world ocean review

Living with the oceans. 2019

6

The Arctic and Antarctic – Extreme, Climatically Crucial and In Crisis

Published by
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future ocean
KIEL MARINE SCIENCES

IOI

KDM
Konsortium Deutsche Meeresforschung
German Marine Research Consortium

mare

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The *World Ocean Review* is a collaboration between the following partners:

future ocean
KIEL MARINE SCIENCES

The Kiel-based Future Ocean research network brings together more than 250 researchers working across the full range of natural sciences, economics and legal and social sciences to explore ocean change and climate change. Their shared goal is to devise options for the sustainable conservation and use of the oceans. The institutional partners are Kiel University (CAU), the GEOMAR Helmholtz Centre for Ocean Research Kiel, the Kiel Institute for the World Economy (IfW) and the Muthesius University of Fine Arts and Design.

IOI

The International Ocean Institute is a non-profit organization founded by Professor Elisabeth Mann Borgese in 1972. It consists of a network of operational centres located all over the world. Its headquarters are in Malta. The IOI advocates the peaceful and sustainable use of the oceans.

mare

The bimonthly German-language magazine *mare*, which focuses on the topic of the sea, was founded by Nikolaus Gelpke in Hamburg in 1997. *mare's* mission is to raise the public's awareness of the importance of the sea as a living, economic and cultural space. Besides the magazine its publisher mareverlag also produces a number of fiction and non-fiction titles twice a year.

KDM
Konsortium Deutsche Meeresforschung
German Marine Research Consortium

The German Marine Research Consortium combines the broad expertise of German marine research. Its membership comprises all of the research institutes that are active in marine, polar and coastal research. A primary objective of the KDM is to collectively represent the interests of marine researchers to national policy-makers and the EU as well as to the general public.

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Laptev Sea
ARCTIC
OCEAN
Banks Island
Victoria Island
Parry Islands
Queen Elizabeth Islands
Severnaya Zemlya
Geographic North Pole
Devon Island
Ellesmere Island
Kara Sea
Baffin Bay
Franz Josef Land
Novaya Zemlya
Svalbard
Fram Strait
Ny-Ålesund
Greenland
Barents Sea
Greenland Sea
Norwegian Sea
Arctic Circle
ICELAND
ATLANTIC OCEAN
NORWAY
SWEDEN
FINLAND
Baltic Sea
North Sea
RUSSIA

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Preface

“Why oceanography?” was a question I was often asked regarding my choice of profession 30 years ago. At that time, the word “ocean” tended to bring to mind the popular TV series *The Undersea World of Jacques Cousteau*, maritime heritage in harbour districts, the beaches of Spain and Italy, or perhaps aquatic sports. A well-known German author once told me: “The ocean doesn’t interest me at all.” Awareness of the sea as an ecosystem was as rare as the recognition of its influence on our lives.

Since then, the situation has changed dramatically – and permanently. Today, we still only have a partial understanding of the many chemical, physical and biological processes and relationships that exist in the ocean, but our knowledge is now at least sufficient to recognize the complexity of this ecosystem, its fragility, and hence the need to protect it. For example, we now know about the significance and influence of nutrients, and about organisms’ sensitivity to changes in pH value and temperature. Such knowledge clearly reveals the vulnerability of ocean ecosystems – and the immensity of our responsibility to this vast realm.

The influence of the oceans on our own lives is also becoming more apparent, and is increasingly shaping our thinking. It is not only the fundamental processes like cloud formation, storms on the high seas, or the climatic influence of the Gulf Stream on western Europe that are becoming more noticeable; so too are the consequences of our actions: more frequent storms along the coasts, flooding due to ocean warming, and the migration of fish species to cooler waters. The ocean has become more visible.

Contact with the press was frowned upon by marine ecologists 30 years ago, but this too has changed: today, the German Marine Research Consortium is a partner of the *World Ocean Review*. Advances in research, the public positions taken by scientists, and progress in understanding the immense impact the oceans have on our daily lives are all positive signs.

The remote polar regions, Antarctic and Arctic, are particularly good examples of this. Until just a few years ago, these realms were seen mainly as the destinations of historic expeditions, like those undertaken by Scott and Amundsen, or as the habitats of rare and exotic species such as penguins or polar bears. But today, we understand the crucial importance of the polar regions for our climate future. They are symbolic of the consequences of our industrial development, and the melting of the once permanent ice cover illustrates our loss of control over our own actions.

In this sixth *World Ocean Review*, we present a wealth of facts and figures about the polar regions, and highlight the daunting threat to these fragile ecosystems. We also demonstrate their crucial role for the future viability of our planet. Nowadays, no one can claim that the oceans do not interest them. They are the future – for each and every one of us.

Nikolaus Gelpke
Initiator of the *World Ocean Review*, mareverlag publisher and IOI President

The poles are the Earth's coldest, harshest and most sparsely populated regions. Due to the role they play in relation to the Earth's climate and oceans, however, they are closely linked to all our lives. These regions are also highly sensitive to climate change, and in recent decades have been warming significantly. This is causing the melting of sea and continental ice. The meltwater from continental ice raises sea levels by the same amount as does the effect of warming on the global ocean. Furthermore, as a result of this melting, extractive resources in once hard-to-reach regions will become more accessible, and new fishing grounds and shorter shipping routes will be opened up. This will especially affect areas where usage rights to resources found in and under the seabed have not yet been fully resolved, mainly in the Arctic Ocean. Due to disagreements among the coastal states over the geographical scope of their rights to oil and gas deposits and over international regulation of access to fish stocks or sea routes such as the Northwest Passage, Arctic issues are the subject of growing foreign policy tension. In Antarctica, the geographical and legal situation is fundamentally different because the Antarctic Treaty does not currently allow for the exercise of sovereign rights by individual countries on this continent. The South Pole is located underneath the glacial ice, and the Antarctic Treaty permits scientific exploration here, but no military use and no resource exploitation except for fishing. However, warmer ocean temperatures under the ice shelves are a cause for concern, as they could lead to instability of the ice sheets and thus to dramatic rises in sea level. Although research on this topic is under way, it is not yet possible to conclusively assess the risks. The developments in the polar regions highlight one of the key challenges facing ocean research, namely to identify interdisciplinary solutions. Are we making the best use of our research findings? The Sustainable Development Goals (SDGs) adopted by the United Nations can serve as a useful global roadmap here, but sadly, there is a lack of awareness of this fact. The upcoming United Nations Decade of Ocean Science for Sustainable Development (2021–2030) gives us cause for hope: it aims to connect, expand and disseminate knowledge in order to promote intelligent approaches to the development of relationships between human society and the ocean. It also calls for more commitment in the areas of global and solution-oriented exploration of the oceans. In Kiel, the Future Ocean Network strives across disciplines to provide a shared flow of information to policy-makers, business and civil society. Working together across national, disciplinary and institutional boundaries, we should be demanding fairer and more sustainable management of the oceans in order to secure their ecosystem services for future generations. In the meantime, we hope that this report will provide you with an exciting and enlightening insight into the Earth's polar regions.

Prof. Dr. Martin Visbeck
GEOMAR Helmholtz Centre
for Ocean Research Kiel
Co-Spokesperson Future Ocean

Prof. Dr. Nele Matz-Lück
Kiel University (CAU)
Co-Spokesperson Future Ocean

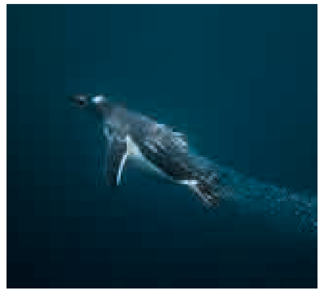
Prof. Dr. Ralph Schneider
Kiel University (CAU)
Co-Spokesperson Future Ocean

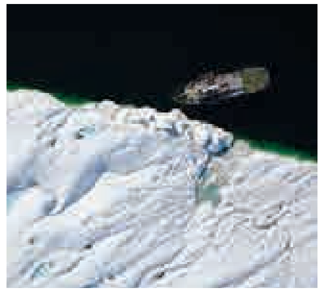
Satellite observations in 2019 continue to reveal the progressive loss of large areas of sea ice in the Arctic region, and the increased mobilization of Antarctic and Greenland continental ice masses. This sixth edition of the *World Ocean Review* presents these and other current research topics in their geological and historical context, and highlights the rate and extent of the ongoing changes.

More and more research results are demonstrating how dramatically the climate – which particularly benefits us in Central Europe – and therefore also life on our planet are influenced by changes in the polar regions. This is particularly evident in the changes in sea level, both in the past and presumably in the near future. The disappearance of large areas of summer sea ice in the Arctic region is not only opening new shipping routes, bringing economic benefits for sea transport between the continents. It could also pose a growing threat to the Arctic ecosystem. This ecosystem is adapted to six-month periods of darkness, very low temperatures, and life-sustaining ice and snow cover. Precisely how the stability of the system depends on the physicochemical conditions and what biological processes occur within and below the ice in winter are being explored for the first time by MOSAiC, an international winter-drift project which began in September 2019 using the German research icebreaker *Polarstern*. Once again, German polar, marine and coastal research is at the forefront of international endeavours. In my opinion, one of the foundations of the innovative strength of our research is the partnership among Germany's 19 largest marine research institutions in the German Marine Research Consortium (Konsortium Deutsche Meeresforschung, KDM). The Consortium has long been committed to active coordination of research at the national level, combined with intensive international exchange. The establishment of the German Alliance for Marine Research (Deutsche Allianz Meeresforschung, DAM) in July 2019 has created an additional pillar in the area of German ocean science, addressing major global questions, acquiring practical knowledge within a broad network of research institutions, and communicating and sharing this knowledge with numerous sectors of society. With the KDM and DAM, Germany now has a marine research architecture that is unique worldwide. It provides ideal conditions for effective action towards the attainment of the Federal Government's research policy goals as outlined in the MARE:N programme.

This latest edition of the *World Ocean Review* casts a multidisciplinary light on the diversity of our polar ecosystems and their influence on our planet in the past, the present and the future, and shows how they affect the well-being of us all.

Prof. Dr. Ulrich Bathmann
Director of the Leibniz Institute for Baltic Sea Research Warnemünde (IOW) and
Chair of the German Marine Research Consortium (KDM)





1 The Arctic and Antarctic – natural realms at the poles

> At first glance, the Earth's two polar regions appear to have much in common: Their terrestrial and marine landscapes are characterized by ice and snow, darkness dominates for half of the year, and survival is limited to those organisms that can adapt to very extreme conditions. But in spite of the striking parallels there are fundamental differences between the Arctic and Antarctic – ranging from their geography and history of ice formation to their conquest by humankind.

A brief history of the polar regions

> People are fascinated today more than ever by the polar regions of the Earth. One reason for this is that wide expanses of the Arctic and Antarctic have not been explored and are therefore still viewed as frontier regions. Another is that they both have very diverse histories with regard to their origins and ice formation. Their numerous aspects still pose many puzzles for science today.

The fascination of the high latitudes

The 21st century is the century of the polar regions. There are hardly any other natural landscapes that fascinate mankind as much as the distant land and marine regions of the Arctic and Antarctic. Most of the practically inaccessible ice and snow regions today are as yet unexplored. There are still no answers to many fundamental scientific questions such as: What exactly is hidden beneath the kilometre-thick ice sheets of Greenland and Antarctica? How did the Arctic Ocean originate?

Besides fascination, the world also views the polar regions with concern because, acting as cooling chambers, they play a crucial role in the planet's climate system and significantly impact the patterns of global air-mass and ocean circulation. Small changes in their complex structures can have far-reaching consequences. This is especially true for the large ice sheets of Greenland and Antarctica. Between them they contain 99 per cent of the ice on the Earth. If they melt, global sea level will rise. The melting of these two ice covers would raise water levels worldwide by around 70 metres, and long stretches of the Earth's coastlines would be flooded.

Today, the impacts of global climate change are more clearly observed in the polar regions than anywhere else, and this is particularly true for the Arctic. Since the middle of the 20th century it has been warming more than twice as fast as the rest of the Earth, and is thus seen as an early warning sign for climate change. Weather services and scientists therefore follow the events at high latitudes closely in real time – at least where satellites and measuring networks have made observations possible.

