the 1930s, earlier than in any other region of the world. This was followed by the tropics and the mid-latitudes of the northern hemisphere, where the distinct warming signal was first seen in the 1950s, and then by Australia and Southeast Asia, where mounting evidence for climate change was observed around 60 years ago.

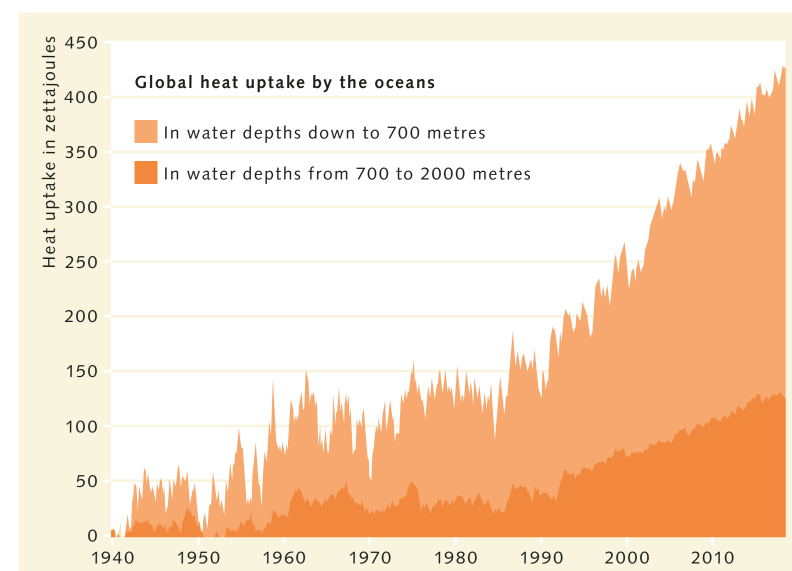
Over the remainder of the world, with the exception of central Antarctica, global warming has been developing at full force since the beginning of the 21st century. Since then, reports of record temperatures have been increasing, and major climate research institutions have begun to rank the warmest years. The list so far is led by the years 2015, 2016, 2017 and 2018. The Arctic region itself experienced its five warmest years from 2014 to 2018.

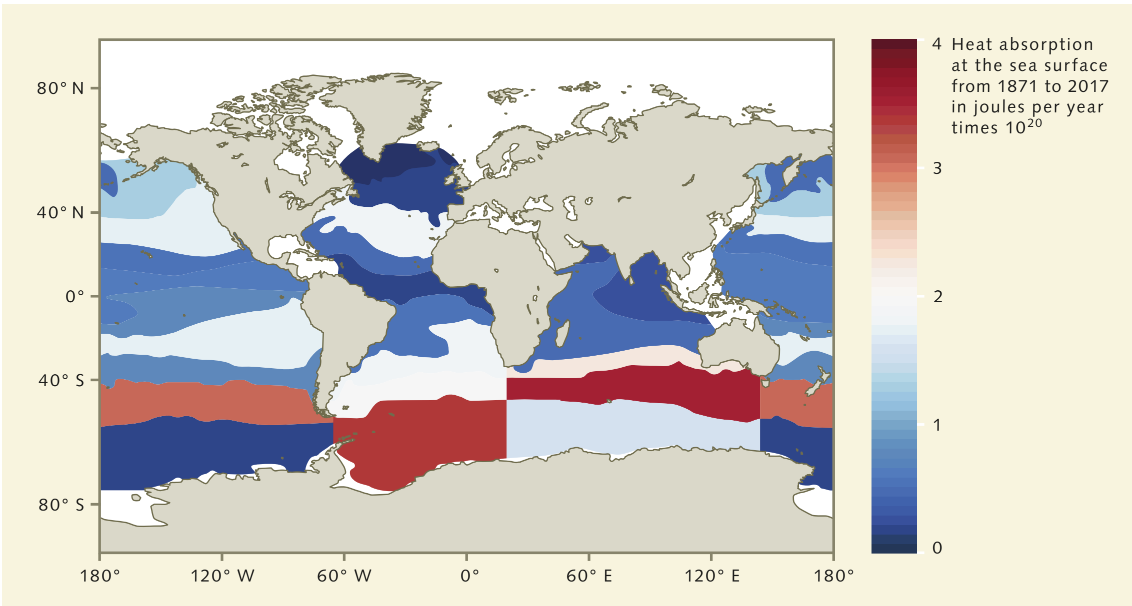
The oceans are warming

The fact that global warming so far has been comparatively moderate at around one degree Celsius can mainly be attributed to the world's oceans. For one thing, the oceans in the past have absorbed 30 per cent of the carbon dioxide emitted by humans and thus noticeably buffered the progress of the greenhouse effect. For another, the oceans possess an enormous capacity to store heat. This is a result of the physical properties of salt water as well as the sheer magnitude of water in the oceans. An example calculation: 1000 times more heat energy would be required to warm all the world's oceans by one degree Celsius than would be needed to heat up the atmosphere by the same amount.

Furthermore, the oceans react very sluggishly to changes in the environment because their water masses circulate and are repeatedly cooled down as they pass through the polar regions. It therefore usually takes around ten years for the surface water of the oceans to

3.4 > The world's oceans continuously absorb immense amounts of heat energy. While this heat was initially stored almost exclusively in the upper water layers, it has now been shown to reach deeper levels.





3.5 > The world's oceans do not all absorb the same amounts of heat energy. The differences can be easily recognized when the oceans are divided into a number of different measurement regions. The regions far to the south absorb especially large amounts of heat.

adjust to globally rising air temperatures. Centuries to millennia, on the other hand, are required before the additional heat reaches the deep sea.

Based on recent research, the oceans have absorbed about 436 zettajoules of thermal energy since 1871. That is equal to a thousand times the amount of energy that humans presently consume each year. In the past 25 years alone, the oceans have absorbed so much heat that, if they were only ten metres deep, it would theoretically have been sufficient to warm the seas by 16.25 degrees Celsius. It is because the average depth of the oceans is almost 3700 metres that the warming is limited to what has been observed to date.

Zettajoule
Zettajoule is a unit of measure used to refer to especially large amounts of energy that cannot be reasonably expressed in the basic energy unit of joules. A zettajoule is equal to 10^{21} joules.

Nevertheless, the trend is clear. For decades the water in all the world's oceans has been continuously getting warmer. Most of the heat energy is retained in the upper 700 metres of the water column, but it must be noted that the temperature sensors used for these measurements could not be deployed any deeper prior to the year 2005. Since then, however, autonomous drifting buoys, called "ARGO Floats" (Array for Realtime **Geostrophic** Oceanography) have been widely deployed. The data from these reveal that the water masses at depths between 700 and 2000 metres are also warming up significantly everywhere, with potentially serious consequences for the global ocean-current conveyor belt. Thermohaline circulation can be weakened by ocean warming in two ways. For one, added heat lowers the density of the water due to thermal expansion. The water becomes lighter. Secondly, the same effect of lowered density results when seawater is diluted with freshwater from increased rainfall or melting of the glaciers in Greenland and Antarctica. Both of these factors, freshwater influx and increasing water temperature, inhibit the sinking of water masses in the North Atlantic and in the Southern Ocean, and this can suppress the driving forces of thermohaline circulation.

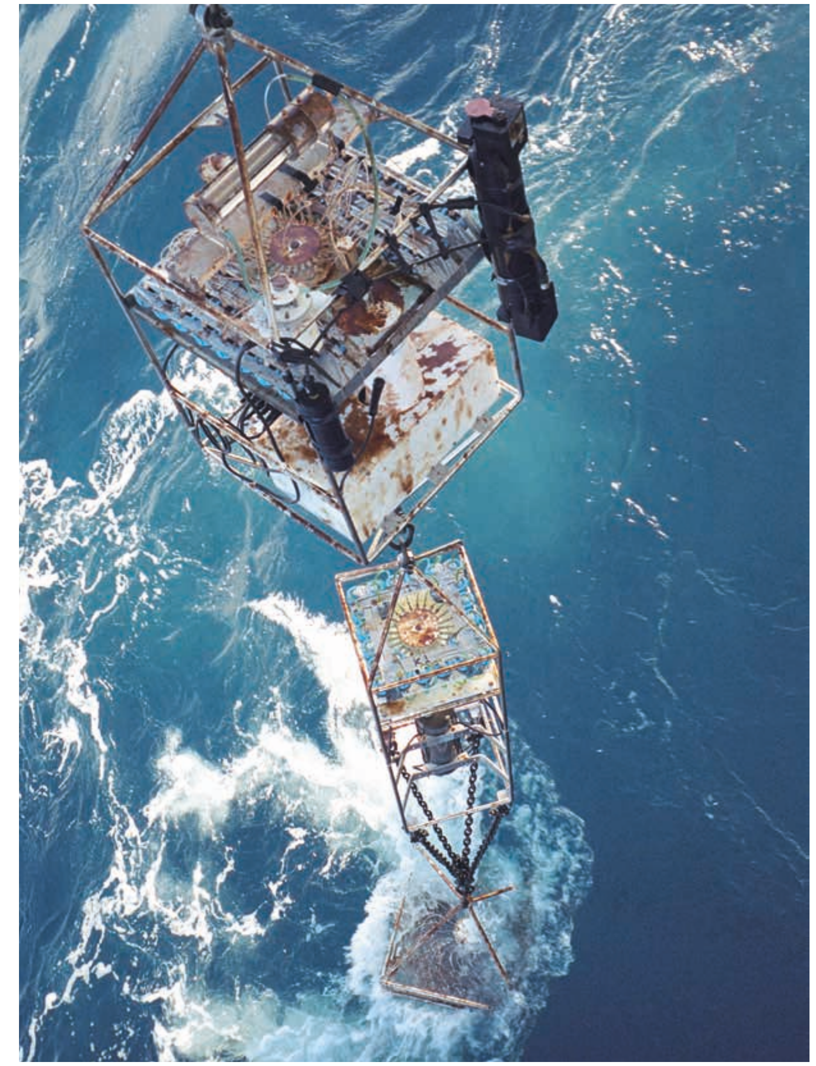
Tracking heat in the polar seas

For the polar regions, warming of the world's oceans is of crucial importance: More heat is being transported into the Arctic and Antarctic regions today than in the past through the ocean currents flowing towards the poles. The Atlantic water flowing into the Arctic Ocean, for example, has become verifiably warmer since the early 1990s. In order to track the pathways of heat into the Arctic Ocean, German and Norwegian Scientists set up a transect of oceanographic survey sites across the Fram Strait at 79 degrees north latitude in 1997, from the west coast of Spitsbergen to the northeast coast of Greenland. At each of the 16 sites in this array of moorings, the temperature, current speed and salinity of the inflowing and outflowing water masses are measured throughout the water column. These data show that the water of the West Spitsbergen Current coming from the North Atlantic is on average one degree Celsius warmer when it passes through the Fram Strait into the Arctic Ocean today than it was when the long-term measurements began 20 years ago. Evidence of this warmer water is already present throughout the entire Eurasian Basin.

Sea-surface temperatures have also risen in most of the ice-free areas of the Arctic Ocean. This is why, today, the sea here not only freezes over later in the year, but the sea-ice also melts earlier, leaving large areas of the Arctic Ocean free of ice for longer periods in the summer. This enables them to absorb more solar energy, which in turn promotes a further increase in temperature.

The Southern Ocean holds a key position in the Earth's climate system because without the cooling and overturning of water masses in the Antarctic region the oceans would not be able to store as much heat and greenhouse gases as they currently do. The sinking of heavy water represents the only possibility of transporting heat and carbon dioxide from the upper water layers to greater depths for long periods of time, and in the Antarctic this occurs on a much larger scale than in the North Atlantic. Researchers have been documenting a ubiquitous rise in water temperatures in the Southern Ocean since the 1950s. Its magnitude indicates that the sea south of the 40th parallel has absorbed significantly more heat from the atmosphere than all other marine regions combined.

The storage of large amounts of heat over a number of decades has other consequences as well. Based on long-term measurements along the prime meridian, German polar researchers have been able to determine that the entire water column in the Weddell Sea, and particularly the deepest water layer, the Antarctic Bottom Water, has been warming since the 1990s. Similar observations have been made in other Antarctic marine regions and scientists have now ascertained that, at depths below 1000 metres, the Southern Ocean has warmed faster in the past three decades than the global oceanic average.



3.6 > The crane on a research ship heaves a mooring chain out of the sea with devices attached for water sampling (top) and for collecting phytoplankton (bottom).

The reason for this warming is still unclear. Is it primarily caused by warming of the atmosphere above the Southern Ocean? When the air temperature rises the sea is not able to release as much of its own heat to the atmosphere. Furthermore, the wind conditions change over the sea, which can increase or decrease the speed of certain ocean currents and in turn influence deep-water formation. Or is the increase in temperature at depth more likely caused by the influx of warmer waters into the Southern Ocean? Presumably all of these factors contribute to some extent.

It is remarkable that researchers can now track the Antarctic-wide warming of deep water northward to beyond the equator. The heavy water masses flow there after they have filled up the deepest level of the Southern Ocean.

More fog, more clouds

The influx of warmer waters along with rising air temperatures in the polar regions is resulting in intense warming of the seas there. The warmer an ocean becomes the more water will evaporate from its surface. The water-vapour content of the air increases, amplifying the greenhouse effect and increasing the probability of fog and cloud formation. Both of these phenomena, particularly in the Arctic, prevent the loss of heat energy into space and therefore promote the warming process.

In spring, for example, the snow cover on the Arctic sea ice is melting earlier as a result of higher atmospheric humidity and cloud formation, and the sea ice is thus also melting earlier. In summer, low-hanging clouds and fog promote warming on the surface of the remaining sea ice. Modelling suggests that a diminished sea-ice cover in autumn tends to increase the formation of clouds over the Arctic Ocean, with the consequence that the newly formed ice is thinner at the beginning of winter than it would be with less cloud cover.

Meteorologists at the AWIPEV polar research station in Ny-Ålesund cannot yet say whether the thickness, altitude or consistency of the cloud cover over Spitsbergen has changed because the necessary measurements have only been carried out for a few years. But from the daily weather-balloon launches that have taken place since 1993 to altitudes of 30 kilometres, they know that the air has become warmer and contains more moisture. The scientists report that the island's climate today, even in winter, is actually more maritime than truly extreme Arctic.

Recent studies support this local perception: Trends in cloud cover vary from region to region, but the Arctic climate has become wetter in many areas. Both the humidity and the amount of precipitation have increased. Researchers see this as a sign that more atmospheric moisture from the middle latitudes is reaching the high north today. They predict a continued increase for the future. Because warmer air masses are able to store more moisture, higher rates of evaporation can be expected over the ice-free areas of the Arctic Ocean, along with more precipitation. The latter will result in a rise in water level in the Arctic rivers. The researchers also expect that summer rain will reduce the albedo of the sea ice and further enhance melting of the ice.

The Atlantic sends out its tentacles

The heat-driven changes in the Arctic Ocean are particularly noticeable in the Barents Sea, the northern European gateway to the Arctic Ocean. The 1.4 million-square-kilometre marine area between Svalbard, Norway and the Russian archipelago of Novaya Zemlya has traditionally been separated into two regions with contrasting sea-ice conditions and water-column configurations.

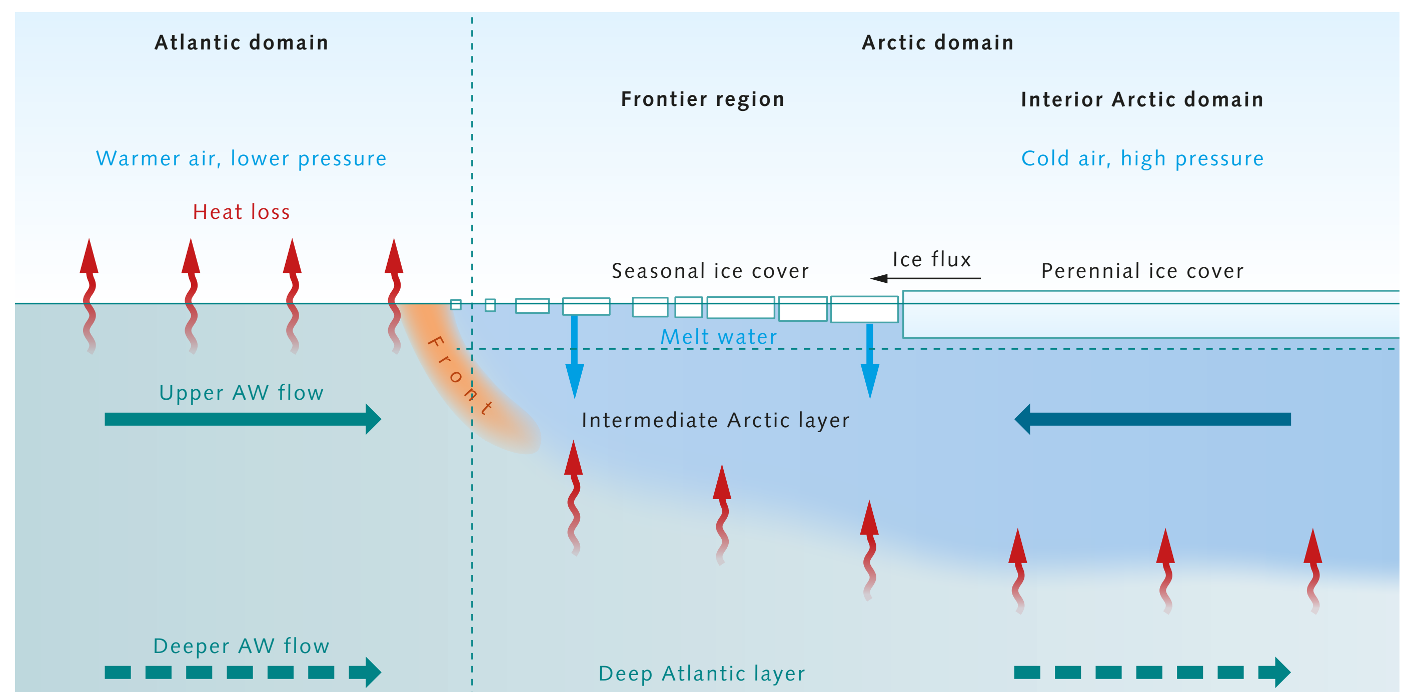
The water masses in the northern part of this sea are vertically layered in typical Arctic fashion. This pattern is characterized by sea ice floating upon a surface layer of cold, rather low salinity water, below which lies another cold but more saline layer called the halocline. These two layers protect the ice floes from the warmer, deeper currents. By reflecting a large portion of the incident solar radiation, the white sea-ice cover prevents large-scale warming of the uppermost water layer during the summer months.

In the southern part of the Barents Sea, however, the sea ice and the cold surface layer are both absent. Here, warm saline water from the Atlantic Ocean flows northward at the sea surface. It loses its heat to the atmosphere, which inhibits the formation of new sea ice in the winter. Furthermore, the ice-free water surface absorbs large amounts of solar energy during the summer months. In August 2018, for example, the surface-water temperature in the southern Barents Sea was eleven degrees Celsius. This was between one and three degrees Celsius higher than the average summer temperature for the years 1982 through 2010. This warming has major consequences.

Studies have shown that, in addition to increasing temperatures and greater amounts of inflowing Atlantic water over the past two decades, the changes are also encroaching further to the north. This advance is facilitated by the drastic decline in sea ice in the northern Barents Sea throughout the year. Because significantly less sea ice is now being formed here in winter than it was at the beginning of the 21st century, there is a diminished input of freshwater into the sea during the normal melting periods in spring and summer. As a result, the temperature and density differences between the surface layer and the deeper layers are disappearing. The once clearly distinguishable water masses are now mixing more often with one another, and the warm Atlantic waters from below more frequently reach the sea surface. There, the higher surface temperatures delay or prevent the formation of new sea ice. When there is less ice available for melting in the spring, the weakened layering of the water masses allows warm Atlantic water to well upward, which in turn inhibits the formation of new ice in autumn. This thus becomes a self-reinforcing process, and scientists refer to it as one of the many "positive feedbacks" acting in the Arctic climate system.

But there is a second important effect of the stronger and deeper mixing of the water masses in the Barents Sea. The Arctic Ocean as a whole loses more heat to the atmosphere because it can be cooled to greater depths through the constant mixing. Until now this process has been primarily typical only for the North Atlantic. In the long term, this change could even result in a northward shift of the elements of North Atlantic overturning circulation into the Arctic Ocean, resulting in even more warming of the Arctic than is already occurring.

Disappearing sea ice and the emergence of a water column without distinctly layered water masses – the Arctic Ocean, as a result of climate change in the Barents Sea, is losing two of its most notable characteristic features. Researchers are now referring to this as "Atlantification" of the Barents Sea, which will bring with it a fundamental change in the living conditions in this marine region. Some climate simulations suggest that the northern Barents Sea may be completely shifted to Atlantic mode by the end of this century. Based on their own observations, however, Norwegian scientists predict that this systemic change could occur much sooner. If the sea ice continues to shrink at the rate it has over the past two decades, such a large amount of freshwater will be lacking



3.7 > Atlantification: As a result of the decreasing sea ice in the Barents Sea, warmer Atlantic Water is advancing further north into this marginal sea of the Arctic Ocean, causing a retreat of the characteristic Arctic sea zone.

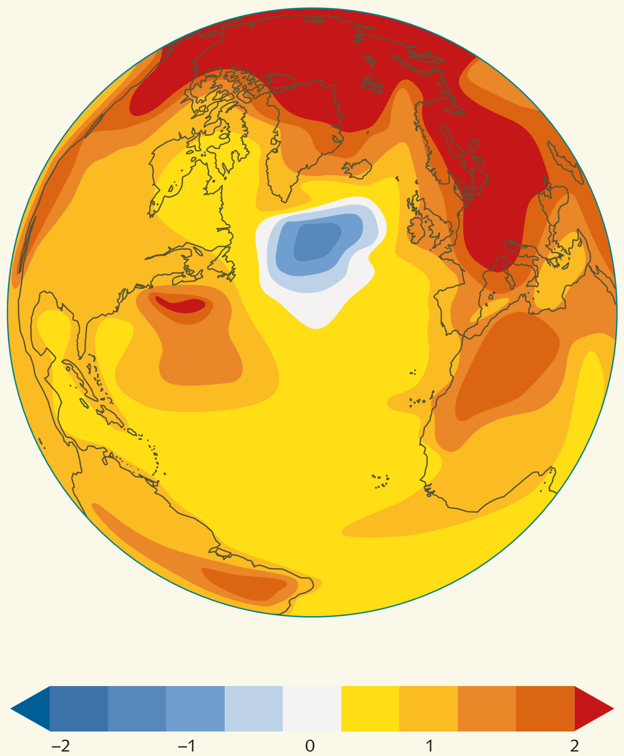
Does more freshwater in the Arctic Ocean weaken the Gulf Stream?

A unique feature of the Arctic Ocean is its thick, lower-salinity layer at the sea surface. Researchers often refer to this somewhat misleadingly as a freshwater layer. It has always been replenished by numerous rivers and the influx of low-salinity surface water from the Pacific Ocean. But in recent decades researchers have observed an increase in the proportion of freshwater in the Arctic Ocean, while the water in the North Atlantic is becoming more saline. One reason for the freshening of the Arctic Ocean water could be the fact that it snows more now in Siberia in the winter and rains more through the rest of the year. The rivers therefore transport more meltwater and rainwater into the Arctic Ocean.

It is still uncertain what consequences the increasing amounts of freshwater will bring. However, scientists believe that this change could influence the overturning of water masses in the North Atlantic, which is a crucial factor for the climate, and could thus also impact the strength of the Gulf Stream. Like all of the Arctic Ocean water masses, the low-salinity surface water is transported southward through the Davis Strait, the Fram Strait, or the Norwegian Sea into the North Atlantic, and dilutes the water masses there. Under certain conditions, therefore, sufficiently large amounts of freshwater could cause the North Atlantic water, despite its low temperature, to be no longer heavy enough to sink to the depths necessary to flow back toward the equator as deep water. The engine in the North Atlantic that drives global ocean circulation would then run more slowly, and important currents like the Gulf Stream would be weakened.

Examples from climate history illustrate the possibility of such a chain reaction occurring. When the prehistoric Lake Agassiz in North America was abruptly emptied 8200 years ago, releasing an immense volume of freshwater through the St. Lawrence Estuary into the North Atlantic, the overturning circulation of Atlantic water masses slowed down. As a result, the warm Atlantic current came to a standstill, or at least weakened, causing the North Atlantic region to cool considerably within a few years. And researchers now know that an interruption in the overturning of North Atlantic water also has a global impact. In the past, for example, a shift in the position of the rain belt over the tropics was related to warming in the Southern Ocean and in Antarctica.

Climate models predict that the Gulf Stream will weaken in the future as a result of increased emissions of greenhouse gases in the atmosphere, and that this will lead to cooling in the North Atlantic. Climate researchers have found that this is already happening. The subpolar part of the Atlantic Ocean is the only marine region in the world that has not warmed since the beginning of the 20th century, but has cooled down. The temperature changes suggest that the Gulf Stream has weakened by 15 per cent.



3.8 > Scientists cite falling surface temperatures in the marine region southeast of Greenland as evidence for a weakening of deep-water formation in the North Atlantic. The logic behind this is: Because, as a result of global warming, less water is being overturned in the North Atlantic, the North Atlantic Current, which transports heat from the US east coast to northern Europe, has weakened. And when less heat flows in, the sea cools down.

that the northern Barents Sea will no longer have clearly stratified water layers by the year 2040, and Atlantification of this water body will be complete.

The Barents Sea, however, is not the only marginal sea of the Arctic Ocean into which warm water is advancing. The Labrador Sea off the east coast of Canada as well as the Bering and Chukchi Seas off the coast of Alaska are warming at comparable rates. In all four of these marine regions the summer surface temperatures are now rising by one degree Celsius per decade. Furthermore, sea ice is receding in all four regions, the ice-free water surfaces are absorbing more solar energy, and warm water masses from below are more frequently reaching the surface. It is therefore extremely difficult to distinguish the individual processes from their effects. What is certain is that climate warming has set into motion processes in the Earth's climate system that are mutually reinforcing in their effects, and that are becoming increasingly evident, especially in the Arctic region.

Arctic amplification – a fatal chain reaction

Which effects contribute to amplification, and to what extent, are matters of substantial debate in the scientific community. Some researchers argue that the drastic warming is primarily due to the decreasing snow and sea-ice covers in the Arctic. The fewer lighter areas there are, they say, the lower the reflectivity in the Arctic, and the more solar energy remains in the polar region to drive changes in the oceans and atmosphere. Others point out that the warmer air above the Arctic absorbs more water vapour, therefore enhancing cloud formation, which in turn impedes the radiation of heat energy back into space. Depending on the season and kind of clouds, however, the effect of this could also be reversed such that the cloud cover has a cooling effect.

Both arguments are valid and each can be verified by measurements. The actual explanation for the amplification presumably lies in the interaction of all of these factors, the magnitudes and effects of which vary not only with the seasons but also from region to region. Moreover, the climate system is not only complex but its individual components also interact with each other in an extremely chaotic way, which greatly complicates the identification of causes and effects. Scientists refer to this as climate noise, climate fluctuations, or the natural variability of the climate system.

It is certain that air and ocean currents today transport more heat and moisture into the northern polar region than they did in the past. According to a widely held hypothesis, this reduces the general temperature contrast between the high and middle latitudes. This contrast, in turn, is the energy source for the polar jet stream. This slightly undulating band of strong winds normally circulates around the Arctic region parallel to the equator between 40 and 60 degrees latitude, and like a protective wall it prevents warm southern air masses from encroaching into the Arctic.

But as the Arctic becomes warmer, the temperature difference between the polar area and the southern regions decreases. As a result, the westerly winds that make up the polar jet stream also weaken. The air flow is thus more easily diverted from its zonal alignment by high- and low-pressure areas, and meanders in large waves across the northern hemisphere (see Chapter 2). This opens the way for two opposing shifts in air masses. Over the North Atlantic and western North America, warm, humid air from the south moves into the Arctic. Over Siberia and the rest of North America, on the other hand, cold polar air from the Arctic penetrates southward into the middle latitudes, bringing with it spells of freezing cold, especially in winter.

At times when the jet stream is weak, it is also more common for shifting high- or low-pressure areas to become stalled and remain in one area for a long time. Such a situation routinely leads to extreme weather events, such as prolonged rainfall with subsequent flooding, or prolonged warm weather and drought such as that which occurred in Central Europe in the summer of 2018.

Scientists do not yet fully understand the details of this high-impact chain reaction. But there has been great progress. New studies indicate, for example, that the drastic decline in sea ice in the Barents Sea and the Kara Sea has played a decisive role in weakening the jet stream over Europe and Asia. Simply stated, the two marginal

Dust and soot particles on the skyway to the Arctic

Not only does a jet stream with a winding course allow warm, moist air to penetrate into the Arctic. Under certain conditions dust clouds from the Sahara, thousands of miles away, can drift into the high north in its wake. In fact, atmospheric scientists observed just such a dust influx from North Africa in April 2011.

At that time the meandering jet stream caused a severe storm over the Moroccan area of the Sahara. The storm stirred up large quantities of desert sand and swept it up to a height of six kilometres. A large dust cloud formed that was initially transported by northward-flowing air masses – and later by the jet stream itself – across Spain, Western Europe and the northeast Atlantic to southern Greenland. There the desert sand settled down onto the ice sheet encased in snow crystals or water drops.

Dust and soot particles carried around the world by the wind are called aerosols by scientists. They are a few nanometres to several micrometres in size, and are therefore so light that once they are stirred up they scarcely fall to the ground again.

Aerosols are formed not only by desert storms, however, but also by field and forest fires, by volcanic eruptions, and by the burning of oil or coal. The barren soils of Iceland, for one, are an important source of aerosols for the Arctic. Furthermore, the pollen from flowers, as well as bacteria, viruses, and sea-salt particles stirred up by the wind may be suspended in the air.

Aerosols are an important element for the Arctic climate because they influence the heat balance in this polar region. Droplets of sulphate compounds, for example, reflect incoming sunlight before it reaches the Earth's surface and thus have a cooling effect. Dust and soot particles, on the other hand, have a warming effect because they absorb the sunlight and thus retain its energy in the atmosphere. To a lesser extent, aerosols also scatter and absorb the heat energy radiated from the Earth. In this case, therefore, they act similar to greenhouse gases and contribute to warming of the atmosphere. This warming effect is mostly evident above surfaces with high reflectivity, such as those with ice and snow. In the polar regions, therefore, aerosols contribute more to warming than they do in the lower latitudes. There they tend to have more of a cooling effect.

Without aerosols no clouds would form. The miniscule particles act as condensation seeds upon which water droplets or ice crystals can form, and thus promote cloud formation. In the Arctic, the clouds amplify the summer melting of sea ice. Dust and soot particles also expedite the melting of snow and ice by eventually settling on sea ice and glacier ice, dirtying its surface and thus reducing its reflectivity. In recent decades, for example, the albedo of the Greenland Ice Sheet has decreased noticeably, partly because more suspended material has been deposited on its surface.

Especially high concentrations of aerosols are measured in the Arctic in late winter and the ensuing spring. During this time there are so many different particles wafting around in the lower troposphere that a whitish to reddish shimmering fog cloud can lie across the entire Arctic.

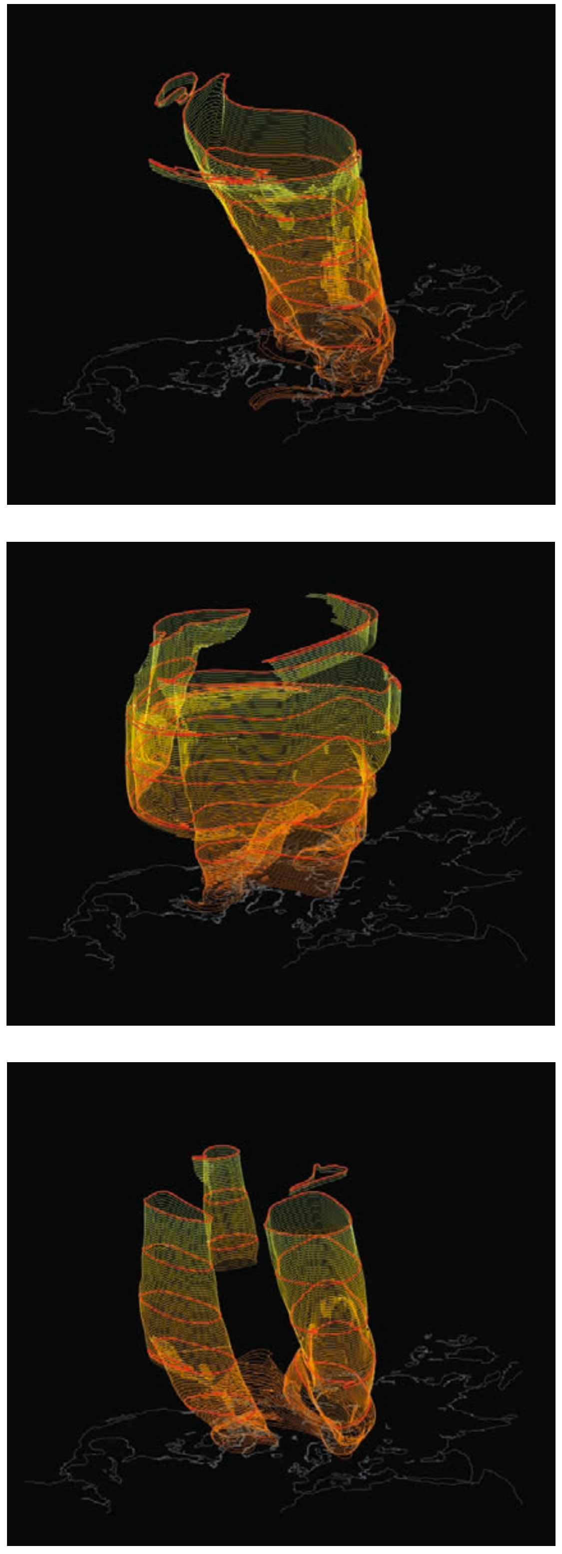
3.9 > Dirty ice: Soot and dust particles darken the surface of the Helheim Glacier in southeast Greenland.

Scientists refer to this phenomenon as arctic haze, and consider it to be a form of air pollution.

Most aerosols are produced by forest fires or are discharged by industrial plants and coal-fired power plants in Europe, North America and Asia. They are transported by wind toward the Arctic, where they remain in the air for long periods of time, especially in the winter. One reason for this is that the air masses there are poorly mixed during this time of year. Another is that very few clouds form in the cold, late-winter atmosphere, so that the pollution particles are hardly washed out by rain or snow.

It is not yet predictable whether aerosol concentrations in the Arctic will increase in the future. When the jet stream meanders, more moisture reaches the northern polar region, and the resulting precipitation washes suspended material out of the air. The question of which aerosols reach the Arctic by what routes, and their influence on the climate there, thus remains an important topic of research.

3.10 > Air pollution: A US research aircraft flies through a dust cloud over the Arctic, which formed as a result of large dust, soot and sulphur emissions from Europe, North America and Asia.



3.11 > In the winter of 2018/2019 the Arctic polar vortex broke down into three smaller vortices within twelve days. In North America, polar air then penetrated far to the south, triggering an extreme cold spell in Canada and the northeast United States.

seas of the Arctic Ocean absorb so much solar energy in the summer that they do not begin to freeze over until October or November, which is relatively late. By then, however, the exposed waters have released so much heat and moisture into the troposphere that more snow falls over Siberia. The increased snow cover, in turn, enhances the reflectivity of the land surfaces, thus facilitating cooling and the formation of a high-pressure area over Siberia.

To the west, meanwhile, a pocket of warmer temperatures forms due to the heat released by the sea. The jet stream, sweeping through the overlying air layers, is thus deflected to the south, but in part also to the north. The warm-air pocket also presents an obstacle for the planetary waves. Air packages coming from the west shoot upwards here like a skateboard in a halfpipe, and maintain enough momentum to rise into the stratosphere and disturb the polar vortex rotating above the Arctic. Under certain conditions they can even split the vortex.

A breakdown of the polar vortex then weakens the jet stream in the troposphere, causing the obstructing high- and low-pressure areas to linger over Europe and Asia. These then divert cold air to Asia and Europe, and warm air towards the Greenland Sea. The latter effect then logically leads to a rise in the air temperature over the Arctic Ocean, a decline in the number of freezing days, and a less strongly frozen or even melting sea-ice cover.

Arctic scientists are predicting an increase in autumn and winter temperatures of up to four degrees Celsius over the next three decades. A warming of this magnitude would result in large areas of the Arctic Ocean to be ice-free for greater parts of the year. Large areas of permafrost ground would also thaw out. Both of these fundamental changes would have direct consequences for the local ecosystems, as well as for shipping, resource extraction and any other human activities in the Arctic.

Different trends seen in the Antarctic

In the Antarctic, climate change is not generating the kind of uniform warming pattern that is observed in the Arctic. This is probably due to the cooling effect of the continental ice masses, in part caused by their high reflectivity, as well as to the insulating effect of the Antarctic Circumpolar Current. In addition, there are great regional differences between marine-dominated coastal areas and the continental conditions over central Antarctica.

In the Pacific sector of West Antarctica as well as in the region of the Antarctic Peninsula, researchers have been observing an acceleration in the motion of glaciers in recent decades along with diminishing sea ice, rising surface temperatures and, in some places, heavier snowfall. These developments are due both to changes in atmospheric circulation, whereby more heat and moisture are transported towards the pole, and to ocean currents that transport warmer water into coastal areas. Westerly winds over the Southern Ocean are responsible for the increase in atmospheric heat transport. These have been strengthening since the 1970s and have shifted their path poleward, triggered by the rising greenhouse gas concentrations and by increasing and sustained ozone depletion over Antarctica in the spring. Both of these processes have led to a greater temperature difference between the tropics and the southern polar region, which has resulted in stronger winds.

The shift of the westerly winds, however, is not the only climatic change in the southern polar region that is driven by the periodic existence of the Antarctic ozone hole. It is now a well-known fact that the regular depletion of ozone over Antarctica has a fundamental impact on the climate of the region.

How the ozone hole alters the Antarctic climate

The Earth has its own sunscreen – a filter composed of ozone. Lying in the stratosphere it almost completely absorbs the shortest and therefore highest-energy rays of the sun, thus preventing this ultraviolet radiation (UV rays), invisible to humans, from reaching the Earth's surface. Without this natural protective screen, life on the Earth would hardly be possible because when UV rays penetrate the skin or other protective layers of plants, animals and people, they can damage the immune system and genetic material deep within their tissues.

Ozone is a highly reactive gas whose concentration in the Earth's atmosphere gradually starts to increase above an altitude of ten kilometres. It is most dense at an altitude of 30 to 35 kilometres. Nevertheless, the total proportion of the gas in the atmosphere is extremely low compared to other gases, as illustrated by this calculation: If one were to take an air column that extends from the ground to outer space and subject it to normal atmospheric pressure at a temperature of zero degrees Celsius, all of the ozone it contains would yield a layer just three millimetres thick.

This fact makes the influence of the ozone layer on the Earth's climate all the more remarkable. In fact, ozone not only absorbs the incoming UV rays; depending on its altitude, as a greenhouse gas it also absorbs heat energy that is radiated from the Earth. The more ozone an air package contains, the more UV rays or heat radiation it can absorb, and the more strongly it heats up parts of the atmosphere. Conversely, this means that if the ozone concentration in the stratosphere decreases, the surrounding air masses cool down.

Assault of the free radicals

It is precisely this phenomenon that scientists have been observing since the ozone layer over the Antarctic began to thin out regularly at the end of (southern) winter and the ozone hole began to appear in September and October. It is due to man-made gases (chlorofluorocarbons and brominated hydrocarbons) that have been used – or are still being used – as propellants, refrigerants or solvents, and contain chlorine or bromine compounds that can destroy ozone. For these gases to unleash their destructive power, however, special conditions are necessary that are only present during the long, dark winters in the polar regions. Therefore, ozone holes can only occur in the Antarctic or, in some exceptional cases, also in the Arctic.

First, the air temperature in the stratosphere must fall below minus 78 degrees Celsius. Such low temperatures only occur in winter, and usually only inside the polar vortex. The polar vortex is a high-altitude depression that forms over a polar region as a result of high thermal radia-

Ice cores – how researchers read the climate record

3.13 > A scientist saws a freshly drilled ice core. He wears protective clothing in order to avoid contaminating the ice sample. The data from these investigations provide important information about climatic changes in the past.

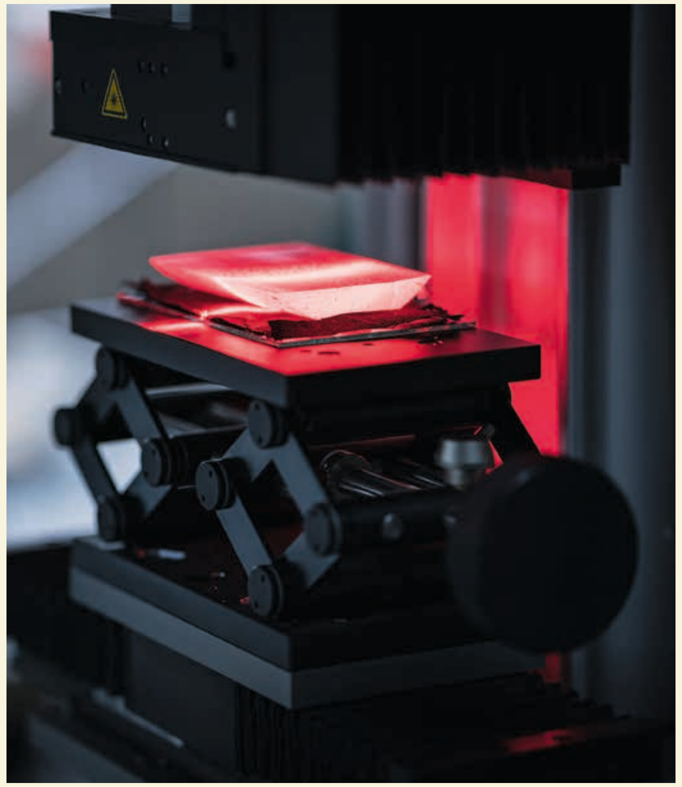
A large part of the knowledge we have about the climate history of the polar regions comes from ice cores. These are cylindrical ice samples with a diameter of ten to 15 centimetres, which researchers drill from glaciers and ice sheets using a vertical hollow drill pipe. The ice cores provide a chronological view of the climate records of the polar regions. Every layer of snow that falls on the ice sheets and glaciers, and over time compacts to firn and ice, has a specific crystal structure and characteristic chemical properties depending on the season and weather conditions, which researchers can use thousands of years later to draw conclusions about the climate conditions at the time of the original precipitation. Furthermore, when firn compacts to form ice, air bubbles are trapped, and these preserve the relative proportions of greenhouse gases. Glacial ice is thus the only climate archive that conserves air over long periods of time, which can then be used to reconstruct the chemical composition of the Earth's atmosphere. Volcanic eruptions and meteorite impacts as well as forest fires and wildfires also leave clear traces in the ice. Their ash particles were originally washed out from the atmosphere by snow or rain. This formerly suspended material forms layers in the ice cores that can be identified by various analytical methods. In some cases they can even be recognized with the naked eye. Based on these layers, scientists can accurately date ice cores from different regions of the world and compare them to each other.

In order to accurately interpret the climate record stored in the ice, its age must first be determined. To do this, one thing researchers do is to look for chemical indicators whose summer and winter concentrations are clearly distinguishable, so that annual layers can be identified. These include sodium and ammonium ions, for example, but also dust particles and calcium ions. Greenland ice cores also often include clearly recognizable melt layers. They represent times when it was so warm in summer that the snow melted on the surface of the ice sheet and the meltwater seeped into the firn and froze again. Based on a thick melt layer of this kind, the Icelandic glaciologist Thorsteinn Thorsteinsson was able to prove that it was actually unusually warm on the island in 985, the year the Viking Erik the Red sailed to Greenland.

For more detailed analyses, however, the ice cores are then investigated using computer tomography, electrical conductivity, and chemical measurements from small melted subsamples of the ice. From these, scientists generate an array of information: (1) From the isotopic composition of the water they can infer the air temperature at the time of the precipitation. (2) The thickness of the annual layers provides an indication of the quantities of precipitation. (3) The researchers can reconstruct the chemical composition of the past atmosphere based on the greenhouse gases contained in the air bubbles. (4) Sea salt, sulphates, and other chemicals in the ice highlight extreme events such as volcanic eruptions or environmental changes related to the biogeochemical cycles. They also allow conclusions to be drawn regarding the past extent of sea-ice cover, incoming solar radiation, wind strength and extreme weather events such as droughts. The temperature of the ice measured in the drill holes provides information about the evolution of temperatures in the past, and can thus verify the theory of polar amplification, which states that the temperatures in the polar regions have always changed by a greater amount than the global average.

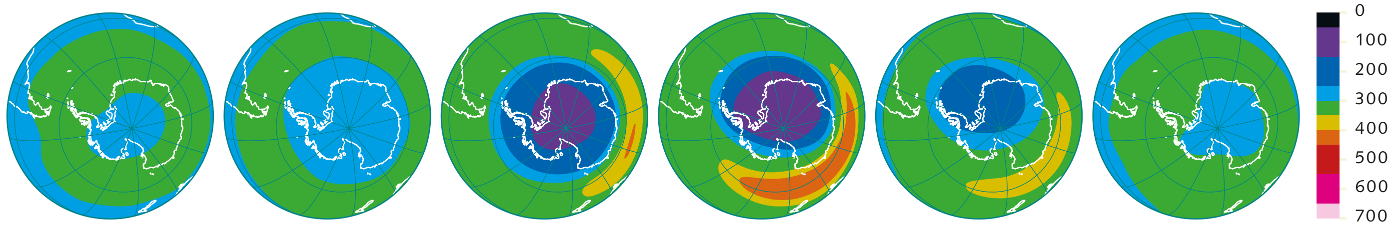
The resulting climate time series from ice cores extends back 800,000 years in the Antarctic while in Greenland it goes to 128,000 years ago. Their high resolution and level of detail have enabled fundamental advances in knowledge. Thanks to the ice cores, we know that the carbon-dioxide concentration in the atmosphere has risen drastically since the 18th century. It was just 280 ppm at that time, and today it is around 410 ppm.

The climate time series from Antarctica, furthermore, shows that the air temperature in the past has undergone regular fluctuations. These were partially caused by recurring variations in the Earth's orbital path around the sun, which led to alternating warm and cold periods on the Earth. Comparison of the ice-core data from Antarctica with that from Greenland, furthermore, has shown that climatic developments in the two hemispheres are closely linked. Rapid temperature increases in the northern hemisphere coincide with an onset of cooling in the south, and vice versa. This phenomenon is called the bipolar seesaw. Researchers are presently looking for new drill sites in Antarctica where ice up to 1.5 million years old could be retrieved. The scientists expect it to provide them with even more detailed insights, and answers to many unresolved questions about the Earth's past climate.



3.14 > A high-resolution scanner analyses this ice sample to identify microstructures.

Ozone thinning over the Antarctic, average from 1979 to 2018



3.12 > Ozone depletion over the Antarctic primarily occurs during a few months of the year. It begins in August and reaches its peak in September and October. Then, in November, the ozone concentration rises again and the hole closes.

tion into space and the associated accumulation of cold air during the polar night. It extends from the upper troposphere into the stratosphere.

The air masses at this altitude contain very little water vapour, but droplets of sulphuric acid are present that mostly entered the stratosphere at some time as a result of volcanic eruptions. At temperatures below minus 78 degrees Celsius, residual water and nitric acid condense on these droplets and freeze. Millions upon millions of acid crystals are formed. From the ground, the crystal accumulations are recognized as polar stratospheric clouds. Colloquially, this celestial phenomenon is called mother-of-pearl clouds.

These clouds are the chemical factories of the stratosphere. Chemical reactions take place on their crystal surfaces which convert the otherwise harmless propellants and refrigerants to highly reactive gases. These are stable as long as it remains dark. But at the end of the polar night, when the sun rises above the horizon again, they begin to decay and release chlorine or bromine radicals, each of which destroys many thousands of ozone molecules. Bromine is 60 to 65 times more effective in this process than chlorine. The high point of this assault by radicals above Antarctica usually occurs in mid-October, and it does not end until the sun warms up the air masses within the polar vortex, the mother-of-pearl clouds dissolve, and more ozone-rich air flows in from the mid-latitudes. The radicals then lapse into a kind of summer dormancy. They react with nitrogen dioxide, which is also brought in with the inflowing air, to form chlorine nitrate ($ClONO_2$) or bromine nitrate ($BrONO_2$), then remain inactive until the next winter.

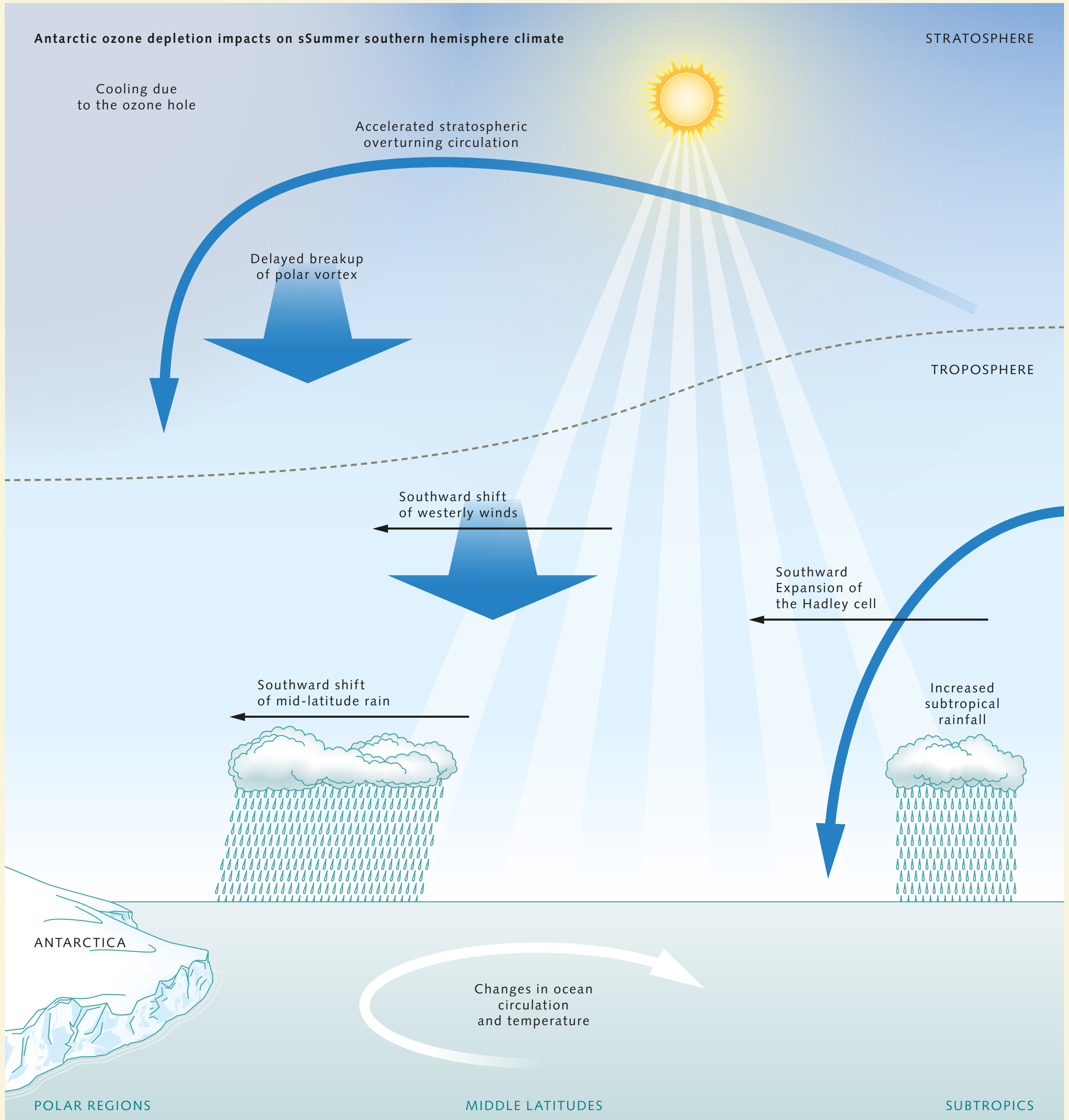
Researchers consider an ozone hole to be present when the ozone concentration in the stratosphere falls below a threshold value of 220 Dobson Units. This unit of measurement, named after the British physicist and meteorologist Gordon Dobson (1889–1976), denotes the total sum of ozone molecules in the atmosphere above a given point on the Earth. For comparison: 220 ozone molecules correspond to 220 Dobson Units, and in terms of the example calculation above this would be equal to a pure ozone layer with a thickness of 2.2 millimetres. Before the first occurrence of the ozone hole, the average ozone concentration in the Antarctic was 250 to 350 Dobson Units. Today, during the Antarctic spring, it regularly sinks to a low value of around 100 Dobson Units.

Cooling in the centre, warming on the Antarctic Peninsula

There are immediate consequences related to temperature developments in the stratosphere and the underlying troposphere when the ozone layer over the Antarctic begins to thin out near the end of the polar night. Initially, the air in the lower stratosphere hardly warms up at all. Without the ozone an important greenhouse gas that absorbs the Earth's long-wave heat radiation is missing. The air layers in the lower stratosphere are therefore now as much as ten degrees Celsius cooler than in the years before the ozone hole developed.