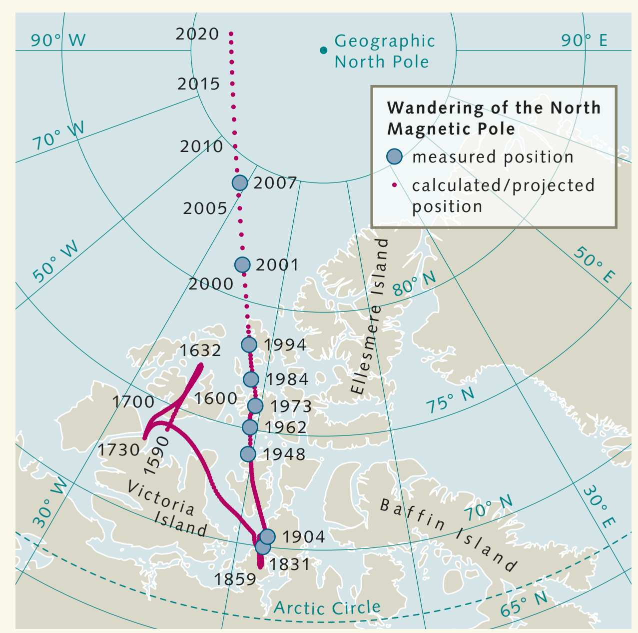
But the fascination of the polar regions also partly reflects the fact that there is nowhere else in the world where ice, snow, biting cold and the long darkness of the polar nights present such huge challenges for life. Both in the Arctic and the Antarctic, animals and plants have developed sophisticated survival strategies and impres-

1.1 > A tourist ship on the coast of the Antarctic Peninsula. 42,000 cruise tourists visited Antarctica during the Antarctic summer of 2017/2018. That was 16 per cent more than the previous summer.

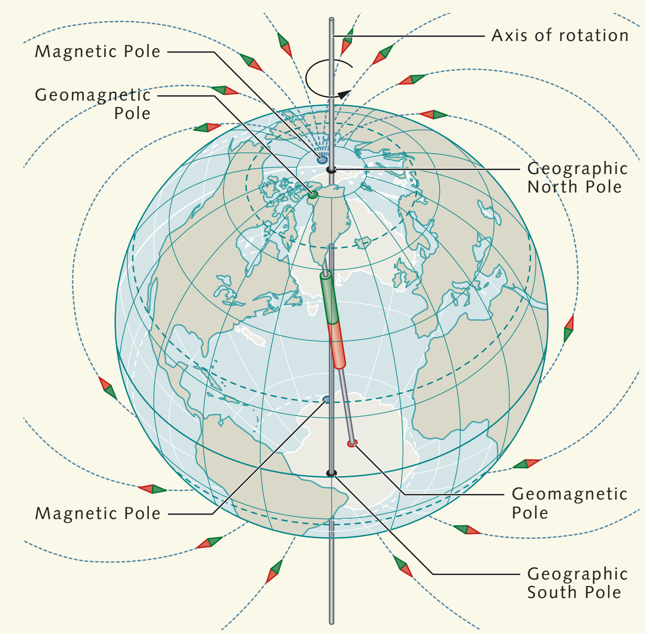
The Earth's wandering poles

The geographic North Pole has a fixed position. It corresponds to the northern intersection of the Earth's rotational axis with the Earth's surface. Its coordinates are thus "90 degrees north". It is not possible to locate this point, however, using a simple pocket compass. The compass needle actually aligns with the magnetic field of the Earth. This field originates because liquid iron located in the outer core of the Earth circulates and swirls in response to the internal temperature differences and rotation of the Earth. The magnetic field extends into space for a distance of many Earth radii. It shields the planet from dangerous radiation and particles from outer space, and it also possesses a north and south pole. These are defined as the two points where the magnetic field lines extend into the Earth perpendicular to its surface. One of these points is located in the northern hemisphere and the other in the southern hemisphere, but their positions are not exactly diametrically opposed on the globe. Neither of them can be assigned a fixed geographical position because, due to magnetic storms and constant variations in the circulation of iron in the liquid outer core, their locations are constantly changing. The changing results of positional measurements indicate that these poles are wandering. When the North Magnetic Pole was discovered in 1831, it was located near the Boothia Peninsula in the Canadian Arctic. From there, it has since wandered to the northwest and is now moving at a speed of around 55 kilometres per year. It is currently located north of the 85th parallel in the middle of the Arctic Ocean and is approaching Russia.

Interestingly, the Earth's magnetic field reverses itself at irregular time intervals. The magnetic north becomes south and vice versa. For the sake of clarity, therefore, specialists use the term North Magnetic Pole to refer to the magnetic pole located in the northern hemisphere, even when it is a magnetic south pole according to the conventional physics definition, as is currently the case. It is not known why this reversal occurs, but it is known that the change occurs over a period of several thousand years. Scientists also define the geomagnetic poles, which cannot be established through direct measurements but only theoretically calculated. These are based on the assumption that there is an infinitely small bar magnet at the centre of the Earth. The geomagnetic poles are located at the intersection of the axis of the bar magnet with the Earth's surface. These are very important because they form the basis of the geomagnetic coordinate system. This system is used for navigation underwater, underground, and for every mobile phone compass app.



1.2 > The North Magnetic Pole is constantly moving. Scientists determine its position using measurements and calculations.



1.3 > The northern and southern hemispheres of the Earth each have three poles – one geographic, one magnetic, and one geomagnetic.

sive species diversity that people want to see for themselves. The number of tourists in the two polar regions is therefore increasing, just as economic interest in the exploitation of polar resources is growing. South of the 60th parallel, the Antarctic Treaty establishes strict limits for the major economic players. In the Arctic, on the other hand, the five bordering states alone will determine what happens. The competition for raw materials and shipping routes there has already been underway for some time.

So similar and yet so different

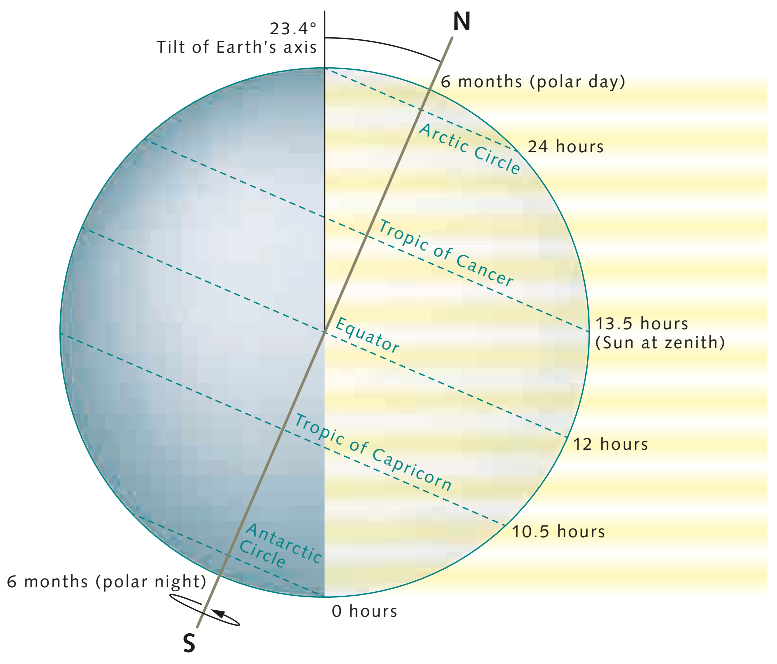
The regions of the Earth designated as polar are those areas located between the North or South Pole and the Arctic or Antarctic Circles, respectively. The northern polar region, called the Arctic, encompasses the Arctic Ocean and a portion of some surrounding land masses. The southern polar region, called the Antarctic, contains the continent of Antarctica and areas of the surrounding Southern Ocean. The diameter of each region is 5204 kilometres because both the Arctic and Antarctic Circles maintain consistent distances of 2602 kilometres from their respective geographic poles, which are not to be confused with the Earth's wandering magnetic poles.

On world maps the Polar Circles are generally marked by dashed lines at 66° 33' north and south latitude. This delineation was originally established based on the orientation of the sun. The Arctic Circle is thus defined as the latitude at which the sun does not set for exactly 24 hours during the summer solstice on 21 June each year. The winter solstice occurs in the southern hemisphere at the same time. Thus, the position of the Antarctic Circle is defined by the latitude at which the sun remains below the horizon for 24 hours.

The many parallels observed between the Arctic and Antarctic realms should not obscure the fact that the two polar regions are fundamentally very different from each other. In the far south, Antarctica is a vast landmass – a remote continent with an area of 14.2 million square kilometres, almost twice the size of Australia. 98 per cent of this area is covered by ice up to 4700 metres thick. The continent is completely surrounded by the Southern Ocean, also known as the Antarctic Ocean or Austral Ocean. This allows an active exchange of water masses among the Atlantic, Pacific and Indian Oceans, and large areas of it freeze over in the winter (seasonal sea-ice cover). This ocean not only separates Antarctica physically from the rest of the world, its clockwise-flowing water masses also insulate the continent climatically, which is one of the reasons why large parts of Antarctica are much colder than the Arctic. As a broad comparison: The average annual temperature at the South Pole is minus 49.3 degrees Celsius, while at the North Pole it is minus 18 degrees Celsius. Furthermore, the Antarctic is considered to be the windiest and driest region on the Earth. The extreme climate here, along with its remoteness, is also the reason why very few animal and plant species have been able to establish themselves on the frozen continent. People come only to visit for a short time. Apart from research stations, there are no permanent human settlements on the Antarctic continent today.

The Arctic, by contrast, is diametrically different in several respects. Here, land masses surround an ocean that is centred on the pole. The Arctic Ocean, also known as the Arctic Sea, is connected to the rest of the world's oceans by a limited number of waterways and, with an area of 14 million square kilometres, it is the smallest ocean in the world. In contrast to the Southern Ocean, the Arctic Ocean has a permanent sea-ice cover whose area varies with the seasons. It achieves its greatest extent at the end of winter and its smallest size at the end of summer, whereby scientists are observing a steady decrease in the extent of summer ice. Since the beginning of satellite measurements in 1979, the surface area of summer ice has shrunk by around three million square kilometres. This is an area about eight times the size of Germany. Because the continents of Europe, Asia and North America extend far into the Arctic region, the Arctic has been more successfully settled by plants, animals and people than the Antarctic. Historical evidence suggests that the first aboriginal people were hunting in the coastal regions of the Arctic Ocean 45,000 years ago. Today more than four million people live within the Arctic polar region.

1.4 > Winter in the Arctic fishing village of Reine, in the western Lofoten Islands of Norway. Due to branches of the warm Gulf Stream, the air temperature in this part of the Arctic does not fall much below freezing.



1.5 > On 21 June, the date of the summer solstice, the sun is at its highest elevation in the northern hemisphere. On the Arctic Circle it does not set for 24 hours, and on the Antarctic Circle it does not rise for 24 hours.

Where does the Arctic begin, where the Antarctic?

The term "Arctic" comes from the Greek word *arktos*, which means bear. Greek seafarers called the Arctic region, into which they had presumably already ventured for the first time around 325 BC, "land under the constellation of the Great Bear". Seamen at that time used the constellations of the northern sky, primarily Ursa Major and Ursa Minor, to aid them with orientation during their voyages of discovery.

Another celestial body, the sun, was decisive in defining a northern and later a southern polar circle as the boundaries of the polar regions. The two circles mark the geographic latitudes at which the sun does not set on the dates of the respective summer solstices. In the northern hemisphere the summer solstice usually falls on the 21st of June and in the southern hemisphere it is usually the 21st or 22nd of December. The precise positions of the polar circles are determined by the tilt angle of the Earth's axis. Because the degree of tilt of the axis (obliquity) fluctuates slightly with a rhythm of about 41,000 years, the locations of the polar circles are also constantly shifting. They are currently moving toward the geographic poles by around 14.4 metres per year.

The Arctic Circle has never become established, however, as the definitive southern boundary of the Arctic region. This is primarily because there is no natural feature coinciding with the astronomically determined path of the Earth-encircling line that clearly distinguishes the Arctic realm from regions to the south. On the contrary, if the Arctic were limited to the regions north of the Arctic Circle, the southern tip of Greenland and large portions of the Canadian Arctic would not be included.

For this reason scientists today define the natural region of the Arctic mostly on the basis of climatic or vegetational features. One southern boundary that is often employed is the 10° Celsius July isotherm. North of this imaginary line the long-term average temperature for the month of July lies below ten degrees Celsius. By this criterion the Arctic Ocean, Greenland, Svalbard, large parts of Iceland, and the northern coasts and islands of Russia, Canada and Alaska all belong to the Arctic realm. In the air above the Norwegian Sea, the 10° Celsius July isotherm shifts northward due to the heat of the **North Atlantic Current**, so that, on the basis of this definition, only the northern reaches of Scandinavia are included in the Arctic. In Siberia and North America, on the other hand, cold Arctic air pushes the temperature boundary further to the south, so that regions such as the northeastern part of Labrador, the Hudson Bay, and a large portion of the Bering Sea are included as part of the Arctic.

Another natural southern boundary sometimes used for the northern polar region is the Arctic tree line. As the name suggests, the present-day climate conditions north of this line are so harsh that trees are no longer able to survive. But because, in fact, the transition from contiguous forests to the treeless grass and tundra landscapes of the Arctic is often gradual, researchers tend to refer to a zone for the boundary rather than a sharply defined line. In North America, for example, this transition zone is a relatively narrow strip. In northern Europe and Asia, however, it can be up to 300 kilometres wide. The course of the northern tree line corresponds in large part with the 10° Celsius July isotherm. In some areas, however, it can be located as much as 200 kilometres to the south of the temperature boundary. According to this definition, western Alaska and the Aleutians would also belong to the Arctic, and the Arctic region would have a total area of around 20 million square kilometres.