Since the 1990s, the cooling of the lower stratosphere has led to far-reaching climatic changes in the Antarctic region. The influence of ozone depletion is so widespread that since that time scientists have been able to attribute a large portion of the changes in the temperature patterns in the Antarctic to the ozone hole. One example of this is the slight drop of surface temperatures in the centre of the

3.15 > Mother-of-pearl clouds shimmer in rainbow colours in the sky over the Antarctic. The clouds composed of acid crystals form when temperatures fall below 78 degrees Celsius. They then trigger ozone depletion.



3.16 > In the recent past, recurring ozone depletion over Antarctica has influenced the climate of the southern polar region significantly. The lower stratosphere has cooled down, which has resulted, for example, in southward shifts of wind and rain systems.

Antarctic continent. This is because the underlying troposphere also tends to cool down more easily as a result of ozone depletion in the stratosphere.

The sustained cold in the lower stratosphere, however, also prevents a timely collapse of the polar vortex. Instead, its lifespan is increased, which also lengthens the time period of ozone depletion. At the same time, the ozone-related cooling of the lower stratosphere amplifies the temperature contrast between Antarctica and the tropics. This causes changes in the atmospheric circulation patterns. Winds in the stratosphere strengthen and the tropopause above Antarctica descends, which causes direct changes in the weather patterns. The tropopause also influences the way high- and low-pressure areas line up and expand. The band of westerly winds over the Southern Ocean has shifted further to the south, while the temperature and precipitation conditions have changed in some coastal areas of Antarctica, especially in the summer.

Since the discovery of the ozone hole in 1985, summer temperatures along the Antarctic Peninsula have risen noticeably, coincident with a retreat of the sea-ice cover. Especially in the Bellingshausen Sea and the waters to the west and northeast of the Antarctic Peninsula, researchers are recording significantly shorter periods of sea-ice cover than 30 years ago. Scientists have also discovered that storm paths and mid-latitude rains have shifted to the south in the wake of the westerly winds. Both of these phenomena influence the water temperatures and currents in the Southern Ocean. Today, for example, considerably more water is being circulated through the Antarctic than in the 1990s. Further north, in the subtropics, the Hadley Cell has increased in size as a result of the changes. It also now rains more there. The climatic impacts of ozone depletion in the Antarctic stratosphere thus extend far beyond the boundaries of the Antarctic region.

Ozone holes are rare in the Arctic

Reports of ozone loss over the Arctic are quite rare because the stratosphere in the high north is considerably warmer than in the Antarctic, and the northern polar vortex is much less stable. Thus, only in very few exceptional cases do the super-cold conditions occur that are absolutely necessary for the formation of polar stratospheric clouds. For example, scientists observed remarkably low ozone concentrations above the Arctic in the spring of 2011 and in January and February 2016, when the temperature in the stratosphere dropped to minus 90 degrees Celsius. As a result, more than a quarter of the ozone was destroyed.

An agreement is working

Overall, the concentration of ozone in the stratosphere has been increasing steadily for several years now. This positive development is a result of the signing and implementation of the Montreal Protocol of 16 September 1987. The Protocol restricts or bans worldwide the production of a range of substances that deplete the ozone layer. Model simulations have shown that without this ban on the production of ozone-depleting substances a large ozone hole would have formed over the Arctic in 2011. Smaller holes in the Arctic ozone layer would by now have become a recurring problem.

Thanks to the international agreement, the amount of ozone-depleting substances in the atmosphere has been reduced and the ozone layer is slowly recovering. Outside of the polar regions, for example, the ozone values in the upper stratosphere, at an altitude above 40 kilometres, have increased by several per cent since the year 2000. Researchers now believe that by the year 2030 the ozone layer over the northern hemisphere will recover and rise again to the levels observed in 1980. Over the southern hemisphere this process will probably take 20 to 30 years longer.

The Antarctic ozone hole has not increased in size in recent years. This positive outcome is attributable to the Montreal Protocol. The hole is still a feature of the climate system and will continue to appear in the coming years. However, it should slowly become smaller and become a thing of the past by the year 2060, provided that all of the stipulations of the Protocol continue to be met.

Retreating ice

> Where the atmosphere and oceans warm steadily, ice and snow retreat. In the polar regions, this has long since ceased to be just a theoretical concept. It is a stark everyday reality, especially in the Arctic, where the snow cover and sea ice are shrinking, glaciers are thinning, and the permanently frozen ground is thawing to greater depths. But climate change has also been impacting Antarctica for some time now, with consequences that are becoming evident on all the coastlines of the world.

The bitter truth

In science, data and facts are rarely presented in an emotionally charged way. As a rule, scientists tend to concentrate rather on presenting new findings as objectively and dispassionately as possible. It is all the more remarkable to note the strong words that climate researchers are now using to describe climate change in the polar regions. The bitter truth is that climate change has long since reached the polar regions, and it is now having a huge impact on all components of the cryosphere – the world of ice. The areas of sea ice and snow cover are shrinking; glaciers are transporting their ice toward the sea more rapidly, causing them to lose mass and retreat landward; the permafrost soils are thawing to greater depths for longer periods of time; floating ice extending from the land, such as the ice-shelf regions in the Antarctic, are being destroyed by the heat. Furthermore, all of these individual changes have direct consequences for the other components of the climate system, and the processes therefore amplify each other.

Cryosphere
Cryosphere is a collective term for all of the components of the Earth System that contain water in its frozen form. These include snow, ice sheets and glaciers, ice shelves, sea ice, and the ice on rivers and lakes, as well as permafrost, which occurs both on land and on the sea floor.

It all starts with snow

In the public debate on climate change in the polar regions, snow generally receives little attention. This is somewhat unjust because, of all natural materials, snow not only possesses the best insulation and albedo properties, but its extent, volume and stability can also determine the fate of all of the other components of the cryosphere except for submarine permafrost – snow never comes into contact with the permanently frozen floor the Arctic shelf seas.

Snow is the basic building material for glaciers and ice sheets. Where there is no snowfall, neither firn nor glacier ice can form. Moreover, in the absence of snow there is little to fend off the sun's energy. Compared to the bare glacier or sea-ice surfaces with reflectivities of 20 to 30 per cent, fresh snow reflects 80 per cent or more of the incoming sunlight. The snow therefore not only protects the ice surfaces or permafrost soils below from the warmth of the sun, it also contributes significantly to the cooling of the polar regions.

As a light and fluffy layer, snow insulates like a down jacket to protect plants, animals and the ground it covers from extreme cold. This property, however, also has disadvantages. In some situations, a snow cover that is too thick can prevent a permafrost soil that has thawed out in the summer from freezing deeply enough again in the winter. And if snow falls on new sea ice, the insulating effect can inhibit the transport of heat from the sea through the ice and into the atmosphere, and thus prevent freezing on the underside of the ice. Ice floes with snow on their surface therefore grow much more slowly than bare ice. In many regions of the world, and especially in the high Arctic, snow also acts as an important water reservoir. On the islands of the Canadian Arctic Archipelago, for example, snow banks feed small pools and wetlands with water well into the summer.

In the Arctic, snow can cover vast landscapes for as much as nine months of the year. The thickness of the snow layer as well as the duration of the snow season depend mainly on the air temperature and the amount of precipitation. Researchers therefore note that, as a result of climate change, the snow conditions will change fundamentally and in very different ways around the globe. In order to accurately track this development, the scientists record three parameters: the area of the snow-covered surface, the duration of the snow season, and the water equivalent, which is the amount of water stored in the snow.

Although there can be large differences in the individual parameters from year to year, scientists have observed some important trends in the Arctic that will become even more pronounced in the future:

Smaller total area, earlier melting

As a response to the rising air temperatures, the total area that is covered by snow today is shrinking because snow is now falling in fewer areas than it did 15 years ago. In addition, the snow now begins to melt much earlier in the year over much larger areas of the northern hemisphere, especially in the Arctic. During the period from 1967 to 2012, the area still covered by snow in the northern hemisphere in the month of June decreased by an average of 53 per cent. This means that large areas of the Arctic are also snow-free, and thus do not reflect solar radiation for extended periods of the year. This trend is confirmed by an additional development: The length of the snow season in the northern hemisphere has decreased by an average of 5.3 days per decade since the winter of 1972/1973. In northern Europe and Asia, the decrease has been as much as 12.6 days per decade.

More snow in Siberia

In northern Europe and Asia, much more snow falls today than it did in the past. This change has had a significant effect on the temperature of the Siberian permafrost soil. It is rising gradually because the growing snow cover prevents the ground from freezing deeply in the winter.

Less snow on the sea ice

The snow cover on Arctic sea ice is diminishing. This trend is due to the fact that the sea ice now begins to form much later in the year. As a result, the early autumn snow no longer falls on new sea ice but into the open ocean, and is thus lost as a reflective layer on the sea ice. Measurements of snow depth show that young sea ice today has a thinner snow cover than in the past. This means that the protective layer also melts away faster in the spring and exposes the sea ice to direct incoming solar radiation earlier than before. The consequences are unmistakeably clear: The sea ice melts earlier, the ocean has a longer period of time to warm up, and the formation of new ice in autumn is further delayed.

Alternating rain and snow

As a result of global warming there is an increased probability of sudden heat surges and periods of melting during the Arctic winter. At these times, precipitation often falls in the form of rain, which, along with repeated melting, also changes the physical properties of the snow.

According to current climate models, the snow conditions will change considerably in a warmer world. In coastal regions such as Alaska and Scandinavia, the area of snow cover and the total amount of snow will decline drastically. Furthermore, the duration of the snow season will shorten all across the Arctic. Only in a few regions of the Arctic, particularly in Siberia, will more snow fall. As a result of the thicker snow cover, however, the ground temperature will also increase in these regions, and the permafrost soil will thaw to greater depths. Plants will therefore have better chances of survival, which leads researchers to expect that vegetation will grow better on the Siberian tundra in the future.

Herbivorous mammals such as caribou, reindeer and musk oxen, on the other hand, will face harder times because it will rain more frequently during the winter. When rain falls on the snow, an ice layer forms that is very difficult for the animals to break through. Multiple ice layers in the snow cover effectively prevent the animals from obtaining their winter food. Short heat spells in winter and the accompanying rain can also damage the vegetation.

The water cycle in the high Arctic will also change. Today, scientists are already observing the complete melting of important snow banks in the spring, which are then absent as water reservoirs in the summer. This problem will continue to become more critical, and will exacerbate the summer dryness in the affected regions. In Siberia, on the other hand, the rivers are increasingly overflowing their banks in spring because the amount of snowfall is increasing and the melting process is accelerating. The snow conditions in the Arctic are therefore changing dramatically in the wake of climate change, and are leading to permanent changes in the climate, ecosystems and for people.

The sea ice makes room

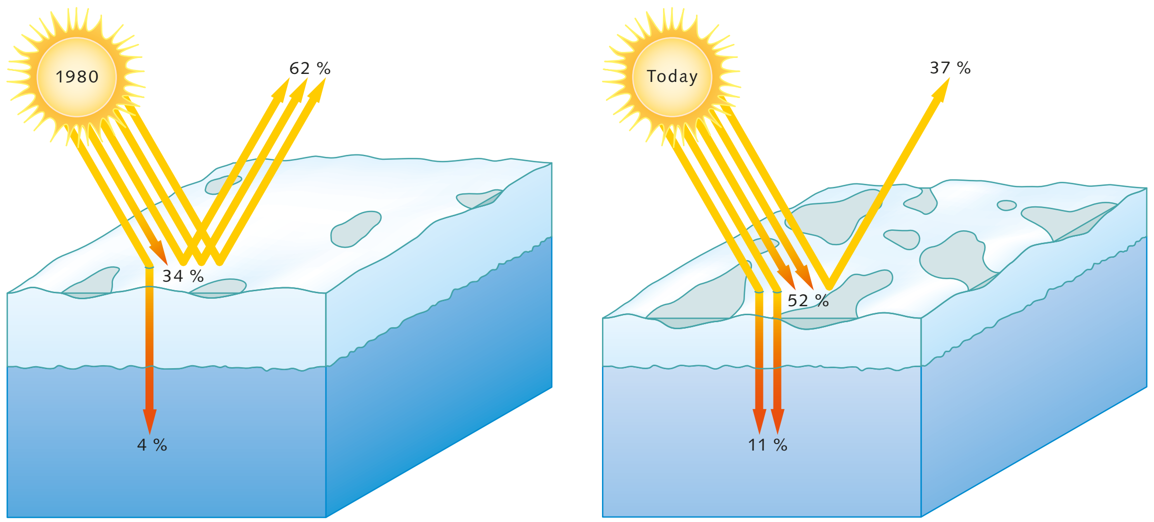
The areas of sea ice in the polar regions react very sensitively to climatic changes. If the geographical range of sea ice increases, it is an indication that the planet is cooling down. But if the area of ice shrinks, it is a sign of global warming. For this reason, climate research also focuses on sea ice. It plays a key role in the Earth's climate system. Where sea ice forms or covers the ocean surface, three things happen:

- Sea ice reflects the incoming solar radiation and this cools the Earth's surface.
- During its formation it releases brine, stimulating the circulation of water by increasing the density of the underlying water masses so that they sink.
- As an insulating cover, it limits the exchange of gases and heat between the ocean and atmosphere, and prevents the wind from mixing the surface waters, which would allow heat from the deeper ocean layers to be released into the atmosphere.

Regional changes in sea-ice cover therefore have an impact not only locally, but usually also at the global level, triggering a number of subsequent processes, the scope and complexity of which are not yet fully understood.

The amount of sea ice in the Arctic has been measured by satellites since 1979. Ocean areas with an ice concentration of at least 15 per cent are considered to have a sea-ice cover. This means that when ice covers 15 per cent of the area of the water surface. The lateral extent of areas covered by sea ice varies with the seasons. In the month of March, at the end of the Arctic winter, the sea-ice cover is generally two to three times as extensive as it is at the end of summer in September. Scientists therefore pay particular attention to the range of sea ice in these two months. The maximum extent of ice in winter and the smallest area of ice in summer are critical parameters for monitoring the development of sea ice over time, which now exhibits a negative trend throughout the Arctic.

As a result of the rising air and water temperatures in the Arctic region, the total area of sea ice over the past four decades has decreased by more than 30 per cent. This decline has occurred not only for all seasons, but also in every region of the Arctic Ocean, and is almost twice as apparent in the summer as in winter. The wide-scale melting of the ice can be attributed mainly to temperature changes in the spring and summer. The melting



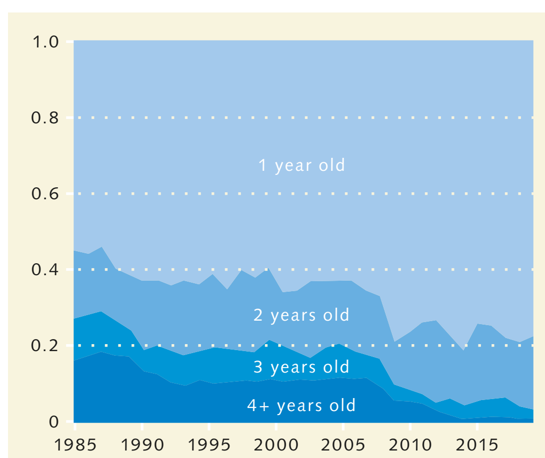
3.17 > The sea ice in the Arctic is thinner today than it was in the 1980s, and larger portions of it are covered by meltwater pools. These two factors lead to increased absorption of solar energy by the ice cover and the ocean below, which further reinforces the decline of sea ice.

3.18 > The wind blows snow out to sea from the surface of Greenland's Petermann Glacier. Meanwhile, sea ice accumulates in front of the glacier's edge, giving the ice tongue additional stability.

3.19 > The European Earth-observation satellite CryoSat-2 is one of the most important instruments used for international sea-ice research. It carries a special radar altimeter that measures the thickness of the Arctic and Antarctic ice from an altitude of 700 kilometres.

season now begins somewhat earlier in the year but, more importantly, it ends much later. So the melting season is lengthening appreciably – by five days every decade. In some marginal seas of the Arctic Ocean the sea ice now melts for eleven days longer each year than it did a decade ago.

Over the past twelve summers (2007–2018), the ice cover has shrunk so much that these years constitute the top 12 on the record-low list. In numbers: The September extent of Arctic sea ice is presently declining by 12.8 per cent each decade. Between 1997 and 2014, this corresponded to losses of 130,000 square kilometres per year. So, on average, the Arctic Ocean annually lost an area of ice equal to the size of Greece. In September 2018 the total area remaining was 4.59 million square kilometres.



3.20 > There is now hardly any Arctic pack ice more than four years old.

The shrinking sea-ice cover in the Arctic region is one of the most visible changes to the Earth's surface over the past three decades. Scientists even go so far as to say that, due to global warming, the Arctic no longer transforms into an extreme ice world in winter as it once did. This statement is certainly true in the case of sea ice, because the white ice cover of the Arctic Ocean is not only shrinking in size, it has also become much thinner, and the ice itself is much younger than in the past.

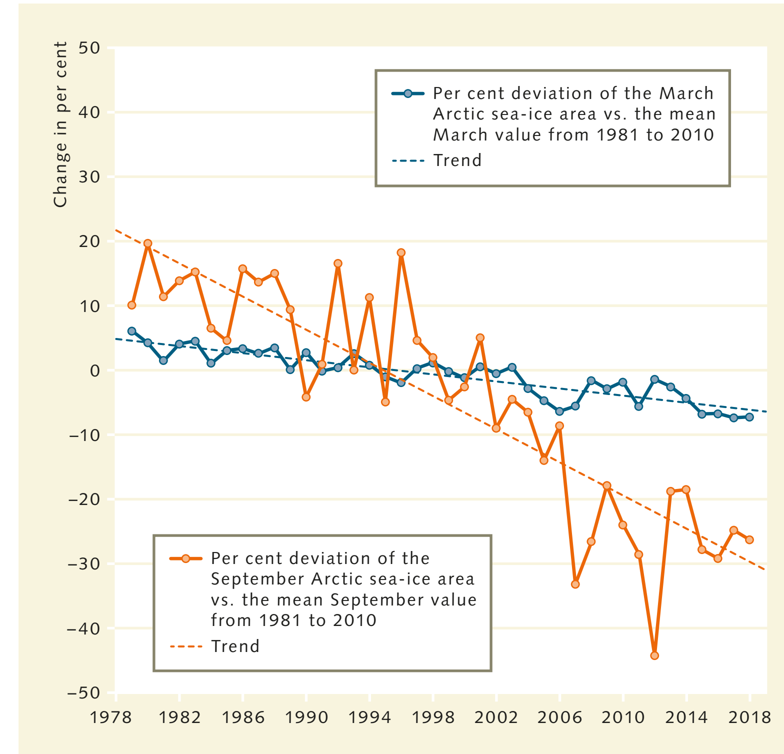
In 1985, researchers also began to measure the thickness and therefore, by proxy, the age of the Arctic sea ice. For the sea-ice-maximum month of March of that year, 2.54 million square kilometres, or 16 per cent, of the ice area fell into the category of "multiyear" ice. This ice had survived more than four summers and was up to four or five metres thick. At the same time of year in 2018, the proportion of multiyear ice was only 130,000 square kilometres, or 0.9 per cent of the ice area. This means that over the past 33 years, the area of thick multiyear ice has decreased by 95 per cent. The major proportion of Arctic sea ice today, 77 per cent to be precise, is no older than one winter.

Measurements by the Earth-observation satellite CryoSat-2 determined that the Arctic sea ice had an average thickness of 2.14 metres at the end of the winter of 2017-2018. Because the satellite has only been in operation since 2010, long-term comparisons of the sea-ice thickness are not possible. The total range of ice thickness within the time frame of measurements so far is 2.03 to 2.29 metres for the month of April. The winter of 2017/2018 therefore falls near the midpoint of this range. Nevertheless, the structure of Arctic sea ice has fundamentally changed. Instead of a several-metres-thick, multiseasonal, and almost impenetrable pack-ice cover, a thin, fragile layer of ice is floating on the Arctic Ocean today.

More susceptible to wind and waves

The thin ice layers are not only more susceptible to rising air and water temperatures. Wind and waves can also break them apart more easily – a phenomenon that until now was more commonly seen in the Antarctic region. But scientists are also now observing the destructive effects of wind and waves on the Arctic sea ice.

In September 2009, for example, scientists observed waves that had formed on the open sea and then travelled up to 250 kilometres into the ice-covered region, where they broke up thick, perennial floes around one-kilometre long into smaller pieces measuring 100 to 150 metres. This fragmenting process made the ice more mobile and, as a result, it probably melted faster. The fact that young sea ice is now observed more frequently on the Arctic Ocean in the form of pancake ice also indicates an enhanced influence of the wind. These plates of ice, which are formed by wave action, were more commonly known in the past from the Antarctic region. There, the winds over the Southern Ocean always have a sufficient distance and ice-free water surfaces necessary to produce waves, which then transform the newly produced ice plates and needles in the coastal areas into pancakes. In the Arctic Ocean, however, similar expanses of open water have



3.21 > The Arctic sea-ice cover usually reaches its maximum lateral area in March, and then shrinks to its smallest size in September. It is evident that the areas of seasonal sea-ice cover are shrinking. The total loss is greater in summer than in winter.

been relatively rare in the past. But now researchers on winter expeditions to the Arctic waters are encountering this conspicuous type of ice more often, particularly in the western Arctic. In the Beaufort and Chukchi Seas, for example, the sea now freezes one month later than it did at the beginning of ice observations. This gives the wind sufficient distance and opportunity to set waves into motion on the water.

There is also another new development: To some extent, the young, thinner, and thus lighter sea ice drifts faster across the Arctic waters than the older heavy pack ice. One reason for this might be that the wind does not need to be as strong to push the ice around. However, there must be other influencing factors, because wind speed and direction alone are not enough to fully account for the ice movements.

Future Arctic sea ice only in winter?

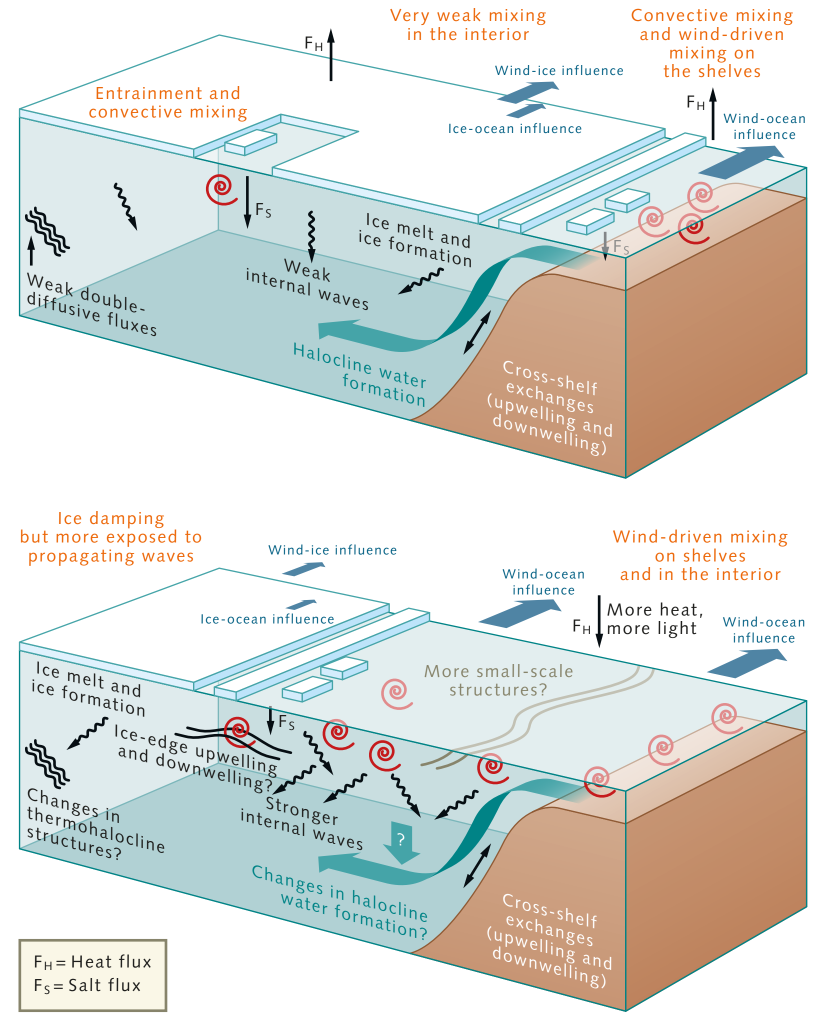
When fractures open up the sea-ice cover, or when polynyas form or large areas of sea ice melt, the ocean and atmosphere come into direct contact. Heat can be exchanged, water can evaporate, and the wind can set the sea in motion. Scientists therefore understand that the driving forces in the Arctic Ocean current system will change in the future, at least during the summer. In the past, during the formation of sea ice, the salinity and temperature of the water masses have primarily determined where they flowed or how they were layered (thermohaline circulation), but in the ice-free phases of the future, the wind will play a larger role. It will mix the upper water layers more often, accelerate surface currents, and amplify heat exchange with the atmosphere, at least during the transitional periods of spring and autumn. But in the winter, when the sea ice spreads out, the influence of the wind will diminish again.

No one doubts that sea ice will continue to form on the Arctic Ocean in the future. The differences between the seasonal maximum and minimum of sea ice, however, will increase. Large areas of the Arctic Ocean will freeze over in the winter, but in the subsequent summer the ice cover will melt again to a large extent. Following this pattern in the future, the seasonal sea-ice conditions in the Arctic Ocean will become more similar to those in the Southern Ocean.

It is not possible to precisely predict by what year the Arctic Ocean might be ice-free for the first time. Most climate models forecast that the ice will completely melt some time around the middle of the 21st century, although polar researchers have a different understanding of "ice-free" than the general public. From a scientific perspective, the Arctic Ocean is considered to be "ice-free" when the total area of ice is less than one million square kilometres. This definition, which at first glance seems unusual, has a logical rationale: The presence of sea ice is not limited to the central Arctic Ocean, it also occurs along the coasts of the surrounding coastal states, as well as in the many small straits and sea routes of the Canadian Arctic Archipelago. This near-coastal ice, as a rule, is thicker than the floes on the open ocean, and will presumably persist much longer than the ice cover in the central Arctic Ocean. In order to account for this fact and still be able to make meaningful predictions, the scientists have chosen the threshold value of one million square kilometres as the parameter for a virtually ice-free Arctic Ocean.

The danger of falling below this threshold increases with the rise of average global temperature. In its special report of 2018, the Intergovernmental Panel on Climate Change concluded that with a global warming of two degrees Celsius, the Arctic Ocean will be ice-free in summer for the first time around ten years from now. If humankind is able to limit the warming to 1.5 degrees Celsius, however, it could be 100 years before the sea ice in the central Arctic disappears in summer, and for the total area to fall below the limit of one million square kilometres.