A third natural boundary can be delineated based on ocean currents. According to this definition, the Arctic waters begin at the point where cold, relatively low-saline surface-water masses from the Arctic Ocean meet warmer more saline waters from the Atlantic or Pacific Ocean at the sea surface. In the area of the Canadian Arctic Archipelago, the island group between North America and Greenland, this convergence zone extends to 63 degrees north latitude. As it continues eastward, it turns to the north between Baffin Island and Greenland. In the Fram Strait, the marine area between East Greenland and Svalbard, it is located as far as 80 degrees north, i.e. well to the north of the Arctic Circle. On the other side of the Arctic Ocean, in the Bering Sea, the definition of a convergence zone is somewhat more difficult, because here the water masses from the Pacific and Arctic Oceans mix extensively with each other instead of one flowing over the other. On maps, therefore, this vague boundary line runs straight across the narrow Bering Strait.

Besides these three boundaries to the Arctic, which are all characterized by natural features, other boundaries have been defined according to different delineating criteria. Various working groups of the Arctic Council, for example, sometimes draw different boundaries. For the group of experts in the Arctic Monitoring and Assessment Programme (AMAP), for example, all of the land areas in Asia north of 62 degrees north latitude belong to the Arctic. On the North American continent they draw the line at 60 degrees latitude. The territory based on this method is significantly larger than the physiographic region defined by the tree line. The most generous definition of the Arctic is found in the Arctic Human Development Report (AHDR), where political and statistical aspects were considered in defining the area, which is why the boundary, especially in Siberia, extends further to the south than any other. According to this definition, the Arctic region has an area of over 40 million square kilometres, which is equal to around eight per cent of the total surface of the Earth.

In this *World Ocean Review*, the term "Arctic" will always refer to the physiographic region defined by the tree line on land and by the convergence zone in the seas. If, in special cases, other definitions of the Arctic region are necessary, this will be specifically pointed out.

In the southern hemisphere, the definition of the boundary is not as difficult. The fact that the continent of Antarctica is essentially an island and the presence of distinctive ocean currents allow a relatively clear delineation of the boundary of the southern polar region. The word "Antarctic", by the way, derives from the Greek word *antarktiké*, which means "opposite to the north". The Antarctic realm includes the continent of Antarctica and the surrounding Southern Ocean, whereby the tip of the Antarctic Peninsula and coastal areas of East Antarctica extend beyond the Antarctic Circle. The northern boundary, therefore, is often considered to be the line at 60 degrees south latitude, which was agreed to by the signatories of the Antarctic Treaty System in 1959.

The Antarctic region becomes somewhat larger if the zone of Antarctic Convergence is used to indicate the northern boundary. This is the encircling oceanic zone where cold, northward-flowing surface water from the Antarctic meets warmer southward-flowing water masses from the north. The cold, saline water sinks as a result of the density differences, and is diverted beneath the warmer water masses. For polar researchers the 32 to 48 kilometre-wide zone of the Antarctic Convergence represents the northern edge of the Southern Ocean because it clearly separates the Antarctic region from lower-latitude waters, and it delineates the natural biological associations of the two marine regions. Generally, the convergence zone is located at a latitude of around 50 degrees south, which means that this boundary definition would also include within the Antarctic region some subantarctic islands such as South Georgia and the South Sandwich Islands. The precise position of the convergence zone, however, varies somewhat depending on longitude, the weather and time of year, and can therefore shift regionally by as much as 150 kilometres to the north or south.

This *World Ocean Review* will conform to the delineation of the Antarctic polar region established in 1959 by the Antarctic Treaty unless otherwise noted. It thus comprises all land and marine regions south of 60 degrees south latitude.

Wandering continents

The fact that both polar regions of the Earth are covered with ice at the same time is an exceptional situation in the 4.6 billion-year history of our planet. Only a few times in the past have the Earth's continents been so arranged that the necessary cold climate conditions prevailed both in the north and the south. It was the migration of the continents, then, which provided the initial impetus for the icing over of the two polar regions.

The German polar researcher Alfred Wegener was the first to scientifically postulate that the continents are moving. In 1912 he published his hypothesis of continental drift, which geologists to this day have only been able to supplement and refine because Wegener's reconstructions of continental motion were so accurate. According to his theory the outer shell of the Earth, the crust, with a thickness of up to 60 kilometres, broke apart into large plates around three to four billion years ago. Since then, these have been moving independently of one another upon the Earth's mantle, which underlies the crust and is composed of molten rock, or magma. The plates travel at speeds up to ten centimetres per year. They collide with one another, are pushed atop one another at their margins or drift apart, creating trenches and fractures through which liquid magma can rise from the Earth's interior. In this way, new continental or ocean crust is formed at the fractures.

Climate researchers consider continental drift to be one of the most influential factors in the history of ice formation in the polar regions. After all, the relative positions of the continents and oceans determine the patterns of air and ocean currents, and thus the distribution of heat on the planet. This applies particularly to the two polar regions, whose geological structures and subsurfaces were shaped by completely different **plate-tectonic processes**.

Antarctica – an ancient continent

In order to understand the origins of the southern polar region, it is necessary to know that the Antarctic continent actually consists of two parts: One is the relatively large, solid landmass of East Antarctica, which is composed of continental crust up to 3.8 billion years old and 40 kilometres thick. The other is West Antarctica, which comprises four considerably smaller and thinner crustal blocks. These four crustal fragments even today are not firmly connected to one another. They are constantly drifting.

Although the land mass of East Antarctica and the crustal blocks of West Antarctica lie on a single continental plate, a wide trench separates the two parts from one another. The Transantarctic Mountains, on the East Antarctic side of the trench, rise to heights well over 4000 metres and extend for a length of 3500 kilometres.

The geographic position and remoteness of Antarctica are relatively recent phenomena from a geological perspective. For most of the Earth's history the Antarctic

1.6 > From a geological point of view, the current positions of Antarctica and Spitsbergen near the poles represent only a momentary glimpse. In the past, parts of both regions have been located in the opposite hemispheres.

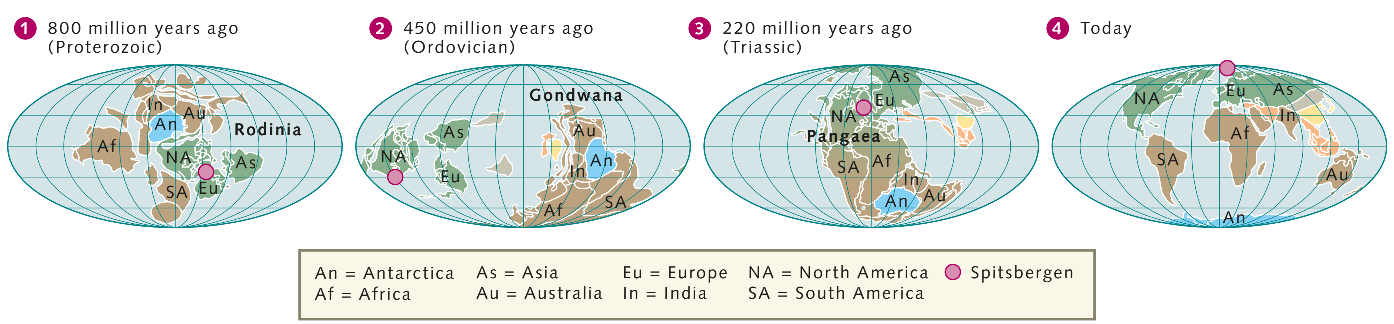
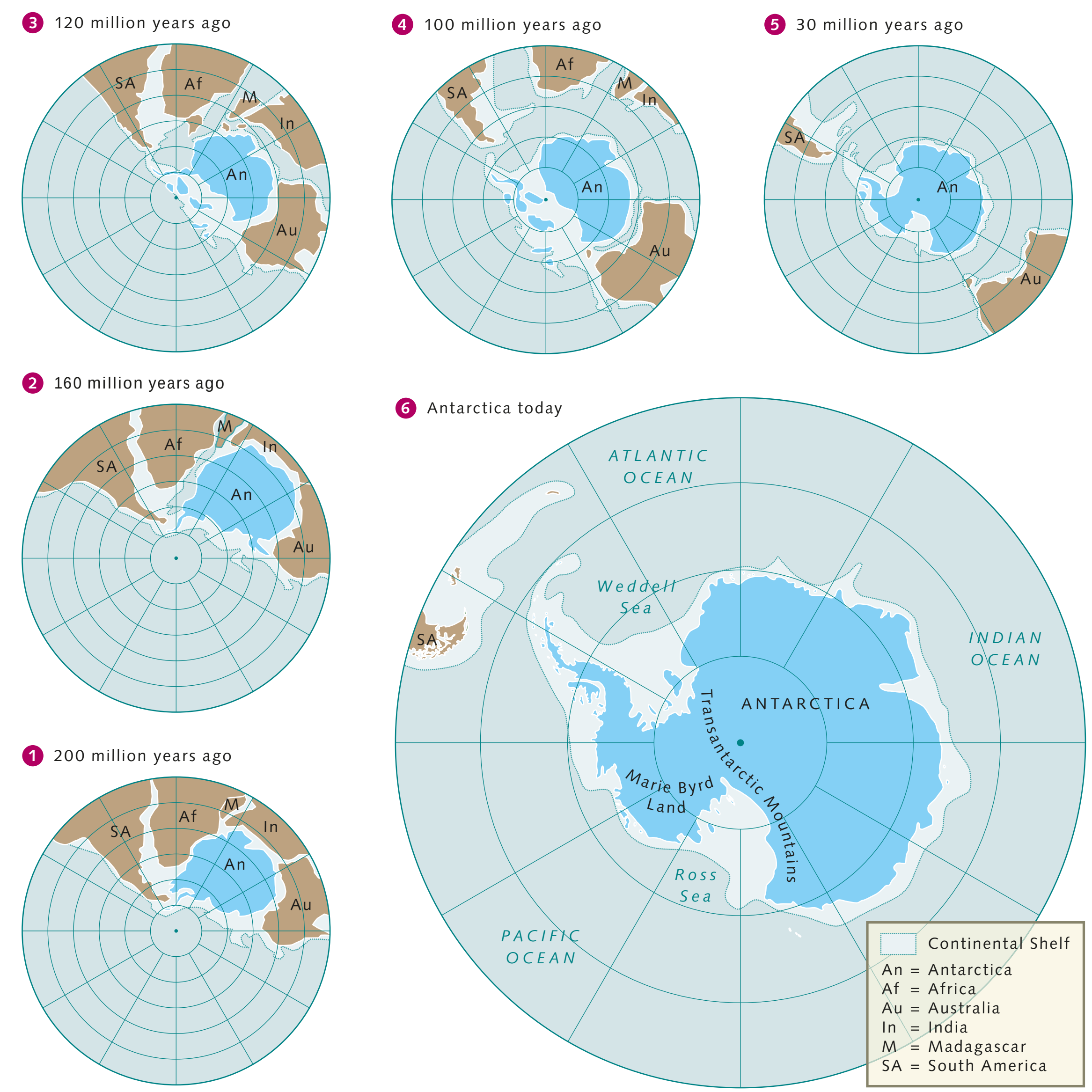


Plate has been positioned directly adjacent to other continents. At least twice, in fact, it has been located far from the South Pole at the centre of a supercontinent. The first time was around one billion years ago, when all of the continents united as a consequence of worldwide mountain building to form the supercontinent Rodinia. The land mass that is now East Antarctica formed its centrepiece and was located north of the Equator, presumably very near the Laurentian Plate, which was the primeval North America. Some reconstructions place it beside Australia or Mexico. Which scenario is correct is still being debated today.

Approximately 550 million years later, during the Ordovician geological period, the Antarctic Continental Plate again moved to the centre of a great continent. This time it formed the core area of the giant Gondwana continent. This land mass united all of today's southern continents as well as the Indian subcontinent, and was positioned such that Antarctica was located between the Equator and the Tropic of Capricorn. This time it was

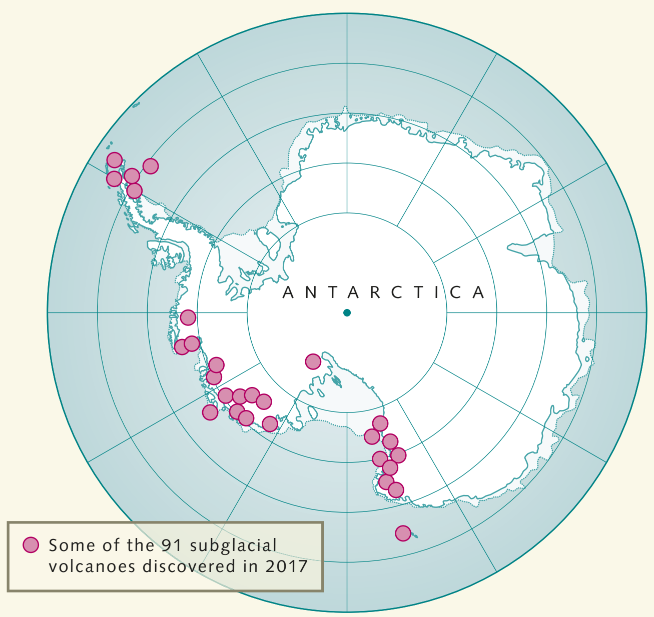


1.7 > As the supercontinent Gondwana began to break apart 200 million years ago, Antarctica gradually separated from the other tectonic plates and drifted toward the South Pole.