3.22 > In the past, researchers encountered pancake ice only in the Antarctic. But now the winds and waves have enough room and the opportunity to create these characteristic deformations.



3.23 > When Arctic sea ice melts, the air and sea come into direct contact with one another. Heat, wind and waves are thus able to significantly alter important processes within the water column.

Antarctic enigmas

In contrast to the Arctic, the seasonal sea ice in the Antarctic region has continued to expand since the beginning of satellite measurements. Record-breaking reports of a winter ice cover of 20.1 million square kilometres made worldwide headlines in 2014, mainly because Antarctica at that time appeared in stark contrast to the shrinking ice cover in the Arctic. While the decline in sea ice in the far north was very pronounced at that time with increasing global temperatures, the contrasting developments in the Antarctic posed a mystery for the researchers and, in the public eye at least, the hope arose that the southern polar region might be spared the consequences of global warming.

This optimism, however, turned out to be unjustified, because the ice cover was only growing in certain regions of the Antarctic, including the Ross Sea, where researchers recorded an increase in ice surface of 5.2 per cent per decade. In the Bellingshausen and Amundsen Seas, on the other hand, the sea ice decreased by 5.1 per cent during the same time period. There were also conflicting developments in the duration of the ice season. While the sea ice began to melt much later in the summer in the Ross Sea, it returned earlier and earlier in the marine regions of West Antarctica. In the Weddell Sea, the researchers even observed both of these trends: In some areas the extent of sea ice expanded and in others it shrank. However, the Antarctic-wide growth was enough to turn the overall balance into a plus by 2014.

There was an abrupt turnaround two years later, in the winter of 2016, when the Antarctic sea ice attained a total area of only 18.5 million square kilometres. Since that time, the area of sea ice in Antarctica has been shrinking. On 1 January 2019, scientists reported a new record low of 5.47 million square kilometres – the smallest area of January ice since the beginning of satellite measurements 40 years ago. Even in the Ross Sea, which normally has a very heavy ice cover, there were areas of ice-free water at this time.

The reasons for the decreasing areas of sea ice in the Antarctic during winter, and for the present rapid melting in summer, are now the subjects of intensive research. A new theory by US researchers proposes the occurrence of natural current fluctuations in the Southern Ocean with a cycle of 30 years. Their study indicates that convection and deep-water formation weakened in some regions of the Southern Ocean between 1980 and 2000. Heat from the intermediate water was therefore trapped in the deep ocean and not able to reach the surface. At the same time, the surface water cooled down, creating ideal conditions for the formation of sea ice in spite of global warming.

Now, however, there is evidence that the overturning of water masses in the Southern Ocean is strengthening again. This could allow the intermediate water, as well as the heat trapped at depth, to rise to the surface and cause the ice to retreat again. If this assumption is correct, the sea-ice cover would again decrease, because the temperature of the intermediate water is increasing.

Other scientists argue that the influence of the atmosphere cannot be overlooked in the search for the causes of diminishing sea ice. The loss of sea ice in the Bellingshausen and Amundsen Seas can be readily explained by the weakening of cold winds that blow over the Southern Ocean and caused wide-scale freezing of the surface waters in the past. Changes in wind patterns could also explain the disproportionate increase of sea ice in the western part of the Ross Sea up to 2014.

A discussion is also underway regarding the effects of melting glaciers and ice sheets. Might this have had a cooling effect on the surface waters in recent decades? Have the surface waters been permanently diluted by the meltwater? Other questions include the role of decreasing ozone concentrations, and the impact of atmospheric changes in the tropics on climate processes in the Antarctic region.

As yet there are no clear answers to these questions, in part because comparatively little measurement data is available from the Southern Ocean. Thicknesses of the Antarctic sea ice, for example, are only known from isolated sampling. A further complicating factor is that climate models have not yet been able to correctly simulate the patterns of sea-ice development in the Antarctic region. For this reason, there are still no predictions for its fate in the future. In its special report on the 1.5-degree target, the Intergovernmental Panel on Climate Change therefore deliberately avoided making any predictions about the future of Antarctic sea ice in a world that is two or 1.5 degrees Celsius warmer.

But such predictions are urgently needed. Firstly, because the sea ice protects the large ice shelves in a variety of ways. And secondly, because it is an important habitat component for the animals that inhabit the Southern Ocean – the small ones like krill, whose larvae spend the winter on the underside of the ice, as well as the larger emperor penguins or Weddell seals who use the sea ice as natural resting areas and nursery grounds for their offspring.

Permafrost – keeping the frozen ground solid

If there is anything the people in the Arctic regions have been able to rely on in the past, it is the load-bearing capacity of the ground. Wherever freezing cold prevailed in winter and the snow cover was too thin to protect the soil from frost, the ground froze to such great depths that it only thawed a little near the surface during the short Arctic summer. Buildings, streets and pipelines rested on a solid foundation of sand, rocks and animal and plant remains, all stabilized by the ice.

These permanently frozen grounds of the polar regions are called permafrost, although the scientific definition is somewhat more specific. This says that all grounds are considered to be permafrost that consistently remain at temperatures of zero degrees Celsius or colder for at least two consecutive years. Permafrost is thus also found in mountain ranges outside of the high northern latitudes, for example in the high regions of the Alps, from elevations of 2500 to 3000 metres, depending on the direction in which the slope faces. The ground temperature of these mountainous permafrost areas is usually above minus three degrees Celsius. Permafrost areas are also found in the highlands of Tibet, in the Andes, and in the non-glaciated regions of Antarctica.

Specialists distinguish between regions with continuous permafrost, which are most common in the Arctic, and areas of discontinuous permafrost. For the former, the ground is frozen on the order of 90 to 100 per cent of its area. In regions of discontinuous permafrost, this value is only 50 to 90 per cent of the land area. Landscapes in which the proportion of permafrost cover is less than 50 per cent are referred to as areas of sporadic permafrost.

20 years ago, scientists added the areas of all the world's permafrost regions together and obtained a total of around 22.8 million square kilometres. This is equal to 24 per cent of the land area of the world. The thickness of the frozen soil layers varies worldwide from less than one metre to several hundred metres. In some extreme cases in central Siberia, the permafrost can have a thickness of up to 1600 metres, but this is only found in regions where there is little geothermal energy. The lowest average annual ground temperature ever measured in the Arctic permafrost was minus 15 degrees Celsius, recorded in the Canadian Arctic Archipelago.

A legacy of past ice ages

Thick permafrost layers are a legacy of the ice ages of the past. These are found in areas that were not covered by glaciers during the past cold periods and, except for a thin layer of snow, their soil has been directly exposed to the icy polar temperatures for thousands of years. As a result, these landscapes are still interspersed with deep ice wedges today. These wedges are formed when the permanently frozen ground contracts in winter and fractures open in some places. When the snow melts in spring, meltwater flows into these fissures. With a ground temperature of around minus ten degrees Celsius, the water freezes rapidly again and expands. When this process is repeated over a number of consecutive years, huge wedge-shaped bodies of ice are formed.

In the Siberian Arctic, ice wedges up to 40 metres deep and six metres wide have formed in the ground,

3.24 > Geoscientists from the German Alfred Wegener Institute having a lunch break. In the background is the steep coast of Siberia with its ice wedges.

3.25 > When the freezing temperatures of winter leave fissures in the permafrost of Spitsbergen, meltwater streams deposit water, small stones and other flotsam in the spring. If the water in the cracks then freezes to ice, it expands and pushes all of the deposits outward. Distinctive ring patterns are created in this way.

some of which comprise ice that is is more than 100,000 years old. They permeate the ground like a network and can be easily recognized in aerial photographs as a net-like pattern. In these areas, 40 to 90 per cent of the sub-surface consists of ice. Scientists refer to permafrost ground with this kind of high ice content as yedoma. Today, it is widespread in the lowlands of Siberia, Alaska and western Canada, but has also survived as submarine permafrost in those Arctic coastal regions that were dry during the ice ages and flooded again later.

When meltwater in the ground freezes to ice, it expands and increases its volume by around ten per cent. Because of this, ice in permafrost regions can expand upward out of the ground to form small hills. Ice hills formed in this way are called pingos, and they occur most commonly in Alaska and north-western Canada. They can also be thousands of years old. Like ice wedges, they exist in part because of the alternate freezing and thawing in the Arctic.

How permafrost responds to warming

As already stated above, the summers in large areas of the Arctic are warm enough to partially thaw permafrost grounds near the surface. Depending on the characteristics of the soil and the local climate conditions, the heat penetrates and thaws the ground to a depth of 20 to 200 centimetres. This upper layer of soil that thaws in summer and regularly freezes again in winter is called the “active layer”. In both the High Arctic and in the tundra its thickness depends primarily on the air temperature and the amount of snow cover. The less snow that falls in winter, the better the cold air is able to cool the permafrost. Scientists refer to this as a climate-controlled permafrost. The further south one moves, the warmer it becomes, and permafrost can only persist in those areas where the vegetation cover or peat deposits insulate the ice in the ground and protect it from the warm air. German researchers have observed the effectiveness of this protective function in the Siberian larch forests.

Unlike pines and spruces, the Siberian larch *Larix gmelinii* has a very shallow root system. This tree can thrive with a summer thawing depth of only 20 to 30 centimetres. Its dense carpet of shallow roots forms a protective layer for the permafrost below, so that in the past, during the transition from cold to warm periods, it often took thousands of years for the permafrost to disappear on a large scale and for the Siberian vegetation to adapt to the warmer climate conditions. Yet the insulating effect can still be recognized today. In regions where deforestation of the larch forests has been carried out, the permafrost thaws much faster than in the forested areas.

When the snow melts and the permafrost thaws, meltwater accumulates near the surface because the frozen layer below prevents it from percolating downward. The resulting thawed layer thus contains very large proportions of water and is highly mobile. This can lead to large-scale landslides and erosion, especially in the tundra and even on relatively small slopes. In other places the subsurface can collapse or subside because the supporting ice disappears.

These kinds of heat-related changes in the permafrost have been observed since the late 1960s in many places in the Arctic, as well as in some high mountainous regions. Now the large-scale thawing and retreat of permafrost is

3.26 > The Dahurian larch has such a shallow root system that it can grow in the thin active layer of the permafrost.

High Arctic
The polar desert regions of the Arctic are called the High Arctic. They are mainly found on Greenland, in the far north of Siberia, and in the Canadian Arctic Archipelago. In contrast to the tundra, trees and shrubs no longer grow here, only specially adapted ground-cover plants. The average temperature for the month of July in these regions is five degrees Celsius.

considered to be one of the most distinctive signs of climate change. In Alaska, for example, the summer heat now persists for so long that the active layer refreezes two months later in the year than it did 30 years ago. Furthermore, in many parts of the Arctic the ground thaws to greater depths in the summer, allowing shallow-rooted trees like larches to expand northward. In British Columbia, Canada, researchers today have to travel about 25 kilometres further up the Alaska Highway than they did in 1964 before they encounter frozen ground, because the southern boundary of the permafrost zone is steadily migrating northward. Recent studies have concluded that the total area of ground that is inundated with permafrost has shrunk from just under 23 million square kilometres in 1999 to the current 19.9 million square kilometres.

Distinct changes can also be seen in the deeper subsurface. Long-term measurements of the global permafrost network indicate that in all areas with permanently frozen soils, the temperature of the frozen subsurface at depths below ten metres rose by an average of 0.3 degrees Celsius between 2007 and 2016. These include the regions of the Arctic and the Antarctic as well as the high mountain ranges of Europe and central Asia. The warming in north-western Siberia was even more extreme. There, the frozen ground deeper than ten metres warmed by almost one degree Celsius at some of the measurement stations. Significant warming is also becoming apparent in the permafrost regions of the high mountains and in the Antarctic. The ground temperatures in the Alps, the Himalayas and in the mountains of the Nordic countries rose by an average of 0.19 degrees Celsius. In the few deep boreholes in the Antarctic, researchers recorded an increase of 0.37 degrees Celsius. Based on these measurements, the soil temperature of the permafrost is rising in relation to the rate of global warming, and is thus effectively changing the character of the polar regions, especially the Arctic.

Thermal erosion
Thermal erosion is a dynamic process by which material is first liquefied through the effect of heat (melting of ice) and then transported away. In the permafrost regions, this transport is usually implemented by water.

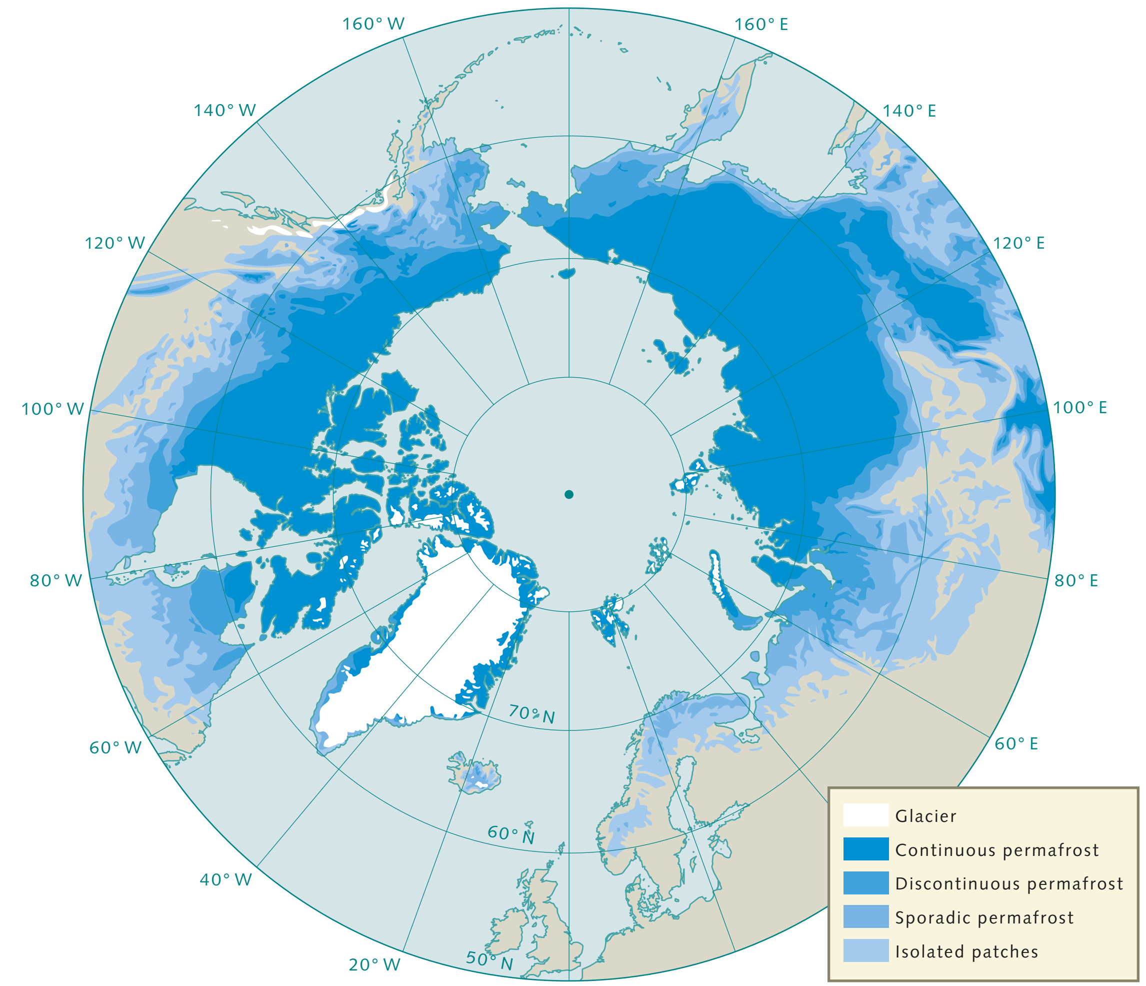
A temporary lake landscape

Tundra areas where the ground ice is disappearing can be recognized by depressions suddenly forming in the ground where ice wedges once grew. In the winter, deep snow initially collects in these depressions, insulating and protecting the subsoil from deep freezing. Then, in the spring and summer, meltwater from the surrounding areas flows into the hollows. A small pond is created that absorbs more solar energy than the surrounding land areas due to its relatively dark water surface. At the bottom of the pond and around its edges, the heat of the water is effectively transferred to the ground below. This results in further thawing of the permafrost near the pond.

The more ice the ground contains, the more pronounced this effect is. Over time, from the original small pond, a larger freshwater body called a thermokarst lake forms, which, when it reaches a depth of around two metres, will no longer completely freeze in winter. As a result, the water at the bottom of the lake remains above the freezing point all year long, and this eventually causes further expansion of the thawing zone beneath the lake.

At some point, the ground thaws to a depth such that the subsoil is no longer impermeable to the lake water. It then seeps to greater depths and the lake drains out. Researchers also frequently observe the formation of small furrows on the banks of thermokarst lakes, through which the water gradually drains off. This flowing water can thaw the surrounding subsoil so extensively that large-scale erosion becomes possible. Specialists call this process thermal erosion. The water masses trigger landslides and carry so much soil material that the original small channels rapidly expand to become larger valleys, and these can also drain the lakes within a few hours to days.

The formation of thermokarst lakes in a permafrost region, therefore, and their destruction as well, are indicators of fundamental change in the permanently frozen ground. A team of scientists from Germany and the USA used these features to identify where the permafrost landscape areas are changing throughout Alaska, Canada and Siberia, by examining satellite images observed from 1999 to 2015. Their findings reveal an expansive deterioration of ice in the soil – in regions with continuous permafrost as well as in areas where the permafrost is discontinuous or sporadic.



3.27 > Geoscientists have divided the permafrost regions of the northern hemisphere into four zones. These are distinguished based on the extent to which the ground is frozen.

In the eastern Siberian region of Central Yakutia, for example, the total area of thermokarst lakes increased by 50 per cent during the study period – an observation that is consistent with observations in other areas with continuous permafrost. On the southern margin of the permafrost region, however, in the zone of sporadic or discontinuous permafrost, more and more of these lakes are emptying out. Researchers have found evidence of this in western Alaska, among other places. Nevertheless, it is difficult to draw objectively valid conclusions regarding a general increase or decrease in the number of lakes. The extent of thermokarst formation depends primarily on the local conditions of weather, soil and climate, which vary greatly from region to region in the Arctic.

Crumbling coasts

The amount of thermal erosion, especially along the permafrost coasts and on river banks, is particularly disturbing. Where the permafrost warms or even thaws as a result of rising air temperatures, the erosive processes of streams and rivers as well as the waves of the sea are much more effective. They undercut the banks or coastal areas, transport the loose material away, and scour their way inland, slowly but surely. On a steep cliff along the Itkillik River in northern Alaska, researchers recorded erosion rates of 19 metres per year from 2007 to 2011. The 700-metre-long and 35-metre-high cliff retreated a total of up to 100 metres during this time.

Catastrophic fires in the tundra

Land subsidence (thermokarst) and thermal erosion can also be caused by forest and tundra fires. These fires destroy the insulating layers of humus, peat, grass and roots that protect the permafrost, and thus effectively accelerate its thawing over the long term. In northern Alaska, for example, after the large Anaktuvuk River fire of July 2007, the land surface subsided more than one metre in some places within a period of seven years due to the formation of thermokarst.

3.28 > Smoke clouds over the Yukon Delta National Wildlife Refuge in south-western Alaska. In June 2015 two tundra fires raged at the same time in the region.

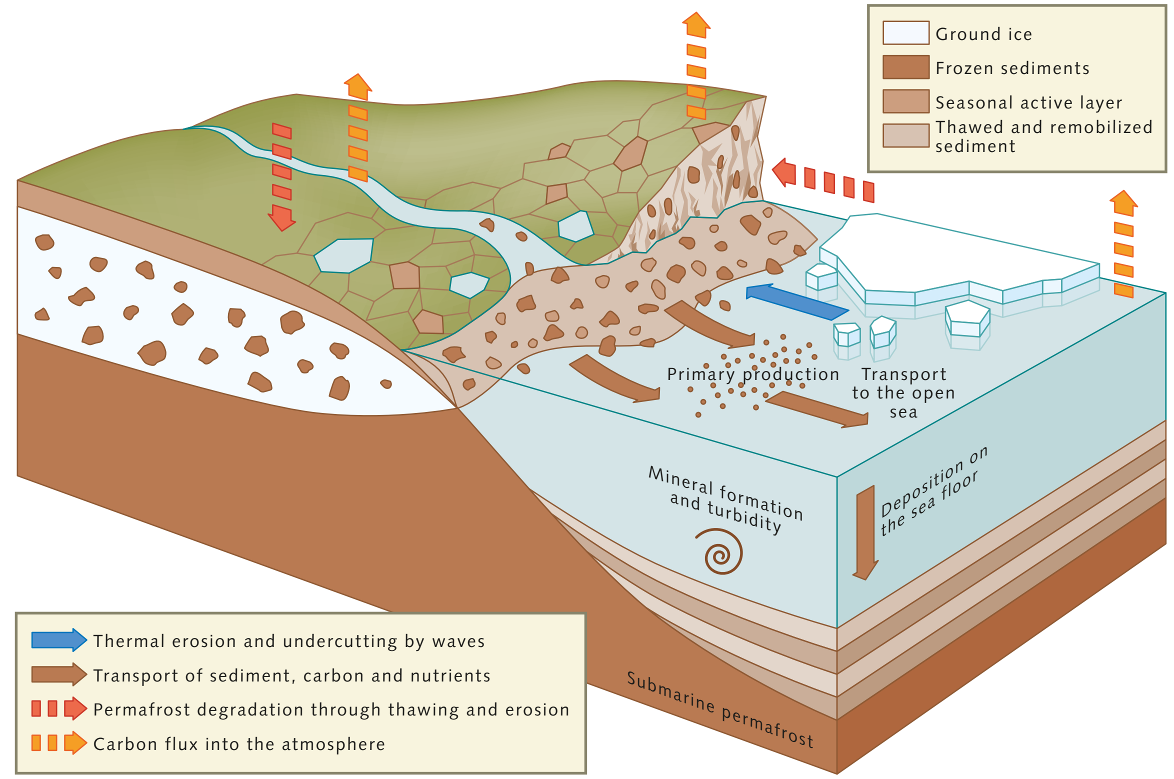
The fire in the tundra was ignited by lightning during the unusually warm and dry summer of 2007, and by the time of the first snowfall in October it had devoured an area of 1039 square kilometres. Investigations following the fire determined that it was the largest wildfire in Alaska's tundra in 5000 years.

Over the past several millennia, thunderstorms have been rare in the North Slope region, as the tundra landscape of northern Alaska is called. For most of the time, the polar air over the region has simply been too cold for the formation of thunderstorm clouds. And when fires did occasionally occur, they were limited to comparatively small areas. But due to the heat and dryness of the summer of 2007, the Anaktuvuk River fire destroyed more tundra in one fell swoop than all of the North Slope fires in the previous five decades combined.

Researchers consider the cause, scope, and above all the duration of the fire to be clear signals of a transformation in the tundra that they attribute primarily to climatic change. The rising air temperatures in the Arctic increase the danger of thunderstorms and the probability of lightning strikes that can trigger fires. At the time of the fire there had already been a recognizable increase in lightning frequency in the official United States lightning statistics. Furthermore, the winter snow cover in Alaska is now melting much earlier. For that reason, Alaska's fire officials had already moved the beginning of the annual forest fire season forward from 1 May to 1 April in the year before the big tundra fire.

Forest and tundra fires ignited by lightning strikes have the potential to fundamentally change the landscape of the high Arctic, and to trigger a climatic chain reaction. Once the tundra is burning, huge amounts of the greenhouse gas carbon dioxide are released. More than two million tonnes of carbon dioxide were released into the atmosphere during the burning at the Anaktuvuk River. This is approximately equal to one month of CO_2 emissions from a city the size of Las Vegas. In addition, the fire left behind a dark, burnt earth that had between 50 and 71 per cent less reflective capacity than an undisturbed tundra, and that absorbed so much solar radiation in the subsequent years that the underlying permafrost thawed to deeper levels, and the landscape subsided over about one-third of the burnt surface.

Similar consequences for frozen soils have been observed by experts following fires in forests with near-surface permafrost, which are abundant in Alaska. In these areas, the ground temperatures generally rose so rapidly and substantially after a fire that permafrost was no longer detectable three to five years later.



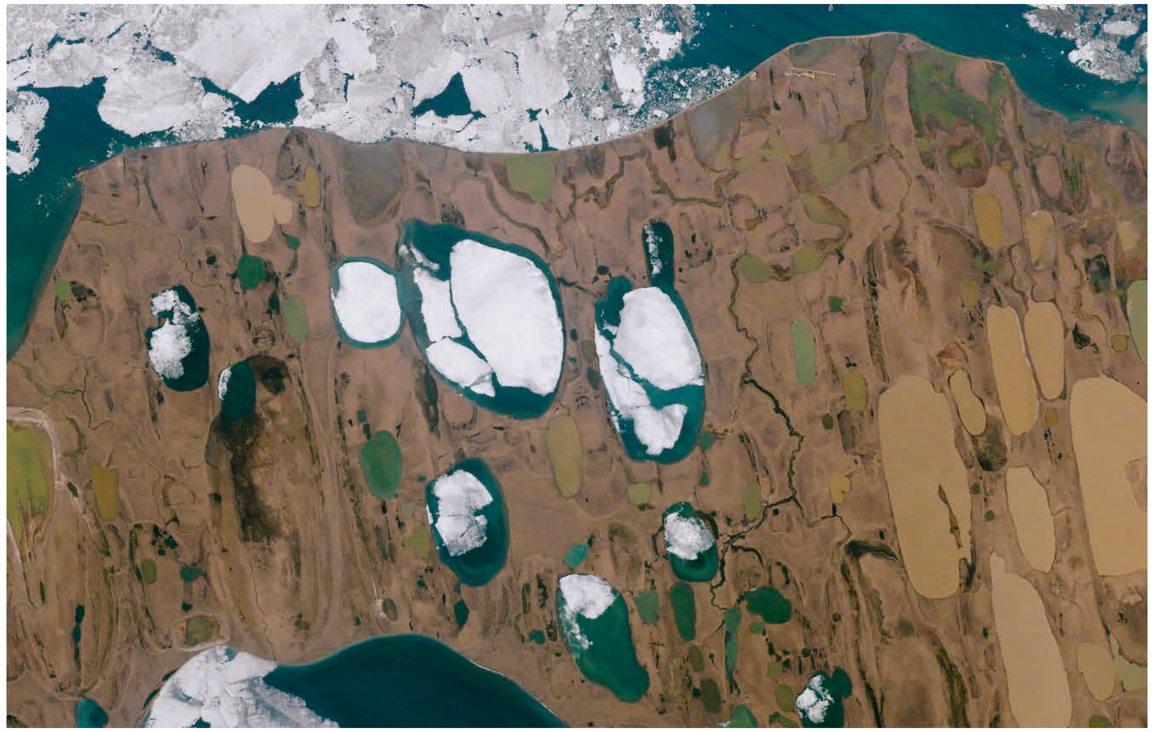
3.29 > Rapid thawing of permafrost soils often results in intensified erosion along the Arctic coasts, and causes permanent changes to sea life. Rivers and waves wash large amounts of mud into the sea, creating more turbidity in the shallow-water areas. At the same time, nutrients and pollutants contained in the material are also released. The long-term consequences of these developments are the topic of current research.