A volcanic landscape hidden below the ice

West Antarctica has recently been recognized as the region with the greatest density of volcanoes in the world. Scientists have counted 138 volcanoes so far. But the remarkable fact about this is that 91 of them lie as much as 2000 metres below the ice sheet, and they were first discovered in 2017 by a team of scientists from the University of Edinburgh. These subglacial volcanoes are 100 to 3850 metres tall and have basal diameters of 4.5 to 58.5 kilometres. Their numbers are particularly high near Marie Byrd Land and along an axis that runs parallel to the Transantarctic Mountains through the centre of the West Antarctic Rift System.

The news of the discovery of volcanoes beneath the ice attracted great worldwide interest. Scientists were concerned that the eruption of one or more of the subglacial volcanoes could lead to a rapid melting of the West Antarctic Ice Sheet. The direct result of this would be an abrupt global sea-level rise of several metres. Observations from other parts of the world suggest that volcanoes can become active when an overlying ice burden melts. Examples of subglacial volcanic activity have been observed in Iceland, for instance, where eruptions have led to melting on the underside of glaciers, causing a significant increase in the velocity of ice flow. It has not yet been definitively determined whether the volcanoes beneath the West Antarctic Ice Sheet are currently active.



1.8 > Most of the volcanoes in West Antarctica lie beneath the ice.

bounded by India and Australia to the west and South America to the south.

Gondwana existed for a period of more than 300 million years. Its landscapes were characterized by widely branching river systems, lakes, dense forests, and intermittently even by a thick ice shield, which covered the continent 300 million years ago near the end of the Palaeozoic Era. Around 180 million years ago Gondwana began to break apart again – accompanied and driven by numerous volcanic eruptions, deep fractures in the Earth's crust, and strong drift movements. These initiated the movement of the Antarctic Plate toward the south, which became possible as all of the neighbouring continents slowly broke off.

This began around 160 million years ago as the southern tip of Africa began to break away from the Antarctic continent, opening the rift that ultimately resulted in the formation of the Weddell Sea. The land masses of India and Madagascar then slowly drifted away toward the north, centimetre by centimetre. Then, between 90 and 80 million years ago, as New Zealand separated from Antarctica, the crustal blocks of West Antarctica were reorganized. Hot magma currents within the Earth began to lift the blocks along their border to East Antarctica. One consequence of this was the formation of the Transantarctic Mountains and the mountain range on Marie Byrd Land. Another was the creation of a fracture in the Earth's crust that still exists today as a vast trench, riddled with faults and extending from the Ross Sea to the Weddell Sea. Geologists call this fault trench that runs parallel to the Transantarctic Mountains the West Antarctic Rift System. It is 800 to 1000 kilometres wide, more than 2500 kilometres long, and is one of the largest continental trench fault systems on the Earth – comparable in size to the East African Rift Valley, which runs through Africa from the Red Sea to Mozambique.

The Antarctic continent could someday break apart along this active fault zone, but currently the trench is only widening by two millimetres per year, which is equal to about one metre every 500 years. In the recent geological past, however, relative movements of the plates and the drifting apart of West and East Antarctica have caused the Earth's crust to become thinner along the fracture zone and deep basins to form in the Ross Sea. This explains why large parts of the subglacial surface in West Antarctica today lie one to two kilometres below sea level, and without their unifying ice sheet would not look like a continuous surface but an assemblage of islands of various sizes.

The formation of the West Antarctic Rift zone about 80 million years ago was not the last tectonic milestone in the drift history of the Antarctic Continental Plate. Two others followed, almost synchronously with one another, and both were again driven by the spreading processes in the Earth's crust. One occurred at the plate boundary between South America and the Antarctic Peninsula where the spreading increased significantly 50 million years ago. Around 41 million years ago the Drake Passage opened here, an oceanic strait that is about 800 kilometres wide today and connects the Pacific and Atlantic Oceans.

The second notable spreading process occurred on the other side, in East Antarctica, where Australia was drifting away from the Antarctic Plate. Researchers today find this separation fascinating because it occurred in part, at least from a geological perspective, at breath-taking speed.

It is now believed that the Australian Plate separated from the Antarctic Plate in two steps. Initially, 95 to 60 million years ago, the southern coast of Australia detached itself from East Antarctica, while the part that is now called Tasmania was still in contact with Victoria Land in the Antarctic via a land connection that was at times flooded by shallow water. This land bridge, however, already bordered on a long, shallow gulf that was formed between the two plates. Around 34 million years ago, the sea floor in the area of the land bridge subsided within a period of just one to two million years, presumably because the drift direction of the Pacific Plate had changed. A strait was created that opened a pathway for cold oceanic deep water from the Southern Ocean, which could now flow unimpeded between Australia and Antarctica. The ring of water around Antarctica was now complete and the Southern Ocean was born. The continuous band

Gulf
Large marine embayments, semi-enclosed seas, or marginal seas that are largely surrounded by land masses are called gulfs. Well-known examples include the Gulf of Mexico, a marginal sea of the Atlantic Ocean enclosed by the coasts of the USA, Mexico and Cuba, and the Persian Gulf – a 1000 kilometre-long inland sea as much as 300 kilometres wide between the Persian Plateau and the Arabian Peninsula.

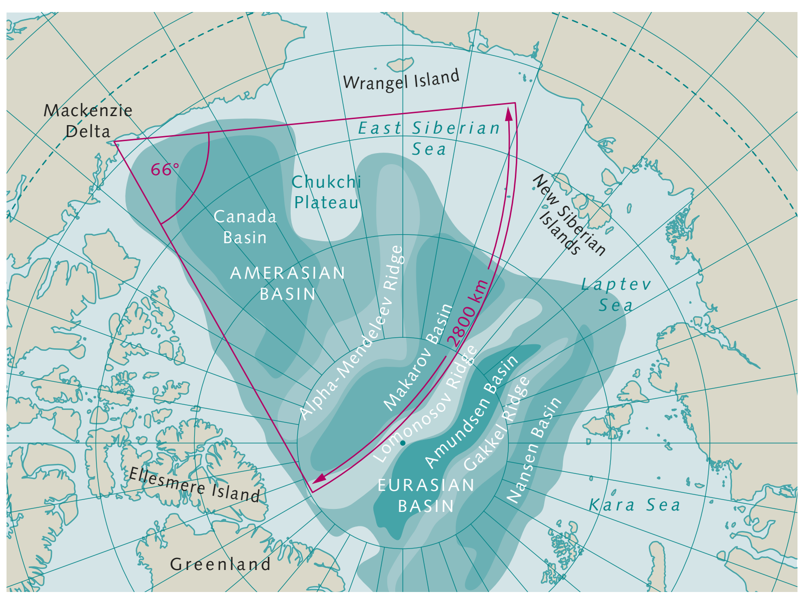
1.9 > Skansen Mountain, at the entrance to the Billefjorden, Spitsbergen, has clearly defined sediment layers that enable geoscientists to trace the history of the island's origins. The limestone layers visible here, for example, dating from the Middle Carboniferous to Lower Permian Periods, are 320 to 290 million years old.

of current today still climatically insulates the southern continent from the rest of the world, and this same situation significantly contributed to the initiation of ice formation in Antarctica 34 million years ago.

The Arctic – an ocean opens

The land masses in the present-day Arctic region have undergone a much longer voyage than that experienced by the Antarctic continent. 650 million years ago the island of Spitsbergen, for example, as a part of a larger land mass, was located near the South Pole, as evidenced by thick glacial-period deposits that scientists can still find on the island today. Since then Spitsbergen has drifted 12,000 kilometres to the north at an average speed of less than two centimetres per year. Evidence for the wandering history is found in the various rock layers on the island.

Rust-coloured rock faces are the vestiges of a time 390 million years ago, when Svalbard was part of a large desert near the equator. 50 million years later, at the beginning of the Carboniferous Period, the region was located in the northern subtropics. The climate was hot and humid, and dense rain forests grew on Svalbard.



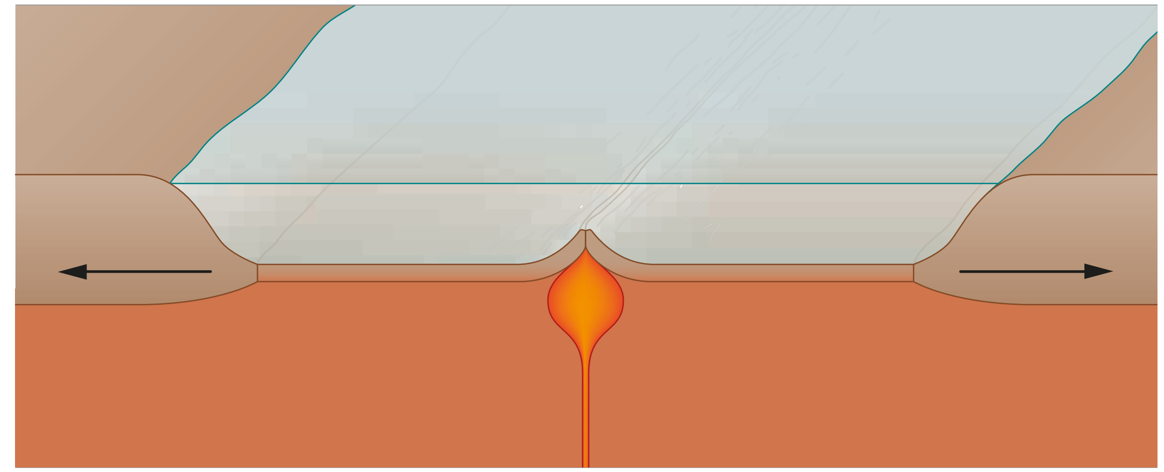
1.10 > The history of the origins of the Arctic Ocean has not been fully researched. One possible explanation is that the continental plates of North America and Siberia drifted apart rotationally, thereby creating room for the Amerasian Basin.

1.11 > Palaeontologists pose beside the fossil remains of marine reptiles found on Spitsbergen.

When the age of dinosaurs began 225 million years ago, the land mass of Svalbard was covered by a sea in which first ichthyosaurs, and a few million years later 20-metre-long plesiosaurs swam and hunted their prey. Researchers have discovered large numbers of the skeletons of both of these marine reptiles.

At the same time, rivers that existed then must have transported large amounts of sediment and organic material into the sea. These sank to the bottom and produced kilometre-thick deposits in large basins. These sediment layers play an important role today in the search for natural-gas and oil reservoirs.

In the Late Jurassic epoch, 150 million years ago, plate-tectonic processes began to act that led to the formation of the Arctic Ocean and the present-day configuration of the continents. At this time, the supercontinent Pangaea split into the southern continent of Gondwana and the northern continent of Laurasia. The latter comprised the continental plates of present-day North America, Europe and Asia, a composite that likewise began to break up around 145 million years ago. Geologists believe that at that time a small ocean basin formed between North America and Siberia, which was the beginning of a division and the subsequent rotational spreading between the two plates. Based on present knowledge, the exact motions that occurred in this scenario can only be surmised. It is



1.12 > Because the two continental plates are moving away from each other, the sea floor is split open. At the opening a mid-ocean ridge has formed where magma rises from the Earth's interior and forms new sea floor.

certain that between Canada and Alaska on one side and Siberia on the other, the present-day Arctic Ocean originated with the opening of the triangular Amerasia Basin, which is now the oldest part of the ocean.

Along the margins of this basin, Franz Josef Land, Svalbard, North Greenland and the Canadian Arctic were sites of intense volcanic activity. Liquid magma penetrated from below into the Earth's crust to form volcanic pathways. Some lava masses also escaped to the surface and formed volcanoes.

About 110 million years ago the opening of the Amerasia Basin came to an abrupt end when the western edge of a piece of Alaska, called the Alaska-Chukotka microcontinent, collided with Siberia. At this time, Svalbard had reached its position in the high latitudes, but was still a part of the large land mass of Laurasia, which, like all of the areas surrounding the new Arctic Basin, was covered with dense forests of giant redwoods. The climate must have been very warm and the vegetation lush because thick coal deposits formed throughout these regions. On Ellesmere Island in the Canadian Arctic, scientists have found the fossil remains of turtles and crocodiles from this time. These are also indicative of the tropical conditions in the high north.

Laurasia began to break apart completely as crustal spreading between Canada and Greenland around 95 million years ago created the Labrador Sea and Baffin Bay. 40 million years later a new phase of repositioning of the continental plates began, during which the North Atlantic opened. At around the same time, 55 million years ago, an 1800 kilometre-long submarine mountain range, named after the Russian natural scientist Mikhail Vasilyevich Lomonosov, detached from the Eurasian continental margin and began to drift toward its present position at the North Pole.