Erosion on the Arctic coastlines averages 50 centimetres each year. But this value is much greater in areas where there is less sea ice, which would otherwise protect the coasts from the destructive power of wind and waves, and in areas where the active layer of the permafrost thaws ever deeper due to warmer air temperatures, resulting in more frequent landslides, especially on steep coasts. On these parts of the coast the waves are now undercutting the slopes so effectively that large blocks of land break off from the coast with increasing frequency.

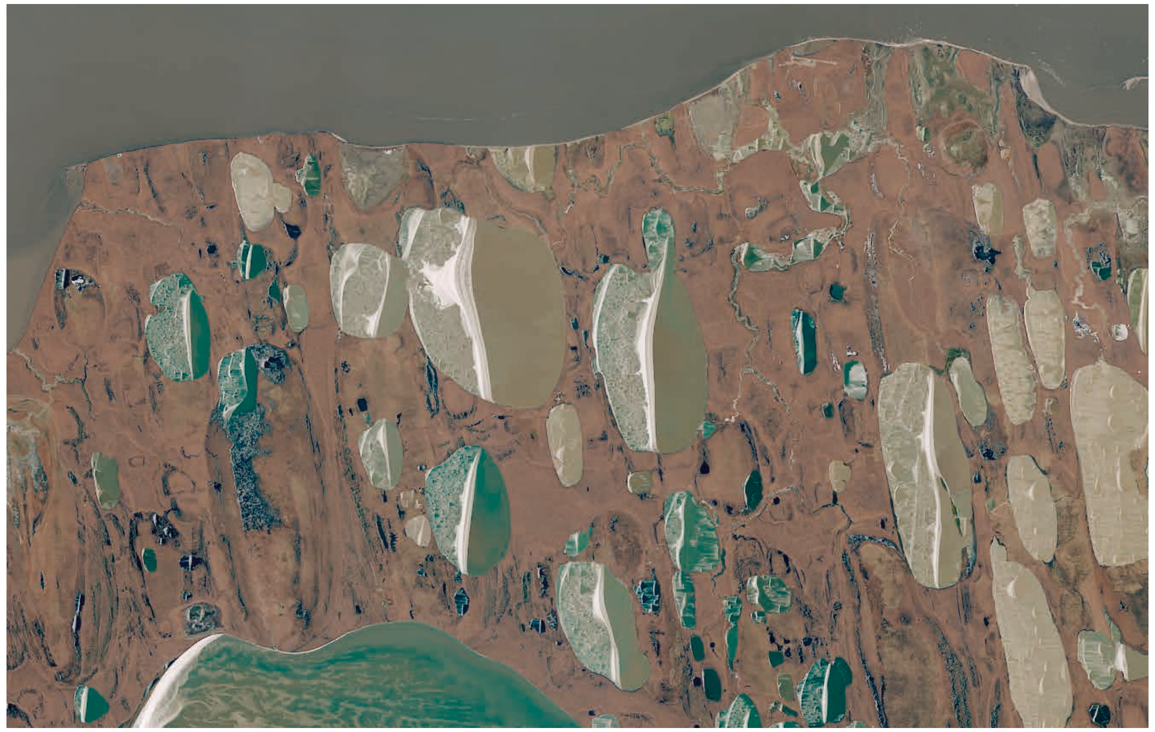
This is what has caused the Siberian permafrost island of Muostakh, for example, to lose more than half a kilometre of its north-south length over the past 60 years, and almost a quarter of its total area. In 2012, the banana-shaped island, which lies off the Lena Delta, was 7.5 kilometres long and measured 500 metres at its widest point. Now it is much smaller because large portions of the icy island coast have been disappearing by up to 3.4 metres per year. On the northern end of the island the erosion rate ranges from 11 to 39 metres annually. If this trend continues, Muostakh will disappear completely within a hundred, or perhaps two hundred years.

Not only does the destruction of the Arctic permafrost coasts endanger houses, streets and other infrastructures constructed near the coast. It also changes the biological conditions in the sea. With the increasing erosion more mud is transported from the land into the sea, which often leads to extensive turbidity in the shallow-water areas.

The eroded material also contains large amounts of nutrients and pollutants, including nitrogen, phosphorus and mercury. When these substances reach the sea, they are either transported away from the coast, broken down, or concentrated to produce permanently altered conditions in the shallow-water zone. Scientists are not yet able to accurately predict the future consequences of this for the ecosystem because there is still a lack of comprehensive long-term studies on this topic.



3.30 > Coastal erosion in pictures: This Landsat image of 8 July 1992 shows a segment of the northern coast of the USA between Drew Point in Alaska (small tip of land on left side of image) and the regional airport (small runway near the coast on right side). At this time sea ice protected the coast from the destructive power of the waves.



3.31 > 26 years later, on 5 October 2018, large areas of land have disappeared northeast of the airport and around Drew Point. Wind and waves were able to carry them away because much of the sea ice had also disappeared in this region. To a large extent, however, the ice differences in the two images are due to seasonal fluctuations.

Permafrost as a carbon reservoir

The Arctic permafrost soils are often referred to as "gigantic ice chests". Large amounts of carbon are stored in the frozen ground in the form of fossil animal and plant remains. Scientists estimate the total amount of carbon locked within these soils to be between 1100 and 1500 billion tonnes. As yet, around 60 per cent of these are permanently frozen and thus not available to the global carbon cycle. Just for comparison, this amount of deep-frozen carbon is equal to the amount of carbon that is now present in the Earth's atmosphere in the form of carbon dioxide and methane, and is already warming the Earth.

If the organic remains of plants and animals stored in the permafrost thaw out, microorganisms will begin to break them down. They transform the organic carbon to either carbon dioxide or methane. Which of these two greenhouse gases is ultimately produced depends on which microorganisms are active in a particular area. Some Archaea exclusively produce carbon dioxide, while others produce only methane. But it also depends on whether oxygen is available during the decay of the animal and plant remains. If it is present, it is respired and carbon dioxide is released. But if the microorganisms consume the thawed animal and plant remains under anaerobic conditions, in an oxygen-poor environment such as the muddy bottom of a thermokarst lake, for example, then the methane-producing groups of Archaea will transform the carbon to methane. This extremely potent greenhouse gas then rises in bubbles from the bottom of the lake and enters the atmosphere. By the year 2100 the permafrost regions of the Arctic could release around 140 billion tonnes of carbon into the atmosphere as a result of the decomposition of thawed organic material. This emission alone would contribute approximately 0.1 degree Celsius to the further warming of the Earth.

How quickly the animal and plant remains can be broken down by the microorganisms depends primarily on the quality of the organic material. Studies so far indicate that the carbon quality in permafrost remains constant even with increasing depth and age. More simply stated, when the organic material has thawed out, the microorganisms show an equal appreciation for the frozen meals whether they have been frozen for 20 or 20,000 years.

Methane production is also influenced by local weather conditions. For example, in a recent study, American researchers were able to determine that unusually early spring rains in the thermokarst regions of Alaska can increase methane production by as much as 30 per cent. This is because in springtime the atmosphere, and therefore the rain, is significantly warmer than the frozen ground.

So, when the seasonal rains begin much earlier in the year, as they did in 2016, the rainwater collects in the thermokarst depressions and thaws the ground there to a depth of one metre. The entire depression then resembles a miniature marshy wetland, with very little oxygen available in the mud. During this thawing process, therefore, it is primarily the methane-producing microorganisms that are active in the ground. They convert the organic material to methane. In addition, the microbes release nutrients that stimulate the growth of certain reed grasses in the depression. Like most plants, the reeds also remove carbon dioxide from the atmosphere and transform it through photosynthesis into sugars and oxygen. Some of the sugar is transported by the plants to the root area where, under certain conditions, it may enter the soil and be processed into methane by the microbes. From this fact, the scientists conclude that the more reed grasses there are in a thermokarst depression, and the earlier in the year they grow, the more methane is produced in the muddy subsoil of the depression.

One question that remains for the permafrost regions is whether the enhanced plant growth may remove more carbon dioxide from the atmosphere than the microbes in the ground release. So far, there is no definitive answer. It is certain, however, that the positive feedbacks between the ground, ice and atmosphere are reinforcing the depletion of permafrost in the Arctic and have an effect similar to pulling the power plug on a freezer chest. In recent years, in order to make more accurate predictions about the future of permafrost, scientists have developed many regional and supra-regional computer models, some of which are capable of mapping energy flux and feedbacks

3.32 > Thousands of methane bubbles pervade the ice on Lake Minnewanka in Canada's Banff National Park. This potent greenhouse gas is released when microorganisms decompose organic material that has accumulated at the bottom of the lake.

between the permafrost, atmosphere and vegetation. Although these models still show large differences in the details of their predictions, they all show a common trend: The continued warming of the Arctic combined with increased snowfall in previously dry areas will lead to a large-scale loss of near-surface permafrost. The scientists can even quantify the reduction. They estimate a loss of 0.8 to 2.3 million square kilometres of permafrost with each degree Celsius of rise in the air temperature.

In its 1.5-degree special report, the Intergovernmental Panel on Climate Change concludes that global warming of 1.5 degrees Celsius or less would decrease the area of permafrost regions by 21 to 37 per cent compared to today. If the Earth warms by 1.5 to 2 degrees, the total area would likely be reduced by 35 to 47 per cent. With a warming of up to three degrees Celsius it can be assumed that the world's permafrost ground would thaw to a much greater extent. Climate simulations for the Arctic show that in this situation ground ice would only remain in a few areas, probably in some parts of the Canadian Arctic Archipelago, on the Russian Arctic coast and in the high-altitude regions of East Siberia.

Permafrost cost factor

These outlooks for the future have made the issue of permafrost one of the most urgent areas of action for the Arctic countries. The economic and social risks posed to cities and communities, and those related to intercity infrastructures such as roads, railways and pipelines are enormous, especially in countries like Canada, half of whose territory is underlain by permafrost. But Russia, of course, where 65 per cent of the land area is permafrost ground, is also seriously impacted. According to a new study, the Russian state could expect repair and maintenance costs of up to 85 billion US dollars if the worst-case scenario of the Intergovernmental Panel on Climate Change should occur, in which the world would warm up by as much as 4.9 degrees Celsius by the end of the 21st century. The damage to personal property due to disappearing permafrost could be as much as 53 billion US dollars under the same scenario.

3.33 > Roads built on permafrost generally subside first at their verges, where the frozen subsoil thaws fastest. Thermosiphons are installed to prevent this happening. They convey ice-cold air in winter to the still relatively warm subsoil, thus keeping it cooled.

The ecological changes that will follow from the loss of permafrost grounds must also be considered. These include, for example, changes in the water cycle and advancing tree lines. A further complicating factor is that the environmental conditions in the Arctic region are changing at a time when this previously sparsely populated area is undergoing a phase of major development and economic growth. There is thus an increased need for new local and interregional observation systems by which to monitor infrastructures as well as entire landscapes. Modern remote-sensing methods such as the use of drones, regular satellite monitoring, and precision laser measurements of elevation will play an important part in the future. With the help of satellite images, researchers are already tracking changes on the permafrost coasts and mapping new landscape features created by rapid permafrost melting, such as thermokarst lakes and depressions, or thermal-erosion valleys. In addition, groups of specialists are developing new risk-analysis procedures that take into account the future effects of climate change. These also assume an increase in extreme weather events such as heavy rains, flooding and storms.

The potential severity of the consequences of these events was demonstrated by heavy flooding on the Dalton Highway in Alaska in the spring of 2015. This road is the only land connection to 24 of Alaska's oil fields in the far

Mysterious craters

In the summer of 2014, Russian reindeer herders discovered a large circular hole in the Siberian tundra of the Yamal region. Photographs of the mysterious crater attracted worldwide attention, and fuelled speculation about meteorite impacts or the activities of extra-terrestrial life forms in the area, 2200 kilometres northeast of Moscow. Russian geoscientists then investigated the 50-metre-deep and 30-metre-wide hole during several expeditions. Their findings indicated that the hole was formed when a gas hydrate, i.e. a large bulk of frozen methane and water, thawed to a great depth during permafrost warming. The methane converted from a frozen to a gaseous state, causing it to expand by a factor of 164. It then rose to the surface with a pressure of up to 30 kilograms per square centimetre. There must have been a powerful eruption at the moment when the gas suddenly escaped into the atmosphere. In any case, material from the crater was hurled through the air for a distance of more than 180 metres.

Researchers now believe that these kinds of methane eruptions are a rather common phenomenon in the Siberian Arctic. They presume, among other causes, that many of the lakes found on the Yamal Peninsula today were formed by this process during a warm period in the past.

3.34 > This crater on the Yamal Peninsula was formed in 2014 when massive amounts of methane gas erupted explosively out of the ground.

north. The Trans-Alaska Pipeline and the Sagavanirktok River, which flooded the highway in that year, both run parallel to the course of the road. A segment of nearly 60 kilometres of the road stood under as much as 75 centimetres of water from March to June. The northern stretch of the highway had to be closed for weeks, resulting in financial losses for the local transport companies. The oil fields could only be reached by air. The governor of Alaska declared a state of emergency twice during this time.

The flood itself damaged both the road and the adjacent permafrost landscape. Ground ice near the surface thawed over a large area and thermokarst depressions formed, into which segments of the highway sank. The direct repair costs ultimately came to 27 million US dollars, and another 50 million dollars were spent to protect the highway against future flooding.

Because of these and similar incidents, new laws and guidelines for the construction of buildings and infrastructures in permafrost regions have been introduced in Canada, Norway and other countries. Major efforts are also being made to develop options for technical adaptation. One important question, for example, is how the cold permafrost temperatures can be preserved beneath the streets, tracks and airports, so that sufficient structural support can be maintained, even under warmer climate conditions.

In Alaska and Canada thermosiphons have been installed adjacent to buildings and streets since the 1970s to keep the frozen ground cool. These systems consist of vertical steel tubes that extend deep into the ground. They are hermetically sealed, and usually contain carbon dioxide in both its gas and liquid phases. The thermosiphons cool the subsurface in winter by extracting heat from the ground with the help of carbon dioxide phase changes. When the air above the Earth's surface is colder than the ground temperature, the gas condenses in the upper part of the tube and flows into the lower part as a liquid. Warmed there by the ground, the liquid evaporates again and rises as a gas. It carries the heat energy used for the evaporation up with it, and releases it to the atmosphere again when it condenses. This cooling mechanism only functions as long as the outside air temperature is colder than that in the ground.

Changes in the glaciers and ice sheets

The answer to the question of whether a glacier or ice sheet is growing or shrinking in response to climate change, or is in a state of equilibrium, can be obtained through a simple mass balance equation. If the amount of snow falling on an ice body exceeds the mass that it loses in a number of ways, the balance is positive, and the glacier or ice sheet grows. But if it loses more ice mass than it receives through precipitation, the ice shield shrinks.

The same parameters apply in this calculation for individual glaciers as for the larger ice sheets. All land-ice areas accumulate mass through precipitation. In the polar regions this usually falls as snow. In some situations, however, rain may also fall on ice sheets and glaciers. The rainwater can also contribute to the mass increase of the ice body, provided it seeps into the snow-firn layer and freezes there. This frequently happens in the polar regions because the firn there is usually cold enough.

There is a much longer list of processes through which the glaciers and ice sheets may lose mass. The following processes of loss are considered to be significant:

- wind transport (mass of snow particles that are removed by the wind),
- sublimation (direct phase change from snow crystals to water vapour),
- meltwater that runs off or evaporates on the glacier's surface,
- breaking off of ice masses on land or in the sea (icebergs),
- basal melting of floating glacier tongues and ice shelves.

In theory, it may be straightforward to arrange these various parameters into an equation and obtain a result. But in practice today, it is still a huge challenge to accurately determine the mass balance of glaciers and ice sheets in the polar regions because only rough estimates are available for many of the variables. Exceptions are provided, however, in the form of accessible glaciers, where researchers have been regularly measuring the snow accumulation and snow densities for more than 40 years. There are only 37 of these glaciers in the world, including some high mountain glaciers in the mid-latitudes.

Scales in space

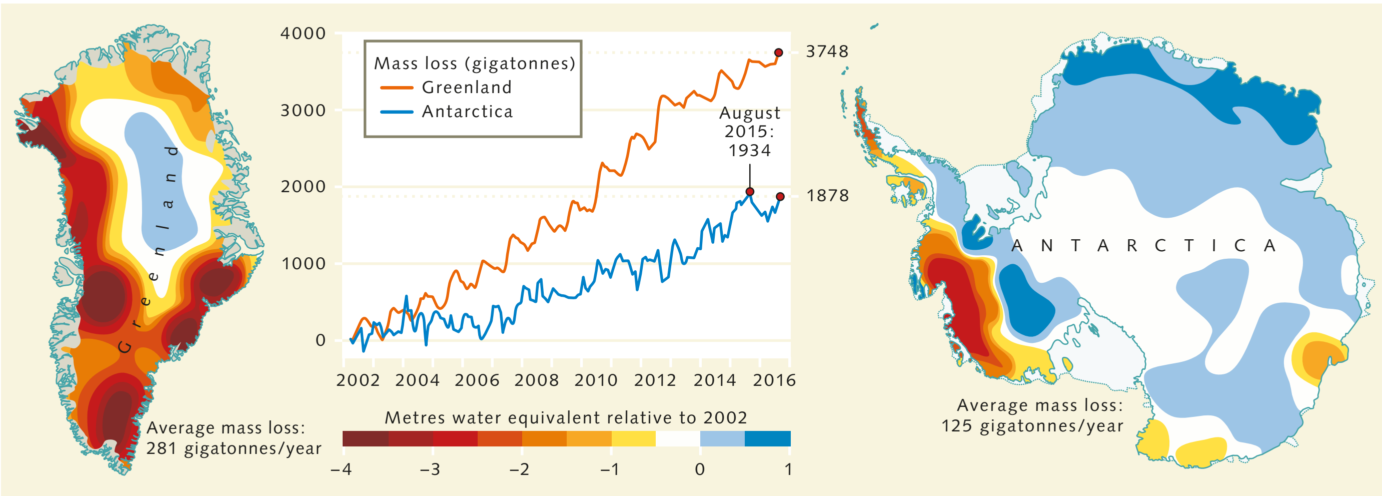
In order to minimize the uncertainty factor in the mass balance calculations for glaciers and ice sheets, the satellite mission GRACE (Gravity Recovery and Climate Experiment) was begun in 2002. GRACE comprises two identical satellites that circle the Earth at an altitude of 490 kilometres, one behind the other, in a near polar orbit, and these are able to achieve what is not possible with land-based measurements: The system measures the total gravitational field of the planet within a single month. The satellites comprehensively document changes in mass on the Earth, and assess the redistribution of water among the oceans, the continents, and especially the ice sheets. The remote sensing data thus provide answers to two of the most urgent questions in climate research: How much ice are the ice sheets and glaciers of Greenland and Antarctica losing due to climate change? And in which regions of the world is sea level rising as a result?

Global sea-level rise from 2005 to 2018

Causes	in millimetres per year
Total global sea-level rise	3.5 ±0.2
Thermal expansion of water	1.3 ±0.4
Melting of mountain glaciers	0.74 ±0.1
Melting of the ice sheet in Greenland	0.76 ±0.1
Melting of the ice sheet in Antarctica	0.42 ±0.1

3.35 > The rise of global sea level has more than one cause. A little less than two-thirds results from the melting of mountain glaciers and ice sheets. Around one-third is due to thermal expansion of the world's oceans.

The first GRACE mission lasted from 2002 to 2017. Because of its phenomenal success, a booster rocket carried the follow-up satellite GRACE-FO (Follow-on) into space on 22 May 2018 from Vandenberg Air Force Base in Santa Barbara County, California. It should continue to



3.36 > With the help of gravity-field measurements by the GRACE satellite system, the mass balance of the ice sheets in Greenland and Antarctica were reliably measured for the first time. Both of these ice shields lost more ice than they gained during the measurement period. The regions where the glaciers transport the most ice into the sea were also identified.

provide climate researchers from around the world with reliable data on the growth and decline of the ice sheets for at least another ten years, and if ideal solar conditions deliver an optimal energy supply, perhaps even for 30 years.

So far, the analyses have mostly been limited to measurements from the first mission. According to these data, the ice sheet in Greenland and its accompanying glaciers have lost an average of 286 billion tonnes of ice annually since 2002. The scientists explain that these losses have mainly occurred because the air over Greenland is getting warmer, causing the intensity and duration of the melting season to increase. Today, Greenland's ice sheet loses almost twice as much ice annually due to melting processes at the surface as it did during the period from 1960 to 1990. As subsequent model calculations have shown, the total ice growth and losses were almost evenly balanced at that time. But the losses in mass due to iceberg break-off have also increased by about one-quarter to the present. Greenland now contributes the greatest share of meltwater to global sea-level rise. The total global rise is currently 3.34 millimetres per year and Greenland's contribution to that is about 0.7 millimetres.

The mass balance of the two ice sheets in Antarctica is also negative, even though around 2000 gigatonnes of snow fall on the Antarctic glaciers and ice sheets each year. Approximately ten per cent of this snow is lost due to surface melting, wind transport, evaporation and sublimation. The remaining 90 per cent is compacted to firn and later to ice. In a study published in 2018, scientists from the USA and Europe compiled GRACE data, altimeter measurements for elevation changes of the ice sheets, and modelling results for the period from 1992 to 2017, to determine the mass balance of the West and East Antarctic Ice Sheets. The study found that Antarctica lost around 76 gigatonnes of ice annually to the year 2011, an amount that added 0.2 millimetres per year to the rise in global sea level. But since 2012, the yearly ice loss from Antarctica has almost tripled to 219 gigatonnes.

The most significant changes documented by the researchers were observed in West Antarctica. In the first five years of the monitoring period (1992–1997), its glaciers and ice streams were transporting an average of 53 gigatonnes more ice per year into the Southern Ocean than was being newly produced by precipitation on the ice sheet. By the 2012–2017 period this amount had tripled to 159 gigatonnes annually. West Antarctica has been losing particularly large amounts of ice since the late 2000s. Around that time the large Pine Island Glacier and the Thwaites Glacier began to flow faster. Both of these flow into the Amundsen Sea, where warm ocean currents rising from below melt the ice shelves in front of the glaciers.

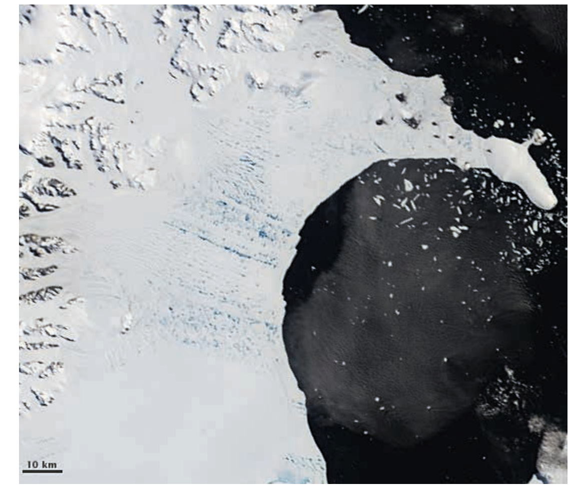
In the northernmost region of Antarctica, the Antarctic Peninsula, four out of twelve ice shelves have collapsed in recent decades, with three of them losing as much as 70 per cent of their ice area. This combination increased the rate of ice-mass loss on the peninsula to 25 gigatonnes per year. In East Antarctica, by contrast, the ice loss vs. growth remained more or less in balance over the 25-year period. According to the data, the mass of the East Antarctic Ice Sheet has actually grown by five gigatonnes per year. However, since the error factor for this value is plus or minus 46 gigatonnes, it is subject to a fairly high degree of uncertainty.

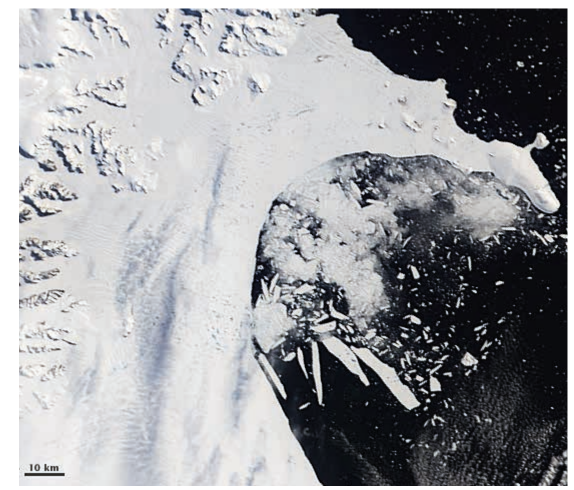
Based on analyses of the GRACE data alone, the Antarctic continent is now losing 127 gigatonnes of ice per year. The greatest losses are occurring in the western part of the Antarctic Peninsula, the coastal regions of West Antarctica, and the coastal areas of Wilkes Land and Adélie Land in East Antarctica. In the southern reaches of West Antarctica, however, as well as the northern part of Queen Maud Land, the ice sheet is actually growing.

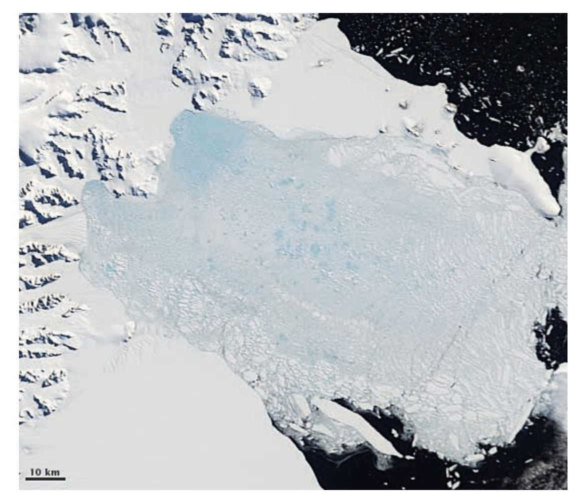
Ice shelves are the weak spot

The increasing losses of ice in Antarctica are primarily a direct consequence of the thinning or even complete disappearance of the ice-shelf areas. The more narrow, lighter and shorter the once-massive ice tongues become, the less able they are to resist the push of the inland ice from behind. The ice sheets are becoming increasingly unstable, primarily due to two processes: basal melting as a consequence of warmer ocean currents acting on the underside of the ice shelf, and melting on the upper ice surface, primarily caused by warm air masses. These surface meltwaters then collect in cracks and crevices in the ice body, deepening them and increasing the likelihood of icebergs breaking off. The degree to which these two processes act depends largely on the regional conditions, as a description of events in West Antarctica and along the Antarctic Peninsula illustrates.