In the process of this separation, the Eurasian Basin of the Arctic Ocean opened between the continental margin of Eurasia and the Lomonosov Ridge. In its centre there is an active mid-ocean ridge today, the Gakkel Ridge, named after the Russian oceanographer Yakov Yakovlevich Gakkel. This ridge is a continuation of the North Atlantic Ridge. It extends from the north coast of Greenland to near the Lena River Delta and divides the Eurasian Basin into the northerly Amundsen Basin and the Nansen Basin, which lies to the south and thus nearer to the coast.

As is typical of mid-ocean ridges, the Gakkel Ridge is a tectonic spreading zone. This means that the ocean floor is spreading apart along the 1800 kilometre-long ridge. Magma flows out of the Earth's interior and creates new sea floor in the rift zone of the ridge. At the Gakkel Ridge these tectonic processes are occurring more slowly than at any other mid-ocean ridge in the world. The sea floor is spreading here at a rate of only one centimetre per year. Nevertheless, it is enough to explain why hot seeps simmer on the sea floor and why the Eurasian Basin is continuously growing even today.

1.13 > In order to better understand the opening of the Arctic Ocean and the associated plate motions, geologists regularly carry out expeditions to the high latitudes of northern Canada. Here they have set up camp on a remote part of Ellesmere Island.

The fragmentation of Laurasia and the opening of the Eurasian Basin over the past 55 million years have induced very complex plate motions between Svalbard and the northern margin of North America. Where plates collide, large zones of deformation and buckling occur. Mountains fold upwards – for example, on the west coast of Svalbard, in northern Greenland and in the Canadian Arctic. Where plates slide past each other, kilometre-long, box-shaped valleys form near the coasts, which are useful for geoscientists in the identification of lateral continental drift. Such fault zones exist today on Banks Island and Ellesmere Island, for instance. Researchers have found that plate movements have shaped the entire continental margin of North America over the long term. This is supported by the fact that the margin of northern Canada is surprisingly straight from the Mackenzie Delta in the southwest to the northern edge of Greenland.

Ocean formation in the Labrador Sea and Baffin Bay ended around 35 million years ago. Greenland, which had existed for some time as a separate continental plate, now became part of the North American plate again. Just ten million years later, however, Spitsbergen detached itself from northern Greenland and drifted with the rest of Eurasia into its present position.

During this separation, 17 to 15 million years ago, a trench up to 5600 metres deep was created between the archipelago and the east coast of Greenland. This deep-sea trench, called the Fram Strait and named after Norwegian polar explorer Fridtjof Nansen's research ship *Fram*, remains to this day the only deep-water connection between the Arctic Ocean and the world's oceans, and is very important for the exchange of water masses.

Despite all of these geological indications, the history of the Arctic Ocean remains a plate-tectonic enigma. Many of the details are still not understood today. For example, geologists do not know the origin of the Alpha-Mendeleev Ridge. This undersea mountain chain divides the Amerasia Basin into the Makarov Basin in the north and the Canada Basin to the south. Ship expeditions to this vast marine region are extremely rare and expensive because, despite climate change, this part of the Arctic Ocean is covered with sea ice even in summer, making geological drilling particularly costly and risky.

Ice formation in Earth's history

In terms of climate history we are living in an exceptional time. For most of the approximately 4.6 billion years since its creation, the Earth has been too warm for the formation of ice covers on large areas of either the North or South Pole. The planet has been predominately ice-free. Large-scale glaciation in the high latitudes has only occurred during the glacial periods. These are defined as times when glaciers and inland ice masses cover extensive areas of the northern and southern hemispheres. The conditions for permanently ice-covered polar regions only exist during so-called ice ages.

The present ice age began with the icing of Antarctica around 40 to 35 million years ago. For about the past million years, colder and warmer periods have been alternating at intervals of about 100,000 years. Climate researchers designate these phases as glacials (ice periods) and interglacials (warm periods).

The Earth is currently in an interglacial period. That means we are experiencing a climate with mild winters, moderate summer temperatures, and glaciers in the two polar regions and in high mountainous areas.

There is much debate about what factors trigger an ice age. What is certain is that pronounced climatic changes are always accompanied by changes in the planet's energy balance. In general, there are four possible triggers:

- cyclical fluctuations in solar activity;
- changes in the Earth's orbital path around the sun;
- changes in the planetary albedo, the amount of solar energy reflected from the Earth back into space. This value is largely dependent on cloud cover and the lightness of the Earth's surface;
- changes in the composition of the atmosphere, particularly the concentrations of greenhouse gases such as water vapour, carbon dioxide, methane and nitrous oxide, or the amount of particulate matter in the air.

If one or more of these changes occurs, the various processes can work to amplify each other to some extent. A good example of this is the ice-albedo feedback: if ice sheets, glaciers and sea ice form as a result of cooling climate, the white areas of the ice surface grow larger, which increases the reflective effect from the Earth – the albedo. This means that a greater proportion of the incoming solar energy will be reflected back into space, causing the air temperature to cool further and resulting in the formation of more ice.

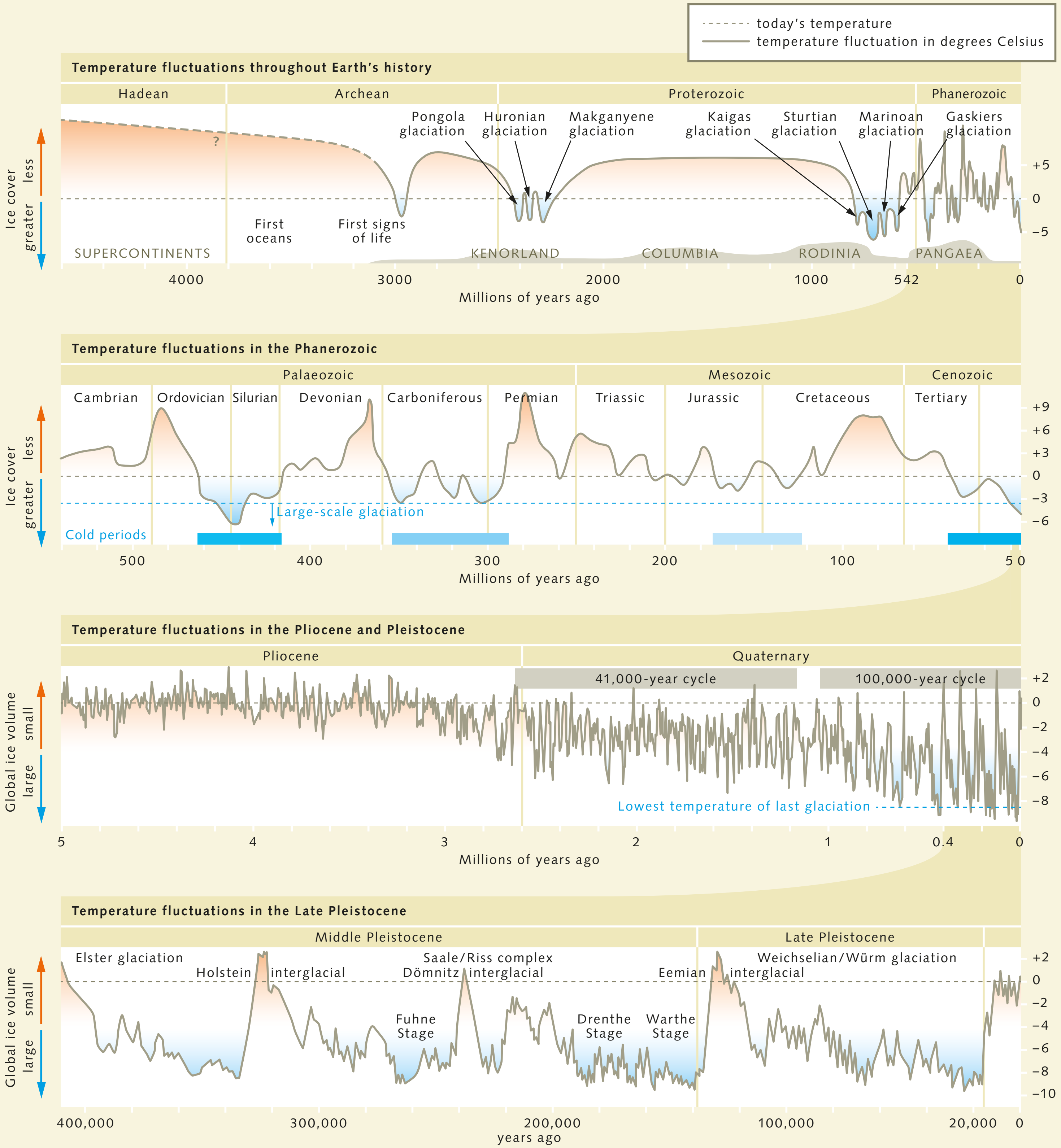
Beside these four main causes of climate change, however, there are additional factors that can influence the weather and climate of the Earth and thus also the extent of ice formation, either in the short or long term. These include:

- meteorite impacts, short-term volcanic eruptions, and regularly occurring marine current-pattern fluctuations such as the El Niño phenomenon;
- decades-long volcanic eruptions or changes in ocean circulation;
- long-term climate swings lasting for hundreds of thousands to hundreds of millions of years, which are mainly controlled by plate-tectonic processes that result in changes in ocean circulation and the carbon cycle.

All of these influencing factors must be taken into consideration when trying to understand why extreme glaciation has repeatedly occurred on the Earth throughout its history, alternating with repeated disappearances of the ice masses.

Climate extreme – snowball Earth

The largest areas of ice covered the Earth between 2.5 billion and 541 million years ago. During this time span there were repeated extremely long-term ice covers, with ice sheets and glaciers so expansive that they extended from



1.14 > In the course of the Earth's history its climate repeatedly cooled so extremely that extensive ice masses formed, beginning on the land masses at high latitudes and eventually resulting in the glaciation of large parts of the planet. The main reasons for the climate swings presumably were decreases and increases in greenhouse-gas concentrations in combination with plate movements.

the polar regions to the equator. This is supported by various lines of geological evidence that prompted researchers for the first time in the 1960s to suggest that the Earth must once have been under a complete cover of ice. Then, in 1992, the US American geologist Joseph L. Kirschvink formulated the hypothesis of the "snowball Earth", which said that the continents and seas were so extensively covered with ice that the planet viewed from space at those times would have looked like a snowball. According to this theory, the global average temperature during these extreme ice periods was minus 50 degrees Celsius. At the equator, with an annual average temperature of minus 20 degrees Celsius, it was as cold as present-day Antarctica, the theory holds.

Kirschvink's hypothesis is still widely debated today. One of the questions raised by critics is how existing organisms could have survived under a completely continuous ice cover. Another is that there is no satisfactory explanation for what processes would have been strong enough at the end of the cold period to return the climate from extremely cold back to "normal". Nevertheless, most of the geological evidence supports the existence of at least three occurrences of these snowball conditions. The first was at 2.3 billion years ago during the Makganyene glaciation. The second one, called the Sturtian glaciation, occurred between 760 and 640 million years ago, and the third, the Marinoan glaciation, around 635 million years ago.

The triggers for these extreme climate conditions are presumed to be a combination of tectonic plate motions, significantly lower greenhouse-gas concentrations in the atmosphere, and a strong ice-albedo feedback. In the build-up to the first snowball ice period, and preceding the later snowball events as well, large land masses were located in the tropical latitudes. This concentration of continental plates near the equator initiated two processes that led to immediate cooling. For one, in regions with humid climates the rainfall led to accelerated erosion of the young rocks and mountains that had been lifted up by plate motions. Whenever rainwater fell on the bare calcareous or silicate rocks, it reacted with carbon dioxide in the air to form carbonic acid, which was then able to dissolve minerals out of the rocks and thus break them down. By this process, the greenhouse gas carbon dioxide was fixed and thus removed from the atmosphere for a very long period of time. In climate models, researchers have been able to illustrate that the global formation of ice is initiated when the atmospheric carbon dioxide concentration is less than 40 ppm (parts per million, millionths).