In the Antarctic summer of 2002, polar researchers in the USA and Europe were waiting eagerly every day for new satellite images from the Larsen B Ice Shelf in the north-western Weddell Sea. From a distance, the scientists were able to witness how a 3250-square-kilometre float-







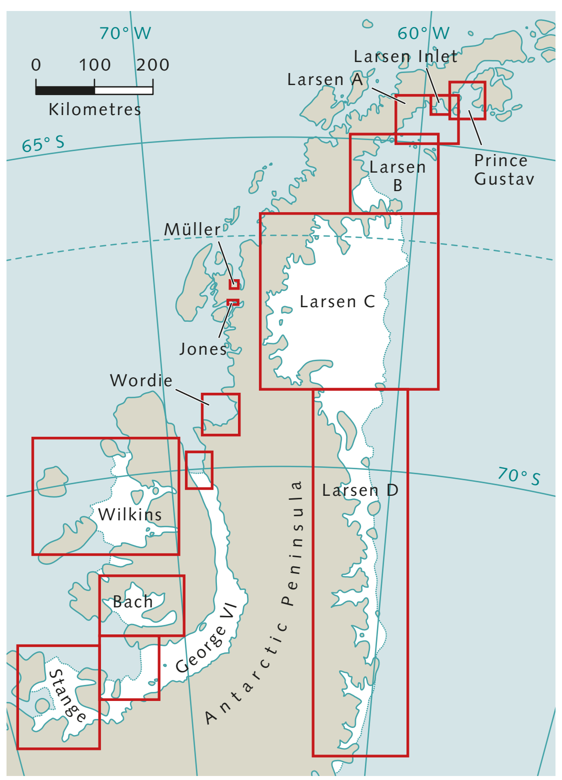
3.37 > The Larsen B Ice Shelf, on the east coast of the Antarctic Peninsula, collapsed during the southern hemisphere summer of 2002 within a period of less than six weeks. The top image (31 January 2002) shows the ice still intact and the many meltwater lakes that had already formed on its surface. In the second image (23 February 2002), hundreds of icebergs are floating in front of the break-off edge. Less than two weeks later (7 March 2002) the ice shelf had lost a total area of 3250 square kilometres (bottom).

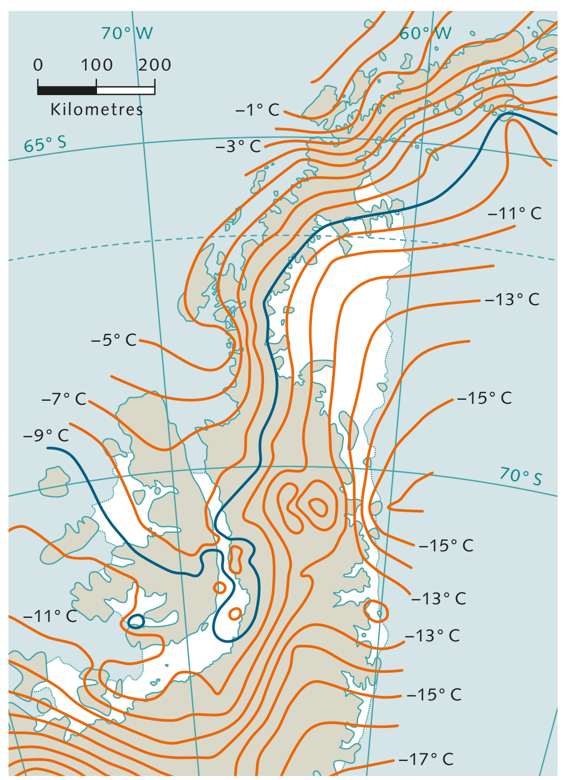
Larsen Ice Shelf
The Larsen Ice Shelf, which is divided into four segments: A, B, C and D, is named after the Norwegian whaling captain and Antarctic explorer Carl Anton Larsen (1860–1942). In December 1893 he sailed along the ice shelf in the western Weddell Sea with his vessel *Jason*.

ing expanse of ice disintegrated into millions of smaller pieces and effectively disappeared within a single month. Until the 1990s, the Larsen B Ice Shelf belonged to a group of five almost contiguous ice shelves that extended up to 200 kilometres (Larsen C) into the Weddell Sea off the east coast of the Antarctic Peninsula. Then, in 1996, the Prince Gustav Ice Shelf and the Larsen A Ice Shelf, the two northernmost segments, broke up. They were followed six years later by Larsen B. The two southernmost, Larsen C and D, still exist today, although a huge iceberg, with a total area of around 5800 square kilometres, broke off from Larsen C in July 2017. With that single event, the shelf lost an area of ice about seven times the size of the city of Berlin.

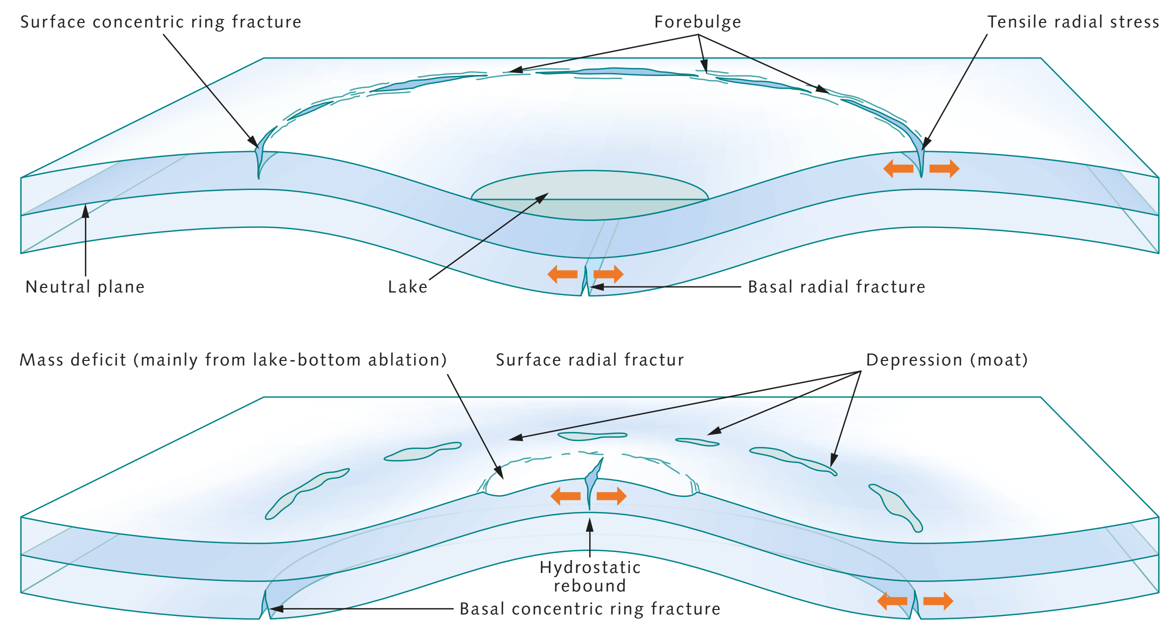
There were originally twelve ice shelves along the length of the Antarctic Peninsula that fed off the glaciers that form in the mountainous regions of the peninsula. The only source of their ice masses were the snow and rain that falls on the peninsula. These glaciers, and those that remain today, were not connected in any way to the West or East Antarctic Ice Sheets. With an average thickness of 200 metres, the ice shelves of the Antarctic Peninsula are also significantly thinner than the well-known Ross or Filchner-Ronne Ice Shelves, both of which transport ice out of the inner regions of Antarctica.

The Antarctic Peninsula is also the northernmost and thus warmest region of Antarctica. Since the beginning of the 20th century, the air temperatures over this elongate mountainous and island region have risen by an average of 3.5 degrees Celsius. Since the 1950s, this regional warming has been impacting the stability of the ice shelves on both sides of the peninsula. The British glaciologist John H. Mercer had already recognized by the 1970s that the ice shelves only occur in those regions of Antarctica where the average annual temperature is not above minus five degrees Celsius. Similar to the 10° Celsius July isotherm for tree growth in the Arctic, for a long time there was also a minus 5° Celsius isotherm for ice shelves in Antarctica.





3.38 > Since the 1960s, seven of the twelve ice shelves along the Antarctic Peninsula have suffered from major depletions of ice. Four of them have completely disintegrated (Jones, Wordie, Prince Gustav, Larsen A). Their disappearance was triggered, among other things, by a rise in the air temperatures of up to three degrees Celsius. Since that time, ice shelves only occur in regions of the peninsula where the average annual temperature is minus nine degrees Celsius or lower.



3.39 > When meltwater collects on an ice shelf, a pond or a lake is created. The ice surface slowly yields under its weight, and a depression is formed. But when the water in the lake drains off, perhaps through a fracture in the ice, the depression rebounds. This creates a ring of concentric fractures around the lake margin and facilitates the breakup of the ice shelf over time.

But with warming, their northern boundary on the Antarctic Peninsula has been shifting steadily further to the south in recent decades, with serious consequences for the ice-shelf areas that now lie to the north of the isotherm. They began to melt regularly on a large scale because of the rising summer temperatures and the warmer foehn winds. The resulting meltwater collected in the cracks and crevices of the ice shelves. Because of the weight of the water, the hydrostatic pressure increased at the bottom of the individual fractures, which resulted in a deepening of the fractures. Similar forces were at work when the meltwater froze again in winter and expanded within the fractures. With fractures eventually permeating the entire ice shelf, the danger of icebergs breaking off likewise increased.

The stability of the ice shelves, however, also suffered under the load of the regularly returning meltwater lakes. According to measurements made on the McMurdo Ice Shelf, when meltwater collects in a depression on the ice shelf, the underlying ice can be bent downward by as much as a metre by the immense weight of the water. The ice shelf thus bulges downward to some extent. If the lake then empties suddenly in the summer, the bulged portion of the ice shelf returns relatively quickly to its original position.

This motion results in the formation of small, ring-shaped fractures in the ice around the lake as well as in its centre. If water from nearby lakes subsequently seeps into these fractures, they continue to grow, and this increases the risk of breaking. This kind of chain reaction of melting, bending, rebounding, cracking and deepening presumably led to the draining of over 2000 closely lying meltwater lakes on the Larsen B Ice Shelf during the Antarctic summer of 2001/2002. The role of melting processes on the underside of the ice shelves is also a hotly debated topic in science. Warm sea water there could very well have made some contribution to the decay of the ice shelf.

But the fundamental cause of the destruction of the ice shelves on the Antarctic Peninsula has been the rise in air temperature. The ice shelves located in the northern part of the peninsula initially retreated gradually over a period of several decades, but later collapsed one after the other – first the Wordie Ice Shelf on the west coast of the peninsula (1980s), then the Prince Gustav Ice Shelf on the east coast (1995), followed by Larsen A (1995) and Larsen B (2002), the Jones Ice Shelf near the Arrowsmith Peninsula (2003), and large parts of the Wilkins Ice Shelf (2008).

The relationship between warmer air and the destruction of ice shelves is also confirmed by satellite images of the Larsen B ice shelf shortly before its collapse. These clearly show the countless rows of blue meltwater ponds. One year after the disintegration of Larsen B, as scientists were analysing the temperature data from the Antarctic Peninsula at the time, they discovered that only the ice shelves that lay south of the minus 9° Celsius isotherm showed no large-scale surface melting and thus no appreciable changes. All of the ice shelves to the north of that line had either shrunk extensively or even completely disintegrated by then. Since that time, the isotherm delineating an annual mean of minus nine degrees Celsius is considered to be the new northern limit for the existence of ice shelves along the Antarctic Peninsula.

The breakup of Larsen B also had consequences for the glaciers that once fed the ice shelf. Within a short time, the velocities of the four affected glaciers increased by two to six times because the ice shelves were no longer there to hold them back. Three of the flows have also undergone losses in elevation, and their ice tongues have become flatter due to the increased flow velocity. The disintegration of the ice shelves has therefore continued to affect the mass balance of the glaciers and ice sheets long after their breakup.

Tracking the paths of meltwater

The fact that ice shelves and glaciers in the Antarctic sometimes melt at the surface is not a new discovery. The members of Ernest Shackleton's *Nimrod* Expedition heard the sound of meltwater streams while traversing the Nansen Ice Shelf in 1908. Four years later, the members of a British expedition to map the Nansen Ice Shelf, led by Robert Falcon Scott, complained that they were repeatedly forced to wade through streams of meltwater, and that their tents were flooded on more than one occasion.

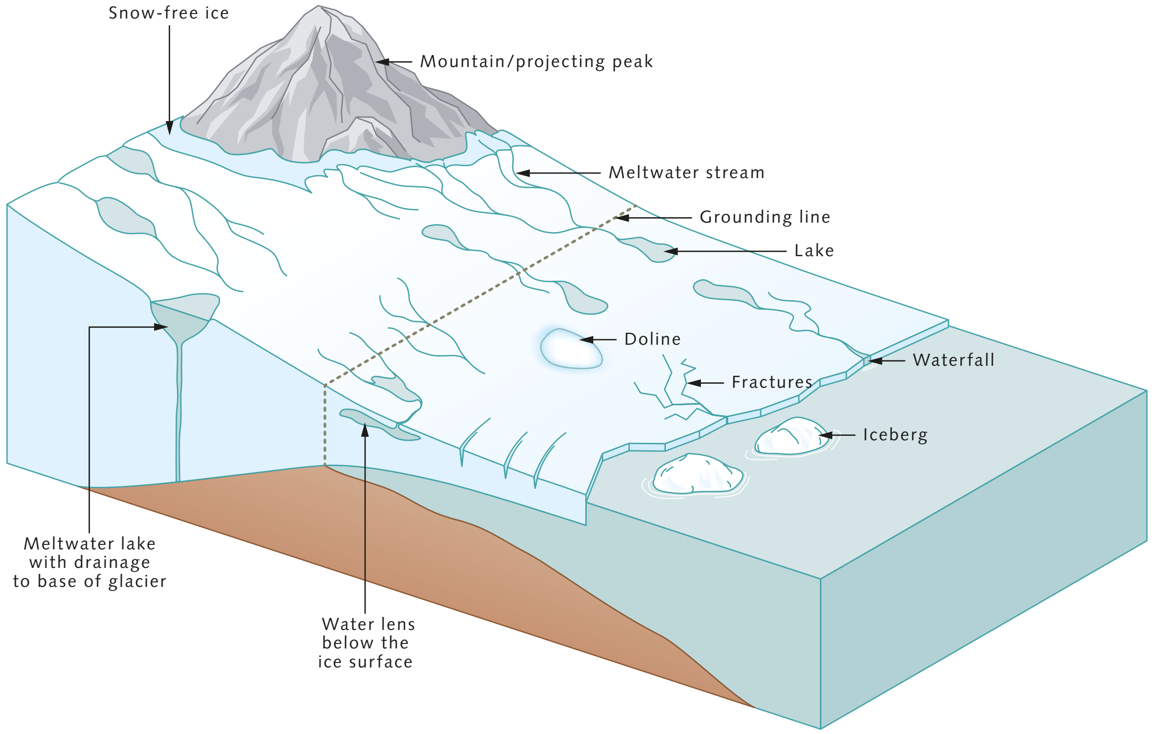
New satellite observations, as well as aerial photographs and mass-balance models, suggest that the extent of ice loss due to melting and its significance for the mass balance in Antarctica are greater than previously believed. In 2017, scientists counted nearly 700 different networks of meltwater lakes and streams transporting liquid water across all of Antarctica's ice shelves.

The highest surface-melting rates on the still-existing ice shelves are now being observed along the Antarctic Peninsula, especially on the Larsen C, the Wilkins, and the George VI Ice Shelves. But meltwater is also forming on the ice shelves in the southern part of East Antarctica, for example, on the West and the Shackleton Ice Shelves. The summer melting is so intense on the Amery and King Baudouin Ice Shelves that networks of meltwater lakes and streams are visible over great distances there. The Ross and Filchner-Ronne Ice Shelves, on the other hand, have so far exhibited only minor evidence of melting events. Throughout Antarctica, all of the ice areas that are now melting on the surface lie at elevations below 1400 metres. In the higher elevations it is still too cold.

Ice areas that have no snow or firn cover, and are thus exposed as bare ice to the sun, are especially susceptible to frequent melting. Because of its colour, bare ice absorbs more solar radiation than the pure-white areas of snow. Scientists have also detected higher melting rates near mountains or rocky peaks that project above the ice surfaces. These also absorb more solar energy and warm up the surrounding ice. Networks of meltwater lakes and streams can transport the water over distances of several hundred kilometres – very often directly to the true weak points of the ice sheet, the ice shelves. The largest meltwater lake known to date, with a length of around 80 kilometres, is located on the Amery Ice Shelf. At the leading edge of the Nansen Ice Shelf, a large portion of the surface meltwater flows in summer into the Ross Sea over a 130-metre-wide waterfall. This has been active at least since 1974. Scientists observed similar waterfalls on the Larsen B Ice Shelf before its collapse. It is believed, however, that ice shelves whose meltwaters drain off over a network of streams on the surface are less likely to break apart than ice shelves on which water accumulates in the crevices and cracks, which has the effect of expanding and deepening them.

While scientists commonly observe meltwater lakes on Greenland draining almost vertically into the interior of

3.40 > In April 2016, the waters of a large meltwater river on the Nansen Ice Shelf plunged 200 metres down into the western Ross Sea.



3.41 > As a result of climate change, surface melting in the Antarctic is intensifying. The resulting meltwater permanently alters the glaciers and ice shelves. More lakes, streams, dolines and water lenses are formed. Furthermore, there is an increased danger of meltwater lakes draining down to the underlying rock bed, as they do in Greenland, and increasing the velocity of the ice mass.

the ice sheet through moulins (or glacier mills), and then flowing towards the sea along the underside of the ice body, this phenomenon has not yet been reported in Antarctica. Here, the emptying of meltwater lakes is so far only known to occur on the ice shelves, which are floating ice. When the lake basins are empty, they look somewhat like large craters. The typically shaped depressions are also called dolines. Meltwater lakes that form directly on glaciers, which lie above a land surface, generally freeze again in winter and are covered by snow. When it becomes cold enough, the hidden lakes can even freeze completely and form huge ice lenses.

Given the rising air temperatures worldwide, researchers note that two to three times more meltwater will be produced on Antarctic glaciers and ice shelves by 2050 than is the case today. This amount of liquid water will probably impact the mass balance of the Antarctic ice sheets, glaciers and ice shelves in three ways:

- If an area of ice melts on the surface, the water will often run off from that area, which results in a thinner ice body overall. In Antarctica, the ice-mass losses caused by surface melting will increase.
- Under some conditions, surface meltwater can seep into the snow-firn layer of an ice sheet and form lenses of water below the ice surface. As a result of global warming, scientists see an increasing probability that the meltwater from lakes in the Antarctic will drain out through moulins in the ice and flow through cracks and crevices down to the bedrock beneath the glacier or ice sheet, where they will either form lakes under the ice or intensify the gliding effect of ice masses on a film of water. These injections of surface meltwater into the inner ice body or even to its base will fundamentally change the dynamics of the Antarctic ice sheets and glaciers.
- More meltwater on the ice shelves will threaten their stability to an even greater degree than before, and even lead to the collapse of ice shelves in more southern regions of the Antarctic. Again, fundamental processes will include the deepening of existing fractures due to the collection of melt water in crevices, and the formation of fractures due to repeated flexing of the ice surface. Researchers furthermore note that, as a result of increased warming, ice shelves that have previously not been greatly affected will begin to form more meltwater. This is mainly based on assumptions that the local winds will become warmer.

So, over the long term, not only the total amount of meltwater in the Antarctic, but also its importance for the Antarctic ice sheets will increase. The magnitude of the already negative balance will therefore become even greater in the future.

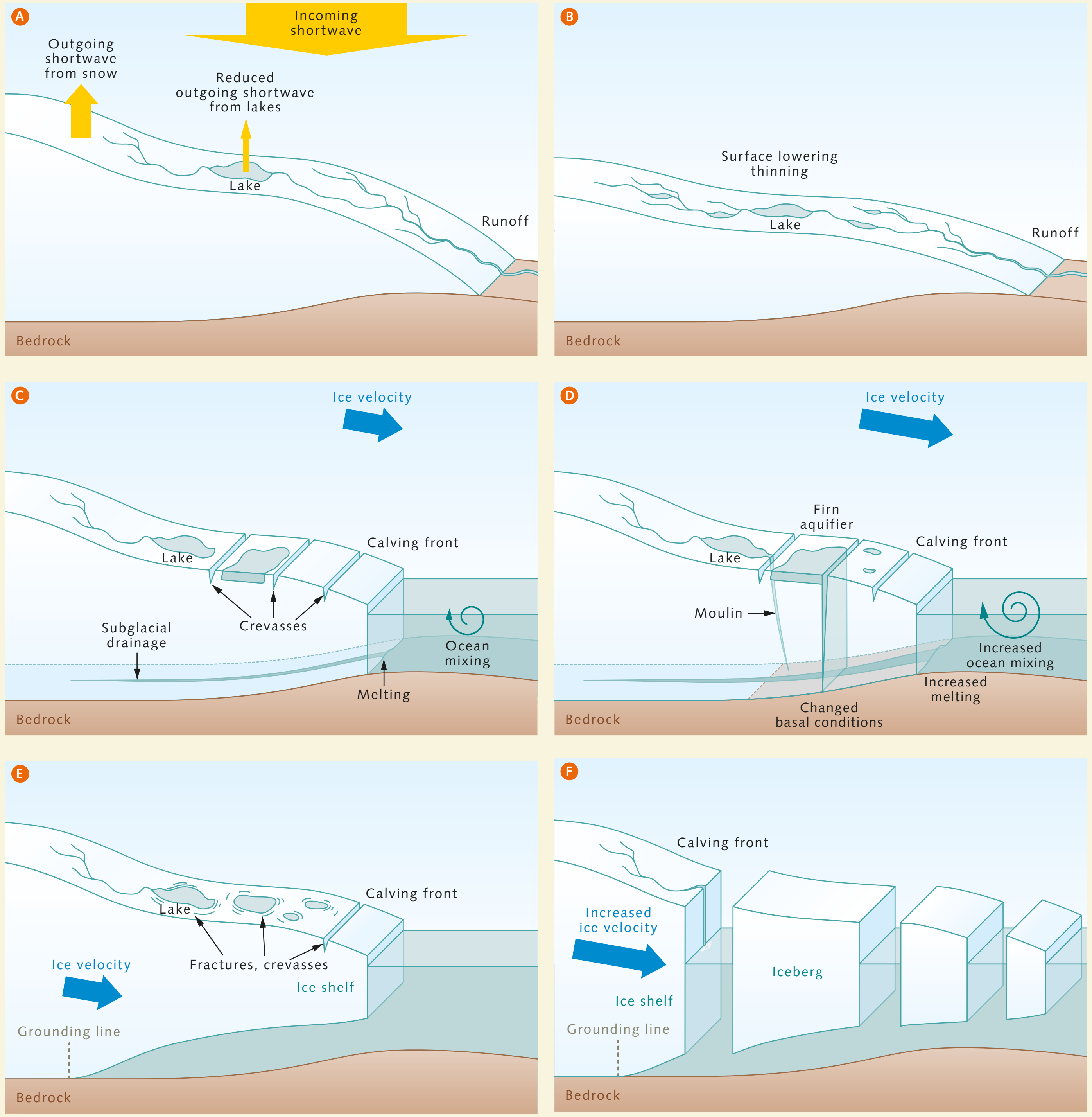
Heat incursion into the Amundsen Sea

While the collapse of ice shelves on the Antarctic Peninsula is primarily triggered by warming of the atmosphere, they are threatened in other coastal regions of the continent by heat in the ocean, particularly the water masses of the relatively warm coastal currents. In some regions, they are penetrating more frequently onto the shelf and beneath the ice shelves. What ensues is a destructive chain reaction like the one that has been taking place in recent decades in West Antarctica and the adjacent Amundsen Sea.

Large portions of the West Antarctic Ice Sheet are resting on land that is not only situated below present-day sea level, but that also slopes downward to the south. So if the Southern Ocean warms up, its waters will come into direct contact with the ice masses resting on the sea floor and could continue to melt them until the ice sheet collapses completely.

In a certain sense, it would be as though a continuous stream of warm water were flowing unrestrained into a gigantic bowl containing a large block of ice. This situation makes the ice shield of West Antarctica especially susceptible to climatic changes in general, and to changes in the ocean currents in particular. If the ice masses of West Antarctica were to completely melt, the direct result would be a global sea-level rise of up to 4.3 metres.

The glaciers and ice flows discharging into the Amundsen Sea can be viewed as the Achilles heel of the region.



3.42 > If glaciers and ice shelves melt on their upper surfaces, the presence of meltwater reinforces the further loss of ice mass in three ways. A/B: The darker surfaces of lakes and streams absorb more solar energy than the brighter ice. The water warms up and promotes continued melting of ice on the glacier's surface. The ice body thus thins from above. C/D: Meltwater that finds its way to the underside of the glacier increases the flow velocity of the ice masses. E/F: Meltwater collecting on the ice shelf deepens existing fractures and creates new ones, so that icebergs break off more often.

3.43 > Warm water masses could be very dangerous for the West Antarctic Ice Sheet because the bedrock under the ice sheet slopes downward to form a number of basins. Once the warm water has breached the margins of these basins, it will flow almost unimpeded along the base of the ice sheet.

For one, because the ice masses here are resting on the sea floor in very deep water and, for another, because there is no longer a massive ice shelf to significantly slow down the flow of the ice from the inland of West Antarctica. One-fifth of the ice mass of West Antarctica flows through these glaciers towards the sea. In recent decades the glaciers in this region have accelerated enormously. The Pine Island, Thwaites, Haynes, Smith, Pope and Kohler Glaciers are now among the fastest-moving glaciers in Antarctica. Together they transport as much ice into the Southern Ocean as all the glaciers in Greenland release into its surrounding seas. The glaciers of the Amundsen Sea alone now add ten per cent to the worldwide rise in sea level (around 0.28 millimetres per year). If all six of these glaciers were to completely melt, the result would be a total global sea-level rise of 1.2 metres.

But the glaciers discharging into the Amundsen Sea today are not only flowing faster, their ice tongues have also become much thinner. And their grounding lines, the point where they lose contact with the ground and begin to float, are retreating landward by as much as one kilometre each year. This is now one of the fastest rates of glacial depletion in the world.