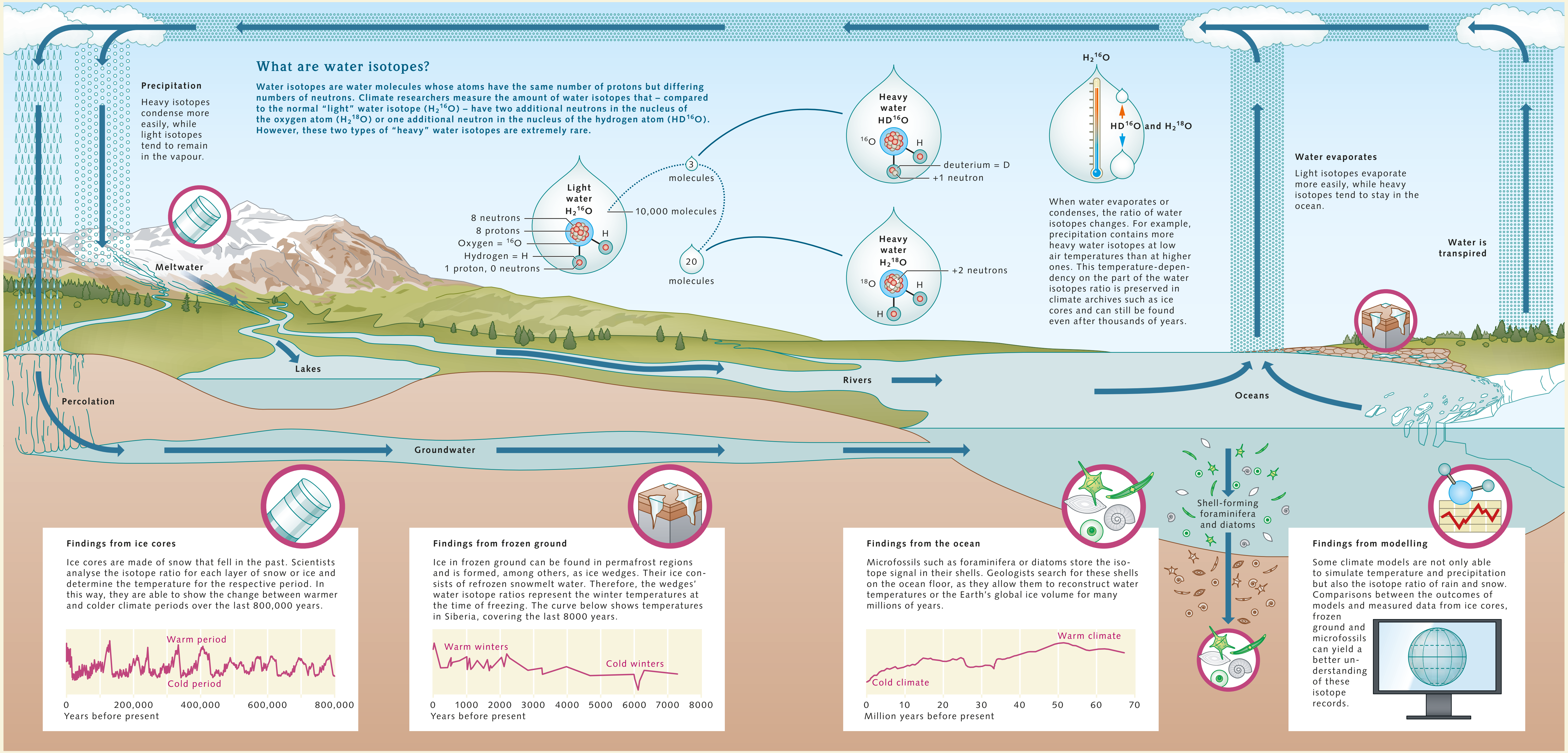
Secondly, the dense conglomeration of continents at the equator prevented the tropical ocean from absorbing a large amount of heat because there was less water surface available as a heat reservoir. The ocean currents therefore were not able to distribute as much heat around the globe. In addition, astrophysicists assume that since its genesis, and up to the present, the intensity of the sun has been increasing. For example, 800 million years ago the Earth was receiving six per cent less solar radiation than it is today.

Under these conditions, a large volcanic eruption ejecting millions of tons of ash particles into the atmosphere and thereby further reducing solar radiation would presumably have been sufficient to trigger the transition to a snowball state. It would only require the formation of the first glaciers. As their surface area increased, more of the incoming solar energy was reflected by the ice, thus promoting further cooling of the Earth.

Scientists can only speculate about the reasons why this spiral of cooling eventually ended. The reasons are probably related to renewed plate-tectonic movements and volcanic eruptions over a time frame of five to ten million years that increased greenhouse-gas concentrations in the atmosphere and brought a return to warmer conditions. Carbon dioxide concentrations in the atmosphere at the end of the third global glaciation reached a level of ten per cent, which is orders of magnitude greater than today's carbon dioxide level of 0.041 per cent (410 ppm). As a consequence, the world flipped from a snowball climate into a super greenhouse climate. Within just a few thousand years, the warmth of this super greenhouse melted the Earth's ice sheet, which probably had a thickness of up to 4000 metres. This theory is supported by characteristic rock deposits found, for example, in Oman and Australia, as well as by the results of various climate models.

Water isotopes – insights into past climate

Decoding the secrets of the Earth's climate history is one of the most difficult tasks for modern research. Reliable thermometers have only been available for around 300 years. Scientists therefore rely on water isotopes as climate tracers. Their occurrence allows us to reconstruct temperature, precipitation and ice volumes over many millions of years.



What are water isotopes?

Water isotopes are water molecules whose atoms have the same number of protons but differing numbers of neutrons. Climate researchers measure the amount of water isotopes that – compared to the normal "light" water isotope ($H_2{}^{16}O$) – have two additional neutrons in the nucleus of the oxygen atom ($H_2{}^{18}O$) or one additional neutron in the nucleus of the hydrogen atom ($HD^{16}O$). However, these two types of "heavy" water isotopes are extremely rare.

Precipitation

Heavy isotopes condense more easily, while light isotopes tend to remain in the vapour.

When water evaporates or condenses, the ratio of water isotopes changes. For example, precipitation contains more heavy water isotopes at low air temperatures than at higher ones. This temperature-dependency on the part of the water isotopes ratio is preserved in climate archives such as ice cores and can still be found even after thousands of years.

Water evaporates

Light isotopes evaporate more easily, while heavy isotopes tend to stay in the ocean.

Findings from ice cores

Ice cores are made of snow that fell in the past. Scientists analyse the isotope ratio for each layer of snow or ice and determine the temperature for the respective period. In this way, they are able to show the change between warmer and colder climate periods over the last 800,000 years.

Findings from frozen ground

Ice in frozen ground can be found in permafrost regions and is formed, among others, as ice wedges. Their ice consists of refrozen snowmelt water. Therefore, the wedges' water isotope ratios represent the winter temperatures at the time of freezing. The curve below shows temperatures in Siberia, covering the last 8000 years.

Findings from the ocean

Microfossils such as foraminifera or diatoms store the isotope signal in their shells. Geologists search for these shells on the ocean floor, as they allow them to reconstruct water temperatures or the Earth's global ice volume for many millions of years.

Findings from modelling

Some climate models are not only able to simulate temperature and precipitation but also the isotope ratio of rain and snow. Comparisons between the outcomes of models and measured data from ice cores, frozen ground and microfossils can yield a better understanding of these isotope records.

Icing of the polar caps

The recent climate history of the polar regions is like a puzzle with many pieces still missing. It is fairly well known that the present ice formation in Antarctica began around 40 to 35 million years ago. At this time there was a fundamental change in the Earth's climate. For one, a decline in atmospheric greenhouse-gas concentrations was accompanied by a drop in the air and water temperatures. Another crucial change was the opening of the Tasmanian Seaway in the southern hemisphere between Tasmania and East Antarctica, followed later by the opening of the Drake Passage. Since that time the Antarctic continent has been completely surrounded by a deep continuous pathway along which the waters of the Circumpolar Current flow. Still today they insulate Antarctica from the warm ocean currents to the north.

The first glaciers presumably formed in the high mountainous elevations of East Antarctica, specifically the mountains in the region of Queen Maud Land, the Transantarctic Mountains, and the Gamburtsev Mountain Range, which is completely covered today under the ice sheet and was named for the Soviet geophysicist Grigory Aleksandrovich Gamburtsev. Because it was cold enough at the time and sufficient amounts of snow fell, these glaciers must have grown rapidly. Climate data from deep-sea sediments suggest that Antarctica had one or more ice sheets as early as 34 million years ago that contained about half as much ice as it currently holds.

Antarctic ice masses subsequently expanded and declined depending on the development of global climate and the amount of incoming solar energy reaching the Antarctic. But the ice has never disappeared completely. The two currently existing ice sheets of East and West Antarctica attained their greatest extent at the climax of the Last Glacial Maximum about 19,000 years ago. The ice tongues extended to the outer edge of the continental shelf, and sea level was lowered by about 5 to 15 metres. By comparison, the West Antarctic glaciers extended about 450 kilometres further out into the Southern Ocean than they do today and transported so much ice that the tongues no longer floated (ice shelf), but lay on the seabed (ice sheet). The same was true for the glaciers in the Ross Sea and Weddell Sea regions. At the peak of the last glacial, global sea levels were about 120 metres lower than today.

Since 2004, the question of timing for the onset of ice formation in the Arctic can no longer be answered with confidence. Until then it had been assumed that the large-scale formation of glaciers in the northern polar region did not begin until 2.7 million years ago, which would be more than 30 million years later than in the Antarctic. In the summer of 2004, however, in sediment cores from the Lomonosov Ridge, scientists discovered coarse rock grains in deposits older than 44 million years that could not have been transported into the ocean by either wind or water. A number of researchers have concluded that there must have been icebergs floating on the Arctic Ocean carrying this debris at that time. This assumption implies that at that time there were already glaciers near the sea from which these icebergs had calved.

Since then there has been heated debate as to whether this interpretation, that the Arctic was glaciated earlier than the Antarctic, is really correct. The presence of firm evidence that forests were growing at the time in the Arctic, suggesting a climate much too warm for glaciers, is one of the arguments against the iceberg hypothesis. Other researchers maintain that sea ice could also have transported the rock grains. As further analyses of the Lomonosov Ridge cores have revealed, the Arctic Ocean may have been covered by an initial permanent sea-ice cover long before the first ice sheets formed in East Antarctica.

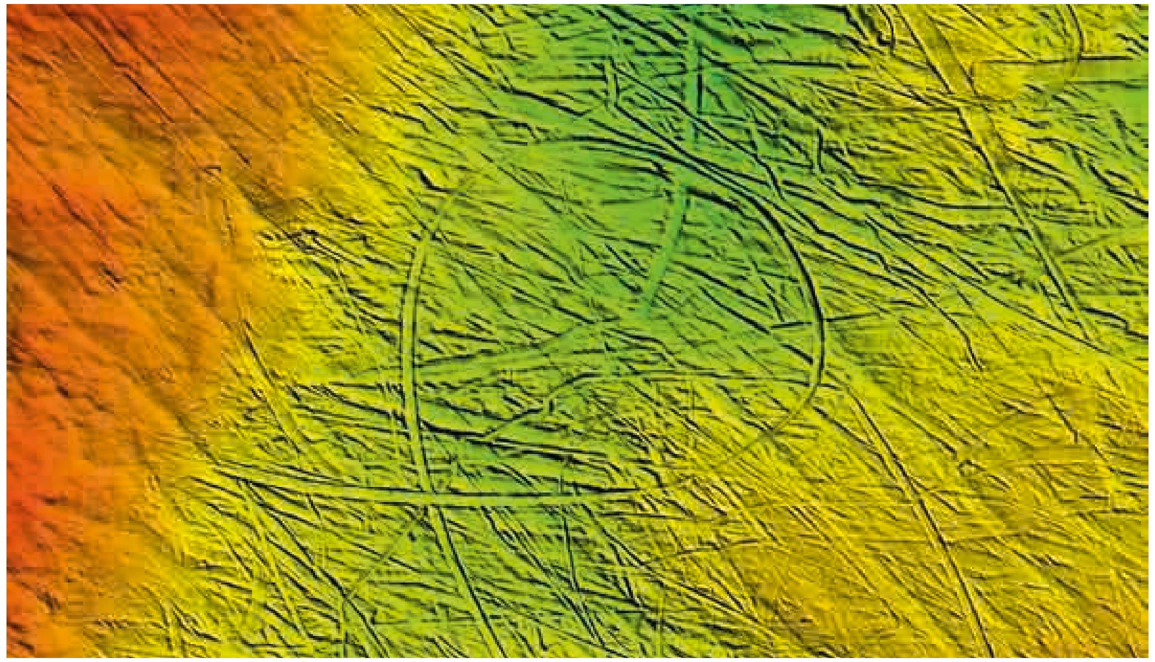
The first glaciers in the northern hemisphere formed during a significant cooling between 3.2 and 2.5 million years ago. Atmospheric carbon dioxide concentrations decreased at that time from about 400 to 300 ppm. At the same time the Panama Strait closed as a result of plate tectonic movements, ending the previously continuous exchange of water between the central Pacific and Atlantic Oceans.

The impact that this change had on Arctic climate is strongly debated. Recent and ongoing studies increasingly indicate that marine currents within the two oceans changed as a result of the interruption of water exchange between them. In the Atlantic Ocean the Gulf Stream was strengthened. Together with its branches, it now transported more saline water, heat and moisture to the far north. The surface waters cooled in the Fram Strait and then, cold and heavy, they sank toward the sea floor. These waters then travelled southward along the path of the global ocean conveyor belt. The heat and moisture above the ocean's surface, on the other hand, was transported by the west winds toward Europe and Siberia. There, it rained and snowed with increased frequency and rivers carried much more freshwater into the Arctic Ocean. During the cold winter months, it should be noted, seawater with a greater proportion of freshwater freezes more readily into sea ice.

Climate researchers believe that more ice floes formed at that time in the Arctic Ocean. The expanding ice area likewise reflected an increasing proportion of the incoming solar radiation back into space, thus inhibiting the storage of heat energy in the ocean. At the same time, around 3.1 to 2.5 million years ago, the tilt angle of the Earth relative to the sun was changing. The planet tilted slightly more away from the sun, so that the northern hemisphere received significantly less solar radiation than it does today. The seasons became colder and less snow melted in the summer, especially in the higher altitudes. Over time the remaining snow masses compacted into firn. Eventually, the ice of the first glaciers was formed from this.

During the subsequent glacial periods, kilometre-thick ice sheets covered large parts of North America, Europe and Siberia. Deep, parallel furrows on the seabed of the East Siberian Sea indicate that ice sheets have even formed in the Arctic Ocean itself within the past 800,000 years, not floating on the water surface like pack ice, but lying directly on the sea floor. These ice masses were at least 1200 metres thick and presumably extended over an area as large as Scandinavia.

This knowledge of the existence of such marine ice sheets raises many questions about the previous ideas regarding Arctic glaciation history. The furrows prove that large-scale freezing does not originate only at high altitudes on the continents, as was the case in Greenland, North America, northern Europe and Asia. Ice sheets can also develop in the seas. The question of what environmental conditions are necessary for this to occur, however, is one of the many uncertainties in solving the puzzle of glaciation in the polar regions.



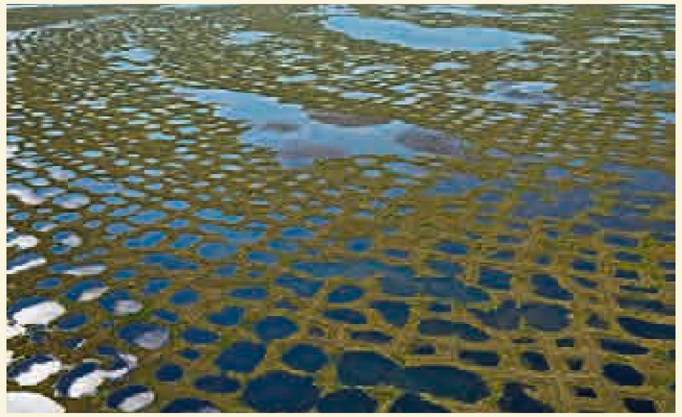
1.15 > Wherever icebergs or shelf ice rest directly on the sea floor, they leave traces of their movements. These almost circular furrows on the seabed were made by an iceberg off the coast of Svalbard.

The many aspects of ice

Ice is formed when water freezes. There is great diversity in the manner in which this happens in the polar regions. Based on their different features, the following types of ice can be distinguished:

Permafrost

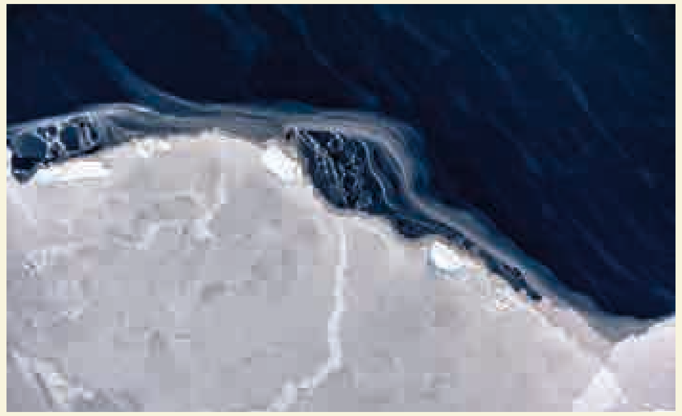
Researchers define permafrost, permafrost soil, or ground ice as the condition when the temperature within the soil remains below zero degrees Celsius for at least two consecutive years, and the water contained in the soil is frozen. The ground can consist of rocks, sediments, or soil, and contain variable amounts of ice. There are areas in the Arctic, in northeast Siberia for example, where the ground contains up to 70 per cent ice. Ground ice can extend to depths of 1.5 kilometres. Permafrost is currently found in as much as 25 per cent of the exposed land surfaces in the northern hemisphere.



1.16 > Most permafrost areas can be recognized by their polygonal patterns. These are formed by repeated freezing of the ground.

Glacier

A glacier is a large ice mass formed from snow that is slowly and independently flowing down a valley due to its great mass, and is then depleted in its lower reaches by the melting of the ice. Some glaciers are not much larger than a football field, while others can be hundreds of kilometres long. Today most glaciers are in Antarctica, Greenland and the Canadian Arctic. But there are also some in the high mountainous areas of the Alps, Andes and Himalayans, where they serve as an important source of drinking water for the surrounding regions. The world's largest glacier is the Lambert Glacier in East Antarctica. It is 400 kilometres long and 100 kilometres wide, and alone it transports eight per cent of the ice masses of the Antarctic ice sheet toward the ocean. Like an ice sheet, a glacier can grow or shrink, depending on how much snow falls on its surface in the winter and how much snow and ice melt in the summer.



1.17 > Icy winds acted quickly to refreeze an open-water area in the Weddell Sea.

Sea ice

Sea ice is formed when seawater freezes. Because of the salt content it must be cooled to minus 1.8 degrees Celsius for this to happen. Freshwater, by contrast, freezes at zero degrees Celsius. New sea ice contains large amounts of brine, which accumulate in droplet form between the ice crystals or in small brine channels. Over time this brine seeps through to the underside of the ice where it is released back into the water. This explains why perennial sea ice contains hardly any salt.

Sea ice begins to freeze with the formation of ice crystals three to four millimetres in size, called ice needles. These collect on the water surface and as their density increases they are mutually attracted to one another. If there is little or no wind a thin continuous crust called nilas is formed. With wind and wave action, however, the crystals eventually form into pancake-like ice plates, which constantly collide with one another and are thus somewhat turned up at the edges. This typical form of sea ice is called pancake ice.

Both the nilas ice and the pancake ice become thicker over time and form ice floes that can grow to thicknesses of up to 90 centimetres in the first year. Wind and waves tend to stack these floes on top of each other, creating pack-ice ridges ten to 20 metres thick. These are impassable obstacles even for icebreakers.

Sea ice forms primarily in the polar regions. It freezes in the winter and, for the most part, melts in the summer. In summer the southern polar ocean loses up to 80 per cent of its sea ice. The total area of ice shrinks from 18.5 million square kilometres (September, end of winter) to 3.1 million square kilometres (February, end of summer). By comparison, the Arctic Ocean loses only about half of its ice mass. Its sea-ice area in winter averages 14 to 16 million square kilometres, and in summer it is seven to nine million square kilometres, with a strongly falling trend.

1.18 > Pancake ice off the coast of Svalbard. The characteristic ice plates are created by surface wave motions.

Ice sheet

Ice sheets, also called ice caps or continental glaciers, are extensive ice shields formed from snow lying on a land surface where the total landscape is covered except for a few isolated peaks, and with an area of greater than 50,000 square kilometres. On the Earth there are currently two ice sheets, the Antarctic continental glacier with an area of 11.9 million square kilometres (without shelf ice), and the Greenland continental glacier with a size of over 1.71 million square kilometres. The Antarctic ice sheet is up to 4897 metres thick in some places and contains so much water that global sea level would rise by around 60 metres if it were to completely melt. The Greenland ice sheet has a thickness of up to 3200 metres and its melting would raise sea level by around seven metres.

Ice sheets are created in regions where the snow falling in winter does not completely melt in the summer. Over time the unmelted snow volumes grow layer by layer and are compacted, first to firn and ultimately to ice due to the increasing weight of the overlying masses with each snowfall. An ice sheet has the shape of a dome. It is thicker in the centre than on the edges. The masses of ice can be thought of as a viscous, unbaked cake batter. Due to their own weight, they flow from the centre of the ice shell toward the edges – just as a lump of cake dough will when it is removed from a bowl and placed on the countertop.

At the margins of an ice sheet, the ice masses usually flow into glaciers, ice streams or ice shelves, and are transported toward the open sea. There are some margin areas, however, where the ice does not move and the ice sheet ends abruptly.

As long as the amount of snow that falls on the surface of an ice sheet is equal to or greater than the amount lost at its margins, a sheet is considered to be stable. If less snow is deposited than is lost to the sea, then the ice shield shrinks.

Shelf ice

Shelf ice is the seaward projection of an ice sheet or glacier floating on the sea, i.e. the part that no longer rests on land or the seabed. The best-known shelf ice in the world is in the Antarctic, where the Filchner-Ronne Ice Shelf (around 422,000 square kilometres in area) and the Ross Ice Shelf (around 473,000 square kilometres), the two largest of their kind, are found.

The thickness of these ice bodies can vary from one ice shelf to another. It can range from 50 metres in the marginal area to 1500 metres in the transitional area between the anchor ice and shelf ice, which is called the grounding line. On the extreme margins of shelf ice, icebergs are constantly breaking off. This process is known as calving.

1.19 > A view of the calving front of the Ross Ice Shelf in Antarctica, the largest ice shelf in the world.

The human conquest of the polar regions

> In view of their extreme climatic conditions, no one ever ventured into the polar regions without good reason. 45,000 years ago, the prospect of abundant prey lured the first hunters into the Arctic. These were followed much later by adventurers and explorers in search of new trade routes. Then the hope of fame became the main impetus. Today – clear economic and political interests notwithstanding – curiosity and a thirst for knowledge have become key motives, and these have promoted peaceful cooperation. Even in politically fraught times, scientists from diverse countries are collaborating closely in the polar regions.

The great migration

The oldest human traces in the polar regions have been found in the Arctic. This is not surprising since, even today, because of its location and land connection, the Arctic is much easier for people and animals to reach than Antarctica, which is surrounded by the Southern Ocean.

Nevertheless, Russian scientists were amazed in the summer of 2012 when they discovered the cadaver of a young bull mammoth preserved in permafrost on the steep shore of the Siberian Taymyr Peninsula, between the Kara and Laptev Seas, and determined that the animal had been slain by humans around 45,000 years ago. This was 10,000 years earlier than hunters were previously believed to have been present in the Arctic. According to detailed reconstructions, the prehistoric hunters had wounded the mammoth with spears in the shoulder, stomach, rib cage and trunk areas so severely that it eventually died. The technique of aiming a spear at the trunk of an elephant is still used by hunters in some parts of Africa today. It has proven to be very effective because vital arteries and veins are located in this part of the head. When these are damaged the animals will soon bleed to death.

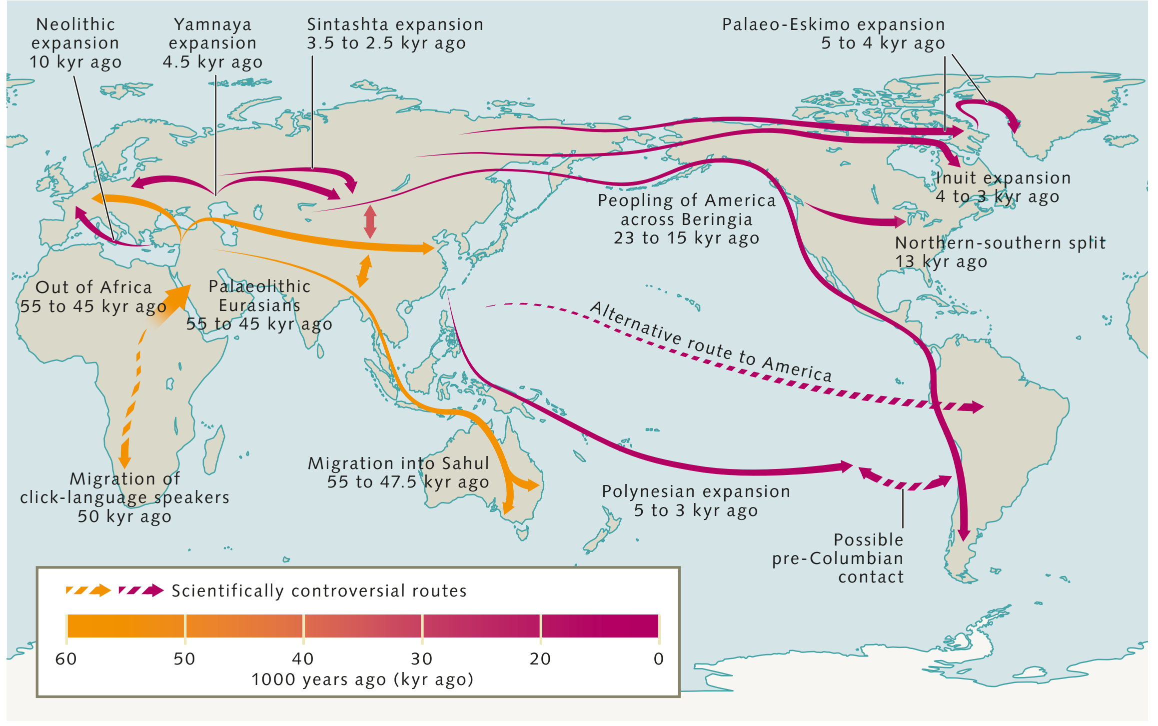
The prehistoric Arctic hunters, however, did not stalk only mammoths. Near the Jana River, about 1700 kilometres to the east, scientists have found the remains of several bison and woolly rhinoceroses. They also discovered the bones of a wolf. These animals were slain by humans about 29,000 years ago. These two excavations prove that modern humans must have roamed extensively in the Siberian Arctic long before the onset of the last glacial period.

This finding also sheds new light on our knowledge about the evolution and dispersal of modern man, *Homo sapiens*. Assuming, as some researchers do, that he left Africa, his continent of origin, for the first time only 65,000 to 50,000 years ago, only a few thousand years remained for the long and arduous migration to the north – a remarkable achievement.

Researchers today cannot say with any certainty how large the first hunting communities in the Siberian Arctic were. The hunters probably lived in small, roving groups at that time, advancing into areas north of the Arctic Circle during the summer, then retreating southward again with the onset of the cold season. Climate data from that period suggest that the average temperatures in the Arctic were somewhat less harsh than today. Nevertheless, people must have been able to sew warm clothes, build shelters and work together in groups. Otherwise they could hardly have survived the climatic conditions.

On their expeditions, the prehistoric hunters probably followed the banks of rivers, which were also followed by the animals of the steppes on their northward migrations. The animals found abundant grazing areas and water in the river valleys. The favourite prey of the early Arctic inhabitants were mammoths, reindeer and horses. Experts believe that it was the ability of the hunters to track the great mammals that made man's advance into the Siberian Arctic possible in the first place.

After the end of the last glacial period, the inhabitants of the Siberian Arctic region learned to make more sophisticated tools and weapons. They began to fish in the lakes and rivers, to catch birds, and even to hunt whales and seals off the coast. They thus had sufficient food and were able to become sedentary, establish settlements and enlarge their family groups.



1.20 > The major migration routes of modern humans as they left North Africa to settle the Earth. The migrating groups left traces in the human genome, which enable researchers today to reconstruct their movements. Their findings indicate that North America was settled from Siberia in three waves – the first time 23,000 years ago.

The first Americans

A comparison of today's Siberian coastline with the coastline at the time of the first Arctic hunters reveals distinct differences. At the peak of the last ice age around 21,000 years ago, global sea level was 123 metres lower than it is today. As a consequence, vast portions of the Siberian shelf seas as well as the area of today's Bering Sea were dry at that time. The Arctic coastlines of Siberia and North America were located further to the north than they are today. Furthermore, a broad strip of land, called the Bering Land Bridge, connected East Siberia with Alaska.

This land bridge had an area about twice the size of the American state of Texas. It stretched from the Lena River Delta in the west to the Delta of the Mackenzie River in the east, and thus extended far beyond the area that we now recognize as the strait between Siberia and Alaska. The region was probably cold, dry, and ice-free – in stark contrast to North America and northern Europe, which were covered by two- to four-kilometre-thick ice sheets at this time.

From sediment cores taken from the bed of the Bering Sea, it is known that the vegetation of the Bering Land Bridge was remarkably diverse. Bushes similar to those found today in the Alaskan tundra grew in the region, as did nutritious grasses and wildflowers that were adapted to cooler temperatures – ideal conditions for grazing animals such as mammoths, bison, arctic camels and reindeer. The question of what vegetation grew on the land bridge and what wild animals were native there is of interest for an important reason: The bridge served as a transit route for animals and humans to the North American continent.

Exactly when and how the first people crossed the land bridge to North America is a subject of much scientific debate and continuing research. Archaeologists search for evidence of settlements, palaeogeneticists reconstruct the migration routes of people based on their genetic make-up, and biologists, geologists and climate researchers study the environmental conditions and landforms of the time. One contentious theory, for example, suggests that the first hunters and gatherers did not cross the land

1.21 > Photograph of an Inuit family printed in the National Geographic journal in June 1917. The accompanying text praises „the tenderness and sense of responsibility“ that the natives of the Arctic have in their dealings with their children.

bridge in one single move, but actually lingered in the area for several thousand years because glaciers and ice sheets blocked their way into the new world. It is also unclear whether the first immigrants made their way along the coast or through an ice-free corridor between the ice sheets. Recent studies indicate that the overland route opened up 15,000 years ago.

However, there is a general consensus that the first North Americans had Siberian ancestors who probably entered the area of the Bering Land Bridge (and here the debate is sparked anew) between 24,900 and 18,400 years ago. Then, about 16,000 years ago, the immigrants began to gradually settle the North American continent. Some of them migrated southward along the west coast and founded the well-known Clovis culture. Others settled in ice-free regions further inland. But none of these first Americans ventured to settle north of the Arctic Circle.

The first inhabitants of the North American Arctic arrived around 5000 years ago in a second migratory wave across the Bering Land Bridge, long after the large North American ice sheets had melted. Within a few hundred years, the people known as Palaeo-Eskimos had spread all the way to Greenland. They lived in small tent camps, hunted reindeer, musk oxen, seals and walruses with stone spears or knives, and had learned to freeze portions of their catch and store them in larder cellars or pits.

About 700 years ago, however, all traces of the Palaeo-Eskimos disappeared. The entire population became extinct. New immigrants from Siberia, called “neo-Eskimos”, the ancestors of the modern Inuit, came to North America with boats around 1000 years ago in the third migratory wave, and gradually displaced the long-established reindeer hunters. The newcomers lived in large, well-organized village communities. They used dog sledges, bow and arrows, and knew how to build boats out of whale bones and sealskins. With these they ventured out onto the Arctic Ocean to fish for whales, a strategy that provided them with new, abundant food sources and guaranteed their survival in the far north reaches.

Pursuing the musk oxen

Around 4500 years ago, the prospect of better hunting probably motivated the Palaeo-Eskimos to cross the 30-kilometre-wide Nares Strait, a waterway between Greenland and Ellesmere Island in Canada. At that time, the Greenland Ice Sheet was somewhat smaller than it is today, so there were sufficient grazing lands for musk oxen and reindeer on its northern and eastern margins. Moreover, abundant ringed seals and harp seals lived in the fjords of the Greenland coast. The Palaeo-Eskimos, however, faced a difficult decision after landing on the inhospitable northwest coast of Greenland. They could either migrate southward along the coast and have to cross a 300-kilometre stretch of glacier-covered coastline in Melville Bay to reach the milder, greener areas of West Greenland, or they could follow the musk oxen northward to a region that was so cold that sea ice remained unmelted off the coast all year long, and where the sun remained hidden below the horizon for five months of the year.

The immigrants chose both options: Some of them moved south and founded the Saqqaq settlement in Disko Bay, whose population grew rapidly in the early centuries. The Saqqaq lived in comparatively large family groups, quickly settled all of the larger fjord systems and islands of West Greenland, and mainly hunted the caribou, harp seals, ringed seals and birds of the west coast. Archaeological digs in former Saqqaq settlements have uncovered the bones of 42 different animal species. Moreover, it is evident that the Saqqaq people dried meat and fish in order to maintain food supplies.

The second group of immigrants chose the northern route. This tribe of Palaeo-Eskimos, known as Independence I, settled on the Peary Land peninsula, where they were confronted with much harsher living conditions than those encountered by their relatives in West Greenland. Moreover, around the time these first immigrants arrived the climate of Greenland began to cool even more. The tundra-like coastal areas in the north gradually transformed into polar deserts. During the summer months, the 100 to 200 pioneers lived in small family clans and set up widely dispersed tent camps, in order to avoid rapidly depleting the sparse food resources offered by the barren landscape and sea ice. Their primary game were musk oxen, caribou, seals and arctic foxes. In winter, however, the people moved back together to spend the colder months in a communal camp.

The tents of these Palaeo-Eskimos were round or oval in shape, and measured three to four metres in diameter. Every third tent or so had a fireplace built of stacked stones. This “stove” in the middle of the tent served as a cooking station, a heating oven and the only source of light, especially during the cold and dark winter months. These inhabitants of the far north heated with what little driftwood was washed up, or with the bones and fat of slain land and sea mammals. The Saqqaq in the west, on the other hand, had sufficient driftwood, allowing them to make larger fires more often and thus heat fist-sized stones. The stones were used not only to heat the areas away from the fireplace, the hunters also used them to cook their meat and fish, because the Palaeo-Eskimos had no pots or other cooking utensils.

The Saqqaq occupied West Greenland over a period of almost 2000 years (from around 2400 to 800 BC). Their neighbours on the Peary Land peninsula, on the other hand, must have given up after just a few generations. Their traces ended about 3750 years ago.

Clovis culture
The Clovis culture is the oldest known culture in North America. It existed about 13,000 to 12,600 years ago across vast areas of North America. These people used stone tools, including spear points of chert with two-sided cutting edges. A number of these points were first discovered at an excavation in Clovis, New Mexico in the USA. The name is derived from this locality.

Arrival of the Vikings

The settlement of northern Europe probably began at the end of the last glacial period. It only became possible for people to advance northward after the large ice sheets had melted around 13,000 to 14,000 years ago. The hunters and gatherers thus migrated from central Europe along the coastline of Scandinavia and into the Arctic region around 10,000 years ago. Stone-age people only settled further inland away from the coasts after the growth of forests there which provided sufficient wood and food sources. In the area that is Finland today, the forests were birch, while in Norway coniferous trees predominated.

From Scandinavia and the British Isles, Nordic sailors then colonized Iceland thousands of years later. According to historical sources, the Vikings landed on the island between 870 and 930 and permanently changed its appearance: in one way by bringing plants and animals from their former homeland, and in another by beginning within a few decades of their arrival to clear the forests of Iceland to let their sheep graze in the highlands.

From Iceland, in the early 980s, the Viking Erik the Red explored the south coast of Greenland. Then, in 985, he set sail with a fleet of 25 ships with the aim of establishing a settlement in Greenland. The seafarers landed in the southern part of West Greenland and founded three settlements, where they mainly lived as cattle and dairy farmers. At that time the climate of Greenland was under the influence of the Medieval Warm Period. The temperatures were similar to today's conditions, so that agriculture was possible to some extent. But the settlers did not depend on their cattle alone. In the early summer they fished for cod, which they preserved by drying (stockfish), and in autumn they hunted reindeer and birds. In addition, the Vikings traded in walrus and narwhal ivory, and explored North America with the aim of obtaining wood there, which was not plentiful enough in Greenland.

1.22 > The Viking Erik Thorvaldsson, known as Erik the Red, sailed from Iceland to Greenland in 982 with a small group of followers, and three years later became the first European to establish a settlement on the island. He called it "Grönland" (green land), hoping that the attractive name would encourage settlers.

At the height of the Viking settlements in Greenland (1300–1350 AD), an estimated 200 farms were inhabited by around 5000 people, although this figure has been disputed. There may well have been fewer than 5000 settlers.

Beginning around the early 14th century, climatic conditions began to worsen. The average temperature dropped by one degree Celsius. Expanding sea ice and increased frequency of storms made it difficult to travel by ship to Iceland and across the North Atlantic. The summer growing season became shorter, and animals that preferred warmer temperatures migrated to the south. Instead of cattle, the Greenland farmers now kept sheep and goats. However, since these did not provide enough meat, the Vikings became increasingly reliant on marine mammals. They hunted bearded, harp, hooded and harbour seals in the open waters. However, they were far less successful at this than the Thule, or proto-Inuit, who had inhabited Ellesmere Island and North Greenland since about 900 AD, and who had learned to lie in wait for ringed seals on the pack ice and kill them using a refined harpooning technique. When the ivory trade with Europe collapsed soon thereafter, the descendants of the Vikings gave up. The last family left Greenland in 1411.

The Age of Discovery

Soon after the Vikings withdrew from Greenland, an era of exploratory voyages to the far north began in Europe. Some of these expeditions were aimed at opening up new areas for whaling and seal hunting. However, most of them served only a single purpose: to discover an open sea route to Asia. Near the end of the 15th century, no merchant ship was allowed to use the southern sea route to India or China without Spanish or Portuguese permission. These two major powers had divided the world between themselves in 1494 with the Treaty of Tordesillas, which gave them control of the shipping routes across the Atlantic and Indian Oceans. For other emerging seafaring

1.23 > Shortly before his death, the cartographer Gerardus Mercator drew the Arctic Ocean as a sea with four large islands in the centre. However, the accuracy of this portrayal was questioned soon after the map was published in 1595.

nations, such as England and Holland, the only alternative was to sail through Arctic waters if they wanted unchallenged trade with China and India. The conditions for finding a navigable route through the Northeast or Northwest Passage, however, could not have been more challenging – the few existing maps of the Arctic region contained gross inaccuracies.

First maps of the polar regions

Many coastal areas of the Arctic have been known and populated for thousands of years. However, around the year 1450 hardly anything was known in Europe about the areas north of Scandinavia. Svalbard, for example, was still undiscovered at that time. What surprises did the regions of the high north hold? Were there perhaps unknown continents waiting to be discovered? Did the pack ice really extend beyond the horizon, or was there, as some had speculated, an ice-free Arctic Ocean?

One of the first maps of the north polar region, drawn by cartographer Gerardus Mercator (1512–1594) and published after his death in 1595, shows four large islands in the Arctic