Because air temperatures in the coastal areas of the Amundsen Sea have so far remained largely below the freezing point, melting processes on the glacial surfaces can be eliminated as a possible reason for the changes. The causes are more likely to be found within the Amundsen Sea itself. Researchers now know that several deep trenches traverse the floor of the shelf sea from the coastal area to the edge of the continental shelf, the point where the continent ends and the bottom slopes more steeply downward. The trenches were scoured into the ground by massive ice flows during past cold periods. At the time of the last glacial maximum, for example, about 22,500 years ago, the region's ice masses are known to have extended to the edge of the continental shelf, and presumably rested directly on the seabed over large portions of the shelf.

A passage through the troughs

The two largest troughs on the continental shelf of the Amundsen Sea are the Pine Island Trough and the Dotson-Getz Trough. They play a decisive role because of the salty, deep water from the Antarctic Circumpolar Current that is slightly warmer than one-degree Celsius, and that flows through them across the continental shelf to the areas directly beneath the floating glacier tongues. When the relatively warm water penetrates beneath the ice masses, its temperature often exceeds the melting point of the ice by as much as 3.5 to four degrees Celsius due to the higher pressure at that depth. The water therefore immediately begins to melt the ice masses from below.

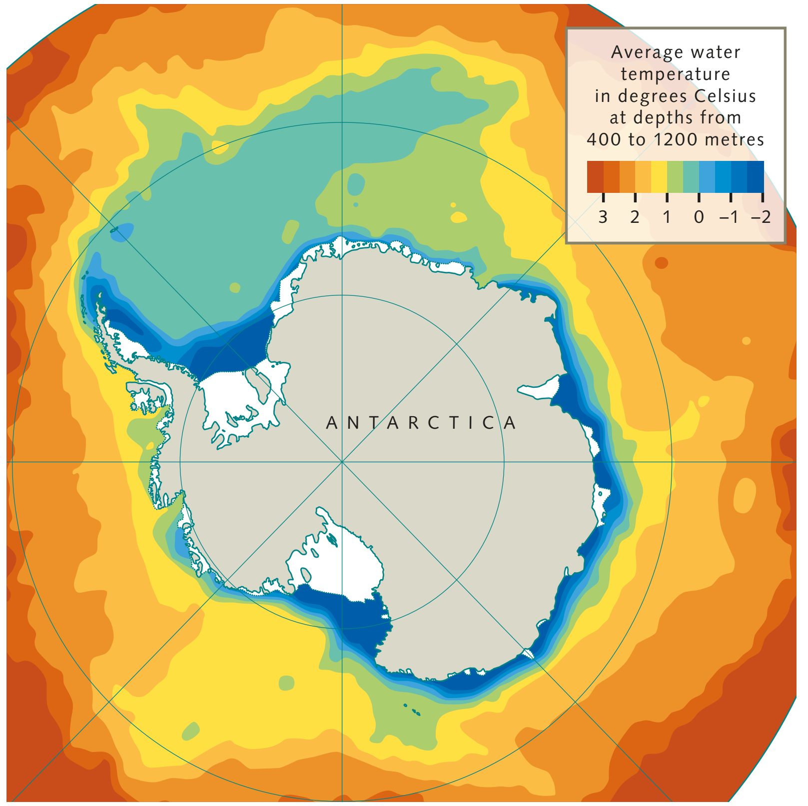
The warm, deep water has its greatest impact near the grounding line. According to estimates, the Pine Island Glacier and the Thwaites Glacier lose an average of between 15 and 18 metres in thickness each year in this way. The ice tongues are therefore constantly getting thinner, but their contact with the sea floor is also steadily receding toward the coast, a process that specialists call "retreat of the grounding lines".

The influx of warm, deep water beneath the ice masses of the Amundsen Sea was first verified in 1994 through extensive on-site measurements. It is also now known that eddies propel the water through the troughs across the continental shelf. The warm water flows in through the troughs in the eastern part of the Amundsen Sea, then the fresh, cold meltwater flows out again through the troughs in the western part. Geological data also suggest that the warm, deep water probably managed to swell upward on the continental slope of the Amundsen Sea for the first time as a result of an El Niño event at some time between 1939 and 1942. Before then, heavy, salty shelf water probably acted as a barrier to prevent this encroachment.

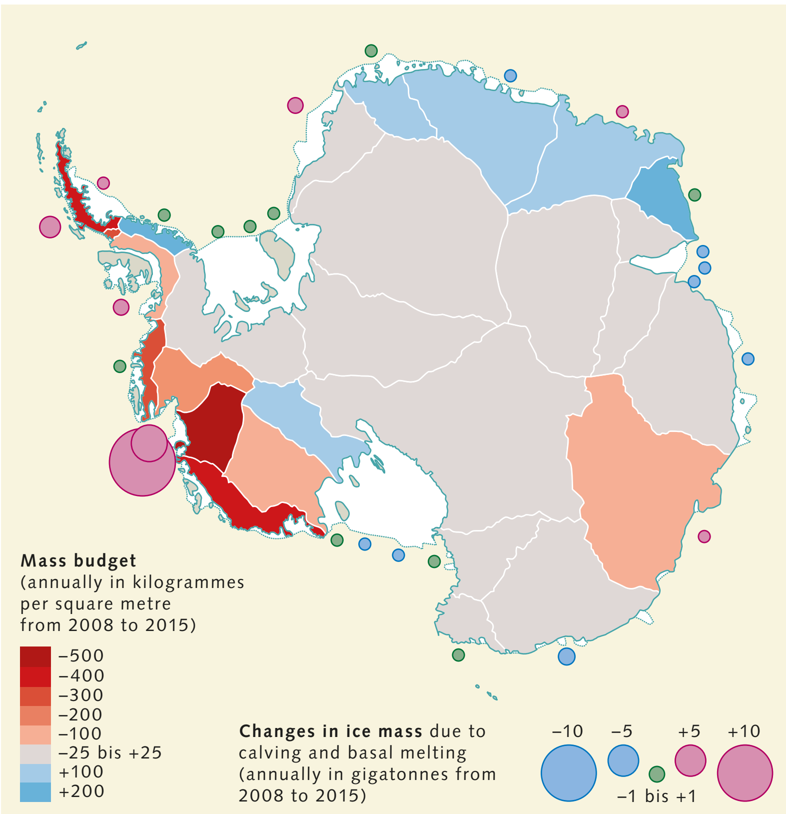
Today, the amount of inflowing deep water is influenced, among other things, by the winds over the Amundsen Sea. If the westerly winds are dominant, a great deal of warm water flows in. But if the easterly coastal winds prevail, the inflowing current weakens. And the El Niño phenomenon in the southern Pacific even has a recurring impact through remote atmospheric effects. Simply stated, during an El Niño, obstructing weather systems form more frequently over the Amundsen Sea, stimulating the westerly winds and increasing the flow onto the continental shelf.

For the coming decades, researchers predict a further increase in the westerly winds as well as continued southward shifts of these air currents.

Furthermore, water temperatures are expected to increase. For the Amundsen Sea, this would mean that the environmental conditions that facilitate the flow of large volumes of warm, deep water onto the continental shelf would prevail even more often. Predicting the reaction of the glaciers is difficult, because it is not yet well understood whether the present retreat of the ice masses is



3.44 > In 2005, a ring of cold, very saline ice-shelf water still formed an effective barrier to protect the ice shelves in the Weddell Sea, in East Antarctica, and in the Ross Sea. But now gaps are beginning to open in this wall of cold water. In West Antarctica, it broke down decades ago, and warm water from the Circumpolar Current has flowed unimpeded here onto the continental shelf and beneath the floating ice tongues.



3.45 > Antarctica divided: While the glaciers and ice shelves of West Antarctica lost large amounts of ice between 2008 and 2015 due to the calving of icebergs and basal melting, the situation in East Antarctica is not quite so discouraging. In some regions, more snow actually fell than was lost by calving or melting of the ice. The region around the Totten Glacier is the only exception.

strictly due to basal melting alone, or whether dynamic processes within the ice itself may also be involved.

But climate-model simulations indicate that the grounding line of the Pine Island Glacier, for example, could retreat much further landward if the melting by warm sea water continues.

US and British scientists are hoping to learn more about the future of the Thwaites Glacier through a new five-year research project that began in January 2019. The project involves the deployment of moorings in front of and underneath the glacier in order to monitor the inflowing and outflowing water masses. They will also send seals with measuring instruments deep under the water. The researchers themselves will traverse the glacier's top surface with geophysical equipment, collect large amounts of remote sensing data, and hopefully be able to learn whether the retreat of Thwaites Glacier is already irreversible.

Bleak outlook for the future of the Filchner-Ronne Ice Shelf

While the ice-shelf regions and glaciers of West Antarctica are in retreat, the largest ice shelves in Antarctica, the Ross Ice Shelf in the Ross Sea and the Filchner-Ronne Ice Shelf in the Weddell Sea, have not shown any particularly noticeable changes so far. This is primarily due to the large-scale formation of sea ice in these two regions. In the southern Weddell Sea, for example, the sea ice formed during the autumn and winter months releases enough salt to transform the water masses at the leading edge and below the 450,000 square-kilometre Filchner-Ronne Ice Shelf into a kind of hydrographic barrier. This wall of very high-salinity water, with a temperature of minus two degrees Celsius, has thus far protected the ice from the influx of water transported along the margin of the continental shelf by the Weddell Gyre that is 0.8 degrees warmer.

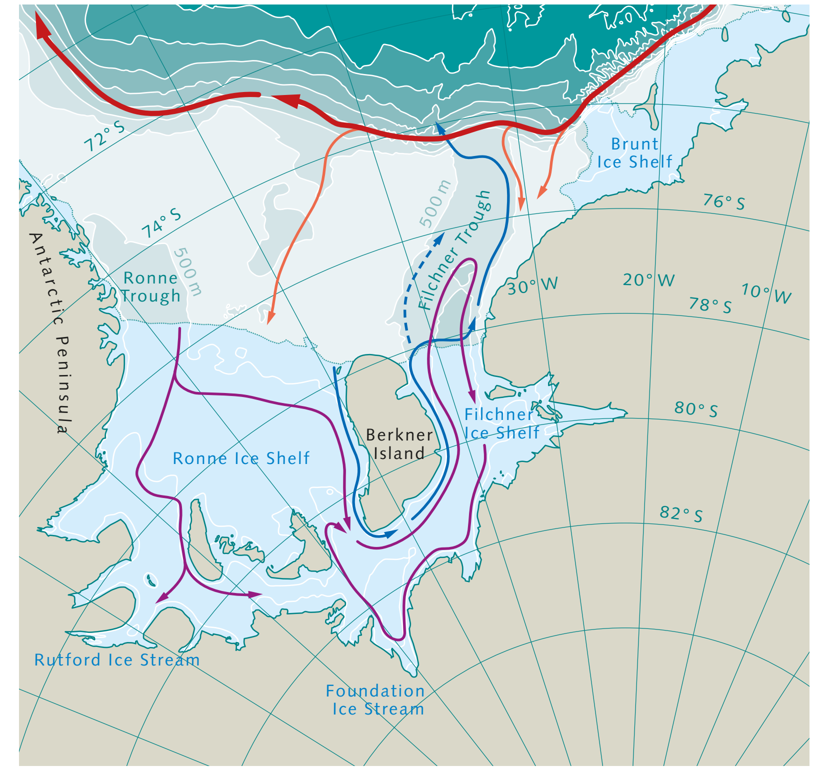
Model calculations by German polar researchers, however, indicate that this cold-water barrier protecting the Filchner-Ronne Ice Shelf could suffer a permanent collapse in the coming decades, triggered by higher air temperatures over the Weddell Sea. Researchers today are already witnessing the first signs of this change. To begin with, less sea ice is being produced in the region. Furthermore, oceanographic measurements on the sill of the Filchner Trough, a deep trench in front of the Filchner Ice Shelf and extending beneath it, indicate that warmer water masses from the Weddell Gyre are already penetrating onto the continental shelf through this trough. Until the year 2016, German and Norwegian researchers had only observed the advances of this minus 1.5-degree Celsius deep water during the Antarctic summer, with some phases even reaching to the ice shelf. The winters at that time, however, continued to be dominated by the cold, highly saline shelf waters. But a more recent series of measurements, obtained in 2017, revealed an influx that researchers had not previously observed in the Weddell Sea. For the first time, the instruments at the entrance to the Filchner Trough revealed the presence of warmer water throughout the entire year, with temperatures well above minus one degree Celsius.

These small-scale changes may signal the beginning of a fundamental and irreversible change in the southern Weddell Sea that will probably become firmly established by the middle of the 21st century. Once the warm water masses have reached the ice shelf, there will likely be no turning back, because their heat will greatly accelerate melting on the underside of the ice. The freshwater released will then reinforce the overturning currents, which will draw even more warm water from the Weddell Gyre into the area beneath the ice.

As a result of the dramatic melting on the underside of the ice shelf, the grounding line of the ice body will shift further to the south, and thus gradually lose contact with the sea floor. Until now, the friction of ice on the sea floor has had the effect of slowing the ice flow. If this braking effect is removed, the flow of ice from the East Antarctic Ice Sheet will accelerate. The cycle of heat and meltwater under the ice shelf will not weaken until the ice shelf has completely disintegrated, or when glacial ice no longer flows out from the continent. These processes will therefore certainly continue for several centuries.

In order to quantify the predicted influx of warm water below the ice, German, British and Norwegian scientists drilled through the Filchner Ice Shelf at seven sites during the Antarctic summer of 2016, and installed moorings with oceanographic measuring devices under the ice tongue. The temperature, salinity, current-velocity and current-direction data for the water masses in the Filchner Trough are transmitted to European institutes daily and provide the scientists with completely new insights into the processes beneath the ice shelf.

According to their initial findings, up to 2017 the ice-shelf waters here originated at some times from the polynyas in front of the Ronne Ice Shelf near the Antarctic Peninsula, or at others from the front of the Filchner Ice Shelf, on the Berkner Rise with the island of the same name. At that time, the first current always flowed in from the west, moved below the ice shelf south of Berkner Island, then proceeded northwards through the Filchner Trough until it emerged, to some extent, from under the ice shelf. The second current flowed in the opposite direction. It ran through the Filchner Trough and flowed under the ice shelf.



But in 2017, it became apparent to the researchers that these two currents were no longer alternating. At present, only Ronne shelf water coming from the west is flowing through the Filchner Trough and, among other things, is causing the Filchner Ice Shelf to melt from below. This is also indicated by changes in the thickness of the ice shelf, which the scientists can calculate from satellite data. But why does the Filchner-Ronne Ice Shelf melt faster in the deep trench? Since the measurements began, the water masses near the bottom there have warmed by 0.1 degrees Celsius. That may not sound like much, but it is a lot considering the size of the ice shelf and the water masses flowing beneath it, and it can lead to significant melting on the underside of the ice and at the grounding line. In the Antarctic summer of 2021, the researchers want to investigate how the Ronne ice shelf water forms and how it has changed in recent decades. They will sail to the Ronne region with the German polar research vessel *Polarstern* to make extensive oceanographic measurements from the ship.

3.46 > Two separate troughs run beneath the Filchner and Ronne Ice Shelves in the Weddell Sea, through which water masses circulate and penetrate deep beneath the two ice bodies. Water coming from the Ronne shelf in the west (purple) is currently predominant. In recent years it has warmed by 0.1 degrees Celsius and is now known to be melting the ice shelf from below.

Deceptive calm in East Antarctica

In the eastern part of Antarctica, the balance of expansion vs. loss of ice mass has so far remained more or less in equilibrium. But the first signs of climate-related changes have already been detected. For example, the large Totten Glacier and its neighbours are transporting their share of ice towards the sea at much faster rates than they did 20 years ago. Scientists are keeping a close watch on these glaciers because their combined catchment area is the size of France, and thus includes large portions of the East Antarctic Ice Sheet. The complete melting of these ice masses would raise global sea level by 3.5 metres. For this reason, the large Totten Glacier is considered to be a particularly useful indicator of climate-induced change in East Antarctica.

The Totten Glacier flows through a long, deep fjord, the bed of which slopes to the south in some parts, similar to the sea floor in West Antarctica. The distal part of the ice tongue floats on the sea and forms the Totten Ice Shelf, which in the past rested on a very rugged bottom at a depth of about 500 to 800 metres. In the Antarctic summer of 2014/2015, Australian scientists were able to sail directly up to the leading edge of the Totten Glacier with a research vessel for the first time, and take detailed oceanographic measurements in the water column and on the sea floor. At a water depth of around 600 metres, on the western side of the glacier, they discovered a trough ten kilometres wide and 1097 metres deep on the sea bed. At the time of the measurements, water masses with temperatures of minus 0.41 to minus 0.57 degrees Celsius were flowing through this trough on the underside of the ice shelf.

The scientists identified the inflowing water as warm, saline, and relatively oxygen-poor deep water that originated from the Circumpolar Current. This influx becomes more important when we consider the fact that the Totten Glacier rests on the sea floor at such a great depth that the higher pressure depresses the freezing point of water to far below the normal values. The scientists determined that the inflowing water, with a temperature of around minus 0.5 degrees Celsius, is about three degrees warmer than the melting point of ice at the grounding line. This means that the melting ability of the deep water is almost as great as that of the warm water flowing into the Amundsen Sea. According to estimates, the Totten Glacier loses between 60 and 80 gigatonnes of ice annually through basal melting. This is equivalent to an average loss of around 9.9 to 10.5 metres in thickness per year, whereby the ice shelf has a total thickness of 200 to 1000 metres.

This confirms that, even on the largest glacier in East Antarctica, warm sea water penetrates to the grounding line and can lead to abrupt losses in mass there. The Totten Glacier is thus more dynamic than previously assumed. It reacts much more sensitively to climate-related changes and, as a result of the basal melting, it could lose contact with the sea floor on a massive scale. Should that happen, it would also lose its ability to hold back the inland ice masses of East Antarctica pressing from behind.

3.47 > Totten Glacier is the largest glacier in East Antarctica, but it is also losing more ice than the neighbouring glaciers.

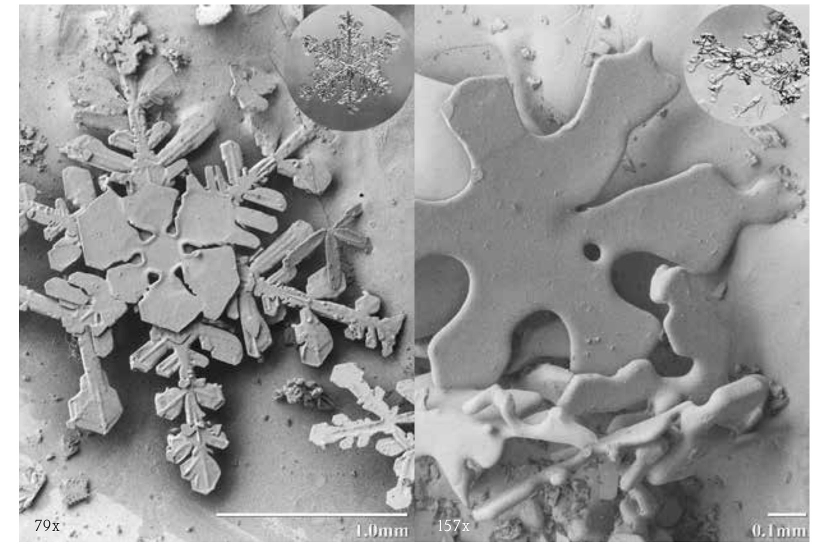
Greenland – warming hotspot

While the loss of ice mass in the Antarctic region is mainly the result of calving of icebergs and melting processes on the underside of ice shelves, Greenland's ice cap has been primarily diminishing from above since the 1990s, as a result of melting on the upper surface. This melting accounts for 61 per cent of the increased ice loss. The remaining 39 per cent is the result of intensified glacier calving. The increased rates of surface melting can be attributed to a rise in summer temperatures by about two degrees Celsius since the early 1990s.

The GRACE satellite system registered extremely high melting rates during the summer of 2012. At that time, unusually warm air and sustained periods of cloudless skies caused surface melting over 97 per cent of Greenland's ice-sheet area. In July alone, there was a loss of 400 to 500 billion tonnes of ice, which resulted directly in a global rise in sea level of more than one millimetre. In that summer, meltwater gushed from the ice sheet in torrents, even damaging bridges and roads in western Greenland that had been built in the 1950s and had never suffered any damage before. Melting events on this scale have only happened twice in the recent climate history of Greenland, as is revealed by the data from ice cores. One of these was in 1889, and the other was seven centuries earlier during the Medieval Warm Period (also known as the Medieval Climatic Anomaly).

To the surprise of the scientists, 2012, the summer of extreme melt, was followed by a relatively cold year, during which the total amount of new snow accumulation was almost as much as the ice lost by melting and breaking off of icebergs. But the overall trend since 1990 is very clear. Greenland is warming and losing more and more ice. However, the GRACE data also reveal large variations in the mass balance of the ice sheet. Researchers say that anything is possible, from extreme melting to years with abundant snowfall and minor loss from melting.

The current continued warming of the summers in Greenland is due to increasing concentrations of greenhouse gases in the atmosphere. Since 2003, they have led to an increased frequency of warmer air migrating into Greenland from the south, which has been instrumental in warming the western part of the island in particular.



3.48 > Freshly fallen snow crystals have a multitude of facets and edges that reflect sunlight. But heat causes these microstructures to melt into one another. The sharp edges are rounded off and the crystals clump together so that the snow cover becomes darker overall and absorbs more solar energy.

Scientists also say that the jet stream is involved to some extent. If this strong wind weakens as a result of the decreasing temperature gradient between the Arctic and the middle latitudes, an obstructing high-pressure area could develop over Greenland, causing cloudless skies, high levels of incoming solar radiation, minimal snowfall, and an influx of air from the south.

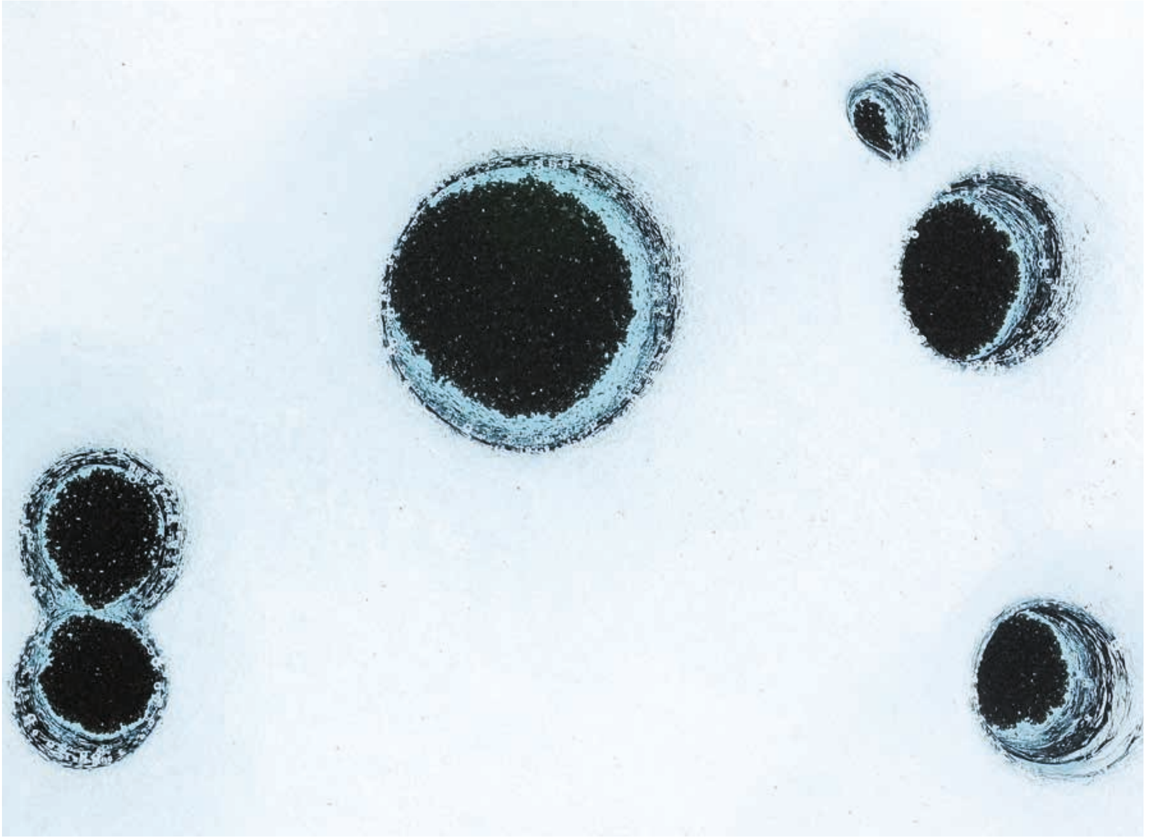
The amount of surface melting is also influenced in a complex way by clouds. Measurements on the highest plateau of the Greenland Ice Sheet, for example, have shown that even at these elevations the snow layer sometimes melts in summer, when clouds comprising a particular mix of water drops and ice crystals drift over the plateau. These increase the optical density and absorption properties of the atmosphere and amplify the long-wave heat radiation on the ice sheet, which then activates the surface melting. At the same time, new studies indicate a general decline in the presence of summer clouds over Greenland because of the increased frequency of an obstructing high-pressure system over the island. In the absence of clouds, the sun's rays fall on the ice sheet practically unobstructed, which reinforces the melting, especially in the marginal areas with lower albedo.

Solar radiation poses very little threat to an ice sheet when it is covered by a fresh layer of dry, fine-grained snow, which reflects up to 85 or 90 per cent of the incident short-wave solar energy. However, even when the snow merely begins to melt and become wetter, a natural feedback process is triggered that plays a particularly important role in Greenland, where 90 per cent of the island's ice is normally covered by snow. When snow crystals become wet, they clump together and grow. As a result, their optical properties change and the reflective power of the snow cover is reduced. So, instead of almost completely reflecting the incoming radiation, the snow grains now absorb more and more light energy, especially in the long-wave infrared range. For example, when the albedo of a snow cover is reduced from 85 per cent to 70 per cent, the snow absorbs twice as much radiation. This added energy, in turn, promotes more clumping of the snow crystals, which makes the snow darker and further reinforces the absorption of energy and melting. Eventually, the snow cover is completely melted. All that remains is bare ice with a surface covered by an uneven mosaic of puddles, runnels and abundant ice humps. Instead of the former white brilliance, the summer takes on a cheerless grey character, especially on the western margin of the Greenland ice sheet.

The peripheral dark zone

The grey shading of the ice is caused by the presence of ice algae that spend the winter in the upper ice layer and produce large algal blooms when the overlying snow cover melts. For this reason, scientists also refer to the snow-free margin of the ice sheet as the "dark zone". The Greek scholar Aristotle (384–322 BC) once remarked that snow is not always only white, but can also sometimes turn a green or a reddish colour. But the discovery that living organisms were responsible for these unusual colours required the later invention of the microscope. It is still unknown, however, how many species of ice and snow algae live in the world's glaciers and ice sheets today, or how they survive. As yet there are also no answers regarding the extent to which their blooms facilitate melting on the Greenland Ice Sheet.

It is now known that snow algae spend about six months in a spore stage during the winter, depending on their location. The unicelled organisms do not begin to divide and grow until the spring or summer when the snow begins to melt, because they need liquid water in order to carry out photosynthesis. In summer, they also produce pigments, known as carotenoids, which they deposit around their chloroplasts and cell nuclei to protect them from the sun. The presence of chlorophyll initially gives young snow algae a shimmering green colour. The older the organisms become, however, the more carotenoids they accumulate, and the more orange or reddish they become. Over the course of the summer, snow algae also store fats in their cells and their cell walls become thicker in order to withstand the potential pressure of the snow masses, and for protection against predators. At the same time, they expel water from their cells to avoid destruction when the water freezes and expands.



3.49 > Wherever dust, ashes or other particles are deposited on the ice, cryoconite forms as cylindrical, finger-sized holes. They are the habitat for many microorganisms, but they also darken the ice sheet and further promote the melting of ice at the surface.

Ice algae, on the other hand, of which there are only three known species so far, are less complex than the snow algae. These one-celled organisms, which often occur in chains, protect themselves from the sun's radiation with a brownish pigment, which is why they typically lend a grey tone to the ice. In contrast to snow algae, ice algae do not reinforce their cell walls. So far, it is known only that the cells survive the winter in a kind of dormant state, and then in summer, when the snow on the glacier surface melts, they begin to divide and grow again.

Over the past two decades, research on the impacts of the algal communities on surface melting on the Greenland Ice Sheet and other glaciers has intensified. Today, it is known that the presence of snow algae, whose communities are dominated by six species, significantly reduces the reflectivity of a glacier during its growth phase. Reddish-coloured snow reflects only about 49 per cent of the incident sunlight, and the shimmering greenish snow only 44 per cent. Bare ice suffused by ice algae achieves an albedo effect of a mere 35 per cent.

Ice whose surface is covered with a biofilm of algae and mineral dust, or is sprinkled with what are known as cryoconite holes, has an even lower reflectivity. Cryoconite consists of small particles of organic (algae, bacteria) or mineral material (dust, desert sand, ash particles) that are transported by the wind and deposited on the ice. As dark spots or dust deposits on the light-coloured ice, they absorb more heat than their surroundings, so the ice melts in the immediate vicinity of the debris and gradually forms cylindrical cavities. Water, as well as algae and other organic and inorganic material, collects in these holes, creating microhabitats in which bacterial communities, viruses, tardigrades, ciliates, rotifers, ice worms and mosquito larvae thrive. The overall reflectivity of a glacier's surface that is riddled with such holes is only 23 per cent of the incident sunlight.

3.50 > Meltwater flows out from beneath Greenland's Russell Glacier. It originates in part from lakes on the glacier that are drained through fissures in the ice.

The area of the Greenland Ice Sheet affected by snow and ice algae is expanding due to the effects of climate change. On one hand, the snow begins to melt earlier in the year, so the algal bloom begins earlier and the organisms have more time to grow and spread. On the other hand, because of the warming, the snow line is steadily advancing toward the continental interior. Under these conditions, individual ice algae carried by the wind can reach remote central regions of the ice sheet and start new blooms there. Extreme melting events, like the one in the summer of 2012, therefore facilitate the spread and the duration of the algal blooms, and further promote surface melting on the Greenland Ice Sheet.

Ice lenses, water reservoirs and turquoise lakes

As in Antarctica, not all of Greenland's meltwater runs off the ice sheet. Especially in the high elevations of the island, up to 45 per cent of the meltwater seeps into the porous firn layer of the ice sheet where most of it freezes again. During this freezing process the meltwater gives up latent heat to its surroundings, which contributes to the long-term warming of the firn layer. Furthermore, the meltwater freezes to an impermeable ice layer or lens that, unlike the firn layer, contains no pores.

If melt water seeps down again in the following summer, it can only penetrate to the meltwater horizon of the previous year. Through this process, the capacity of the firn layer to take up more meltwater diminishes over time, which means that more meltwater collects on the ice surface as meltwater lakes or streams. In south-eastern and north-western Greenland, heavy snowfall in the winter and high melting rates in the summer have even led to the formation of water lenses in the firn. These accumulations of water can persist for several years before they finally seep to greater depths via cracks and crevices in the ice, and eventually emerge as a meltwater stream on the underside of the glacier.

Meltwater that cannot drain away usually collects in depressions on the surface of the ice sheet. In the past, prominent meltwater lakes were formed in this way, especially on the low-lying periphery of the ice shield. But now these lakes are also found at higher elevations. In south-western Greenland, for example, the upper limit of meltwater lake occurrence has migrated inland by 53 kilometres over the past 40 years, shifting to higher elevations on the ice sheet. Up to 1995, this shift was occurring in small increments, and the upper limit was only moving inland by about 500 metres each year. Since then, however, the summer temperature in the region has risen by 2.2 degrees Celsius. More snow and ice has melted in the summer, and in some years the elevation limit of the meltwater lakes has migrated inland by up to three kilometres.

This trend will persist in the future. Climate models indicate that, by the year 2050, meltwater lakes will be forming even at elevations above 2200 metres in south-western Greenland. The elevation limit of the lakes will then have migrated more than 100 kilometres landward and more than 400 metres higher on the ice sheet. The area of ice upon which meltwater lakes can form will have doubled compared to today.

However, these lakes are not destined to last indefinitely. Many of them drain off after only a few days when the ice below them shifts, causing cracks and fissures to form. When a fracture extends from the ice surface to the base of the glacier, it is called a glacier mill, or moulin. All of the water in the lake then flows through this drain to the base of the ice, a process that often only takes a few hours, and through which the water releases heat to the ice body. In some situations, when the lake water reaches the bedrock below the ice sheet or glacier, it can increase the water pressure and thicken the film of water upon which the ice masses are gliding. This tends to increase the velocity of the glacier, at least for a short time.

Retreat from the sea

Despite the importance of surface melting, it is important to note that Greenland's glaciers also lose mass when ice blocks break off and melt on land, or when glaciers push their tongues of ice out into the sea where icebergs calve. The word "sea" in this case, however, is not completely accurate. The glaciers generally discharge into fjords, which can have a significant effect on their flow velocity

3.51 > Meltwater lakes absorb a large proportion of the incident solar energy and melt deep cavities into the ice. If these connect with a deeper-lying crack or crevice, the lake can drain out in a short time.

and stability. The ice rubbing along the steep rock walls of the fjords is subjected to an effect similar to that generated by the brake shoes on a car, which tends to slow the glaciers down. But the shorter the distance of contact between the sides of the glacier tongue and the rocks, the less braking effect is applied to the sides, and the faster the glacier can flow. This has been demonstrated, for example, by studies on the Petermann Glacier, whose ice tongue extends into Petermann Fjord. This large outlet glacier in the extreme north-western part of Greenland lost a large portion of its floating ice tongue in 2012 with the break-off of an iceberg. As a result, the braking effect of the rocks on the glacier was diminished, and the rate of ice flow increased by ten per cent.

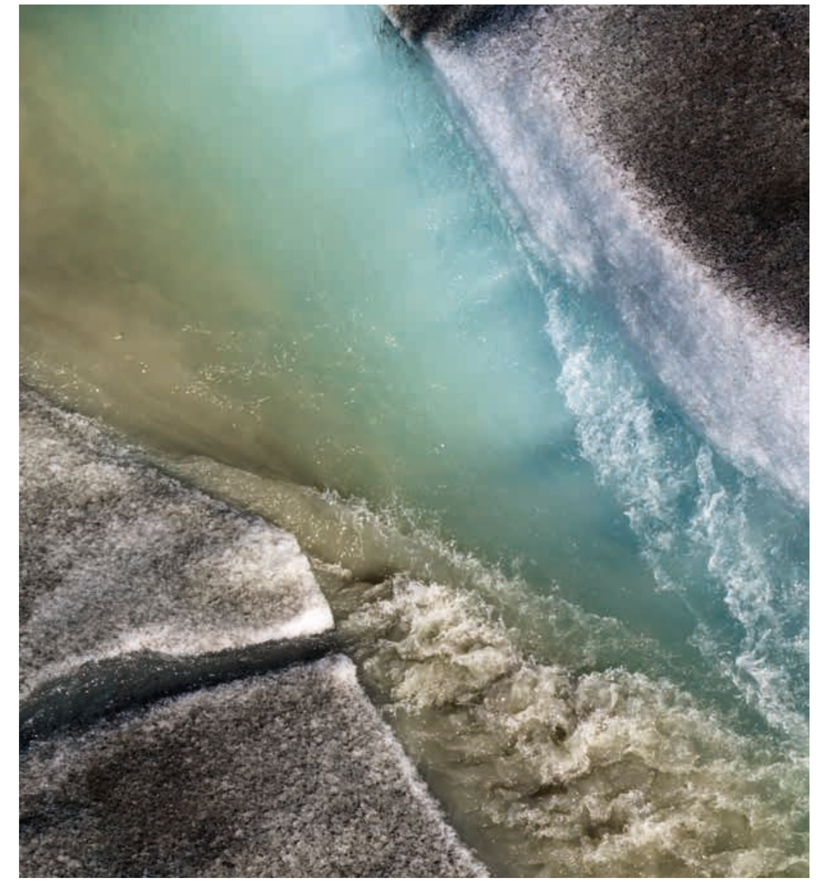
The Petermann Glacier is one of only three remaining outlet glaciers in Greenland that have floating ice tongues. All of the other previous glaciers of this type have already lost all of their floating ice. Their total ice masses are now lying on the sea floor or they have retreated completely back onto the land. The once-floating ice areas have succumbed to the warmth of the sea. Warm water currents with temperatures of up to four degrees Celsius have largely melted the ice bodies from below, causing them to become thinner and forcing the ice to break off, particularly in south-eastern and south-western Greenland. Prior to the loss by the Jakobshavn Glacier (Danish: Jakobshavn Isbræ) on the west coast of Greenland of a 15-kilometre-long piece of its floating ice tongue after 2001, for example, the water temperature had risen by one degree Celsius and, as a result, the melting rate at the base of the floating ice area increased by 25 per cent. In addition, melting processes below the water surface had contributed to a

landward shift of the glacier's grounding line, and to a reduced braking effect of friction with the fjord bottom.

Of the 13,880 glaciers on Greenland, a mere 15 account for half of the total loss of mass by iceberg break-off or basal melting. Researchers refer to these losses as dynamic ice loss. Five of these glaciers alone contribute more than 30 per cent of the loss. These are the Jakobshavn Isbræ, located on the west coast of Greenland, and the Kangerlussuaq, the Koge Bugt, the Ikertivaq and the Helheim Glaciers, all of which are situated in close proximity on the south-eastern coast of the island. But a relatively large proportion of the present losses can also be attributed to the Upernavik Ice Stream and the Steenstrup Glacier on the west coast, and the Zachariae Ice Stream (Danish: Zachariae Isstrøm) in north-eastern Greenland.

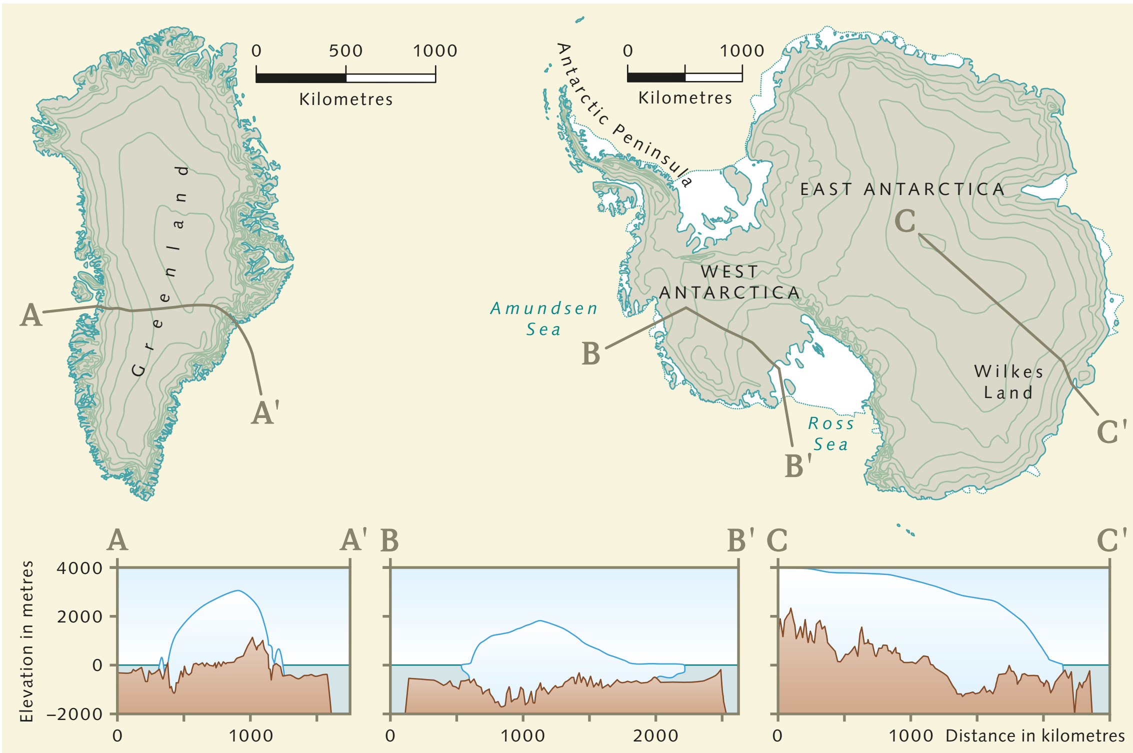
Although the flow velocities of most of Greenland's glaciers have increased, the number of iceberg break-offs, and thus the rates of retreat of the ice tongues are highly variable. While some glaciers appear to be rather stable, the ice tongues of others are rapidly becoming shorter, as exhibited, for example, by the Zachariae Ice Stream and its neighbour the Nioghalvfjerdsbrae, sometimes called the 79° North Glacier. This kind of inconsistent behaviour is usually due to differences in the topography of the various fjords and glacier beds. If the glacier flows through a very narrow or flat passage in the fjord, for example, or if there is an island in the middle of the fjord, these obstacles can prevent ice from breaking off, and thus preserve the stability of the glacier for several decades. As soon as the glacier loses contact with the braking element, however, it may quickly thin out and retreat.

The Zachariae Ice Stream experienced a sudden retreat of its ice tongue in the fjord after it lost contact with the bottom in a shallow passage, and eventually lay with its ice tongue in an area of deeper water behind the shallow part. The warm sea water then came into contact with a larger surface area of ice, and melted it. By contrast, the 79° North Glacier flows through a fjord whose profile gradually rises landward over a distance of 150 kilometres, thus creating ideal conditions for a slow retreat of the glacier.



3.52 > Meltwater loaded with sediment flows out from under the floating ice tongue of a Greenland glacier and colours the sea brown.

Another decisive factor in glacier stability is the quantity and temperature of the meltwater flowing towards the sea at the base of the ice stream. On sonar scans of West Greenland's glaciers, scientists have discovered that these subglacial meltwater streams carve channels and cavities into the ice bodies from below. At these thinner sites, the ice not only loses its restraining contact with the subsurface, the risk of iceberg calving also increases. If the meltwater spreads out over a wide area under the glacier, it may even quintuple the basal melt rate at the leading edge. The extent to which these meltwater streams penetrate beneath the ice can often only be surmised from above. At the Humboldt Glacier in north-western Greenland, for example, there is so much water flowing into the sea from the underside of the glacier that the large amounts of sediment it carries give the water at the leading edge a coffee-brown colour.



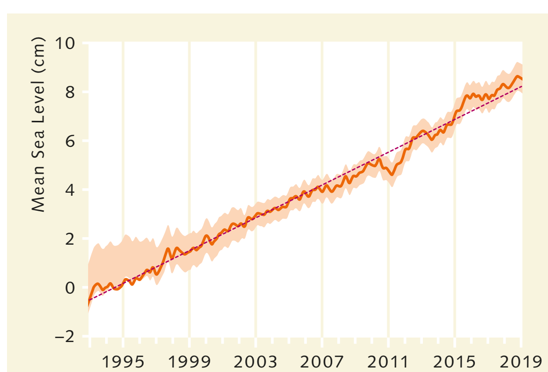
3.53 > While large portions of the two Antarctic Ice Sheets rest on land surfaces that are below sea level and are thus accessible to warm water masses, in Greenland this configuration is only known in areas where the ice bodies occupy deep glacial troughs. The rest of Greenland's land surface is still higher than the sea surface.

And, finally, the stability of the ice masses at the leading edge also depends on the amount of sea ice that builds up in front of the glacier and tends to hold it back. In winter, when the sea is frozen over and the ice floes are piled up in front of the glacier, only a few icebergs will break off. But in summer, when the melange of ice floes and iceberg remains is melted, the frequency of calving events increases again. Thus, the general decline of Arctic sea ice is also directly influencing the mass loss of the Greenland glaciers and the long-term rise of global sea level.

Accelerating sea-level rise

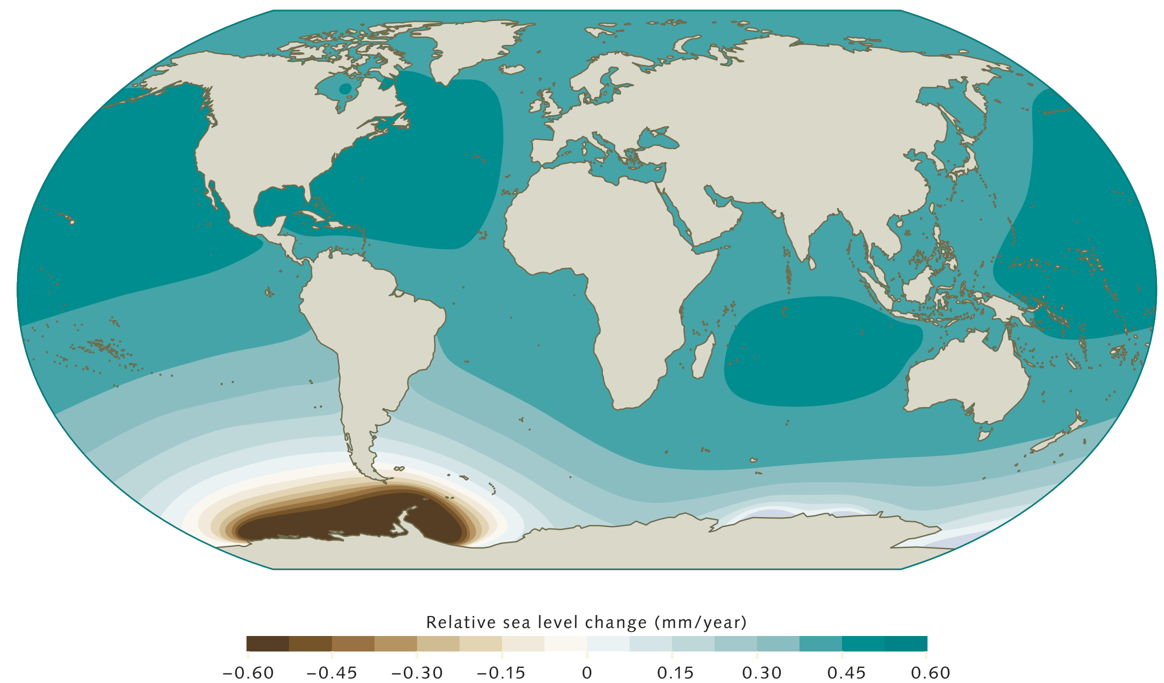
Global sea level has been rising since the peak of the last glacial period 21,000 years ago. At that time, it was about 123 metres lower than it is today. But a glimpse into more recent climate history also reveals that since humankind began to settle down, sea level has never risen as fast as it is rising now. From the beginning of satellite-based altimeter measurements in January 1993 to 2017, the annual increase surpassed the previous year-to-year increase no less than 22 times.The global level is now rising by 3.34 millimetres per year. At the beginning of the satellite measurements in 1993 it was 1.7 millimetres, and around the year 1900 the rise was only 1.2 millimetres.

This disturbingly sharp increase is primarily due to two factors. On one hand, the ice sheets and glaciers of



3.54 > Global sea level continues to rise. Since 1993 it has risen by a little more than eight centimetres.

Ice loss in West Antarctica and its influence on sea level



3.55 > If the mass of an ice sheet decreases, its gravitational pull on the water masses of the oceans is also reduced. The water is then attracted by the heavier land masses and redistributed around the world. For this reason, the melting of ice in West Antarctica results in a greater rise of water levels in the northern hemisphere, while the levels in the Antarctic region fall.

the world are losing large amounts of ice, and the resulting water either enters the ocean directly or is carried in by rivers. On the other hand, the temperatures in the world's oceans are rising, and warmer water expands and takes up more space than cold water. In addition to these, less water is stored on the land. Because of the huge amount of water consumption by human society, the lakes, rivers, dams, reservoirs, groundwater bodies and wetlands now contain significantly less water than they did in the past. Instead, a large proportion of utility, process and tap water ends up in the sea and contributes, albeit to a very small degree, to the rise in water levels.

But how much of the rise is a result of thermal expansion and how much is due to the input of meltwater? Until ten years ago each contributed approximately an equal amount to the rise of sea level. But since then the global loss of ice mass from the ice sheets and glaciers has increased significantly. Now the meltwater contribution to the rise is almost two-thirds and the effect of thermal expansion of the sea water accounts for about one-third.

The amount of sea-level rise is different in every coastal region of the world. In some locations it is far less than the average, for example, in Antarctica and the west coast of the USA. In other areas it is rising much faster than the global mean. Examples of this include South East Asia, Indonesia, and the Philippines. These regional differences are the result of three factors:

Local postglacial uplift or subsidence of land

The elevation of a land body is not a static, invariable factor when it comes to determinations of sea-level rise, because it can rise up or sink in coastal zones. These processes can be readily observed in the northern hemisphere, especially in regions that were covered by large ice sheets during the last glacial period, like the north-western USA. These land areas subsided under the weight of the ice while areas on the margins of the ice masses were uplifted in response. Then, as the ice sheets gradually disappeared, these motions were reversed. Some stretches of the coast in North Carolina and bordering the German

North Sea are still subsiding today, while areas that were formerly lower are now rebounding upward.

Redistribution of the water masses due to gravity

When meltwater flows into the sea as a result of ice loss by ice sheets and glaciers, it does not remain at that location, but is redistributed according to the Earth's regional gravity. Areas with relatively weak gravitational fields and thus lower attraction receive less water, while regions with stronger gravitational attraction receive more. And because both Greenland and Antarctica are losing their attractive force due to the loss of ice mass, the water is presently collecting mainly in the mid-latitudes.

Redistribution of heat in the oceans

Warm water expands and takes up more space than the same amount of cold water. Some regional differences in sea-level rise can therefore be attributed to the heat distribution in the world's oceans. The differences in how ocean currents distribute heat around the globe also influence the local levels. The wind plays an equally important role. It can blow water masses away from the coasts or, coming from the opposite direction, pile them up in front of the coast, thus significantly changing the local level.

Global sea-level rise is one of the most severe consequences of climate change, and mainly affects low-lying islands and the densely populated coastal areas of the world. With a worldwide temperature increase of four degrees Celsius, sea level would rise enough to flood regions that are home to 470 to 760 million people today. The Intergovernmental Panel on Climate Change is forecasting a rise of 0.3 to one metre by 2100, depending on how fast the Earth warms up. It is uncertain, however, how quickly the ice sheets and glaciers will react to the warming, and how much the corresponding sea-level rise will be. It now appears that the changes are occurring faster than many expected.

3.56 > Some icebergs are comprised of marine ice that once formed on the underside of an ice shelf. It contains small air bubbles and is initially clearer and bluer than normal glacial ice. If reddish, yellow-brown iron oxide is frozen into the ice, it can also exhibit a luminous greenish colour.

Conclusion

More heat – much less ice

The atmosphere is warming as a result of increasing greenhouse gas emissions and the greenhouse effect. But more importantly, the world ocean is warming. It has absorbed 93 per cent of the additional heat so far. Particularly in the polar regions the rising air and water temperatures are causing fundamental changes that are occurring earlier and more noticeably in the Arctic than in the Antarctic. The Arctic region is warming twice as fast as the rest of the world because processes in the ice, land, sea and atmosphere of the polar regions are so closely interrelated that changes in one of these components has a direct effect on the others, and they reinforce one another. Scientists call this "Arctic amplification". The effect is especially pronounced in winter. Many regions of the Arctic are receiving significantly less snow. At the same time, not as much sea ice is forming. Since 1979, the ice cover on the Arctic Ocean has lost more than 30 per cent of its area. Furthermore, the sea ice today is younger and thus thinner, more fragile, and more mobile.

The rising temperatures also affect permanently frozen soils in the Arctic. The permafrost is warming to greater depths and thawing ever deeper and over larger areas in the summer. As a result, portions of the Alaskan and Siberian coasts are eroding, entire landscapes are subsiding, and the once-frozen subsurface is losing its load-bearing capacity, causing substantial damage to buildings, roads and other infrastructures.

The ice masses on land in the Arctic are undergoing substantial change. The Greenland Ice Sheet, as well as the glaciers in Alaska and Canada, are losing more ice than is being replaced by new snowfall. This is the result of melting processes on their upper surfaces and on the underside of the ice tongues where they are in contact with sea water.

In Antarctica, the atmosphere had only warmed noticeably by the end of the 20th century in the region of the Antarctic Peninsula. This was evidenced by the breakup of the northern ice shelves, and by a decline in sea ice on the western side of the peninsula. In all other regions of Antarctica the air temperature has only risen slightly or not at all – a situation that scientists attribute to the cooling effect of the Antarctic ozone hole. Nonetheless, warming in the Southern Ocean is causing profound changes in the Antarctic, with effects that vary from area to area. The loss of ice in West Antarctica gives major cause for concern. In recent decades, warm water from the Circumpolar Current has been penetrating far beneath the ice shelf in the Amundsen Sea and melting it from below. These ice masses are thus retreating at a record pace, a process that will probably not end until the part of the West Antarctic Ice Sheet that is resting on the sea floor has completely disappeared.

There are now signs of a similar development in East Antarctica, where the Totten Glacier is losing contact with the bottom, and in the Weddell Sea, where warm water is threatening Antarctica's second-largest ice shelf.

Overall, the rate of ice-mass loss in the Antarctic region has tripled since 2012. The share of its contribution to global sea-level rise has risen accordingly. At 3.34 millimetres per year, the global rate is twice as high as it was in 1990, whereby the rise is due mostly to the losses of ice in Greenland and glaciers outside of Antarctica, as well as to the thermal expansion of water. However, it is a fact that, because of the rising water levels, the decline of polar ice is becoming a threat to coastal regions around the globe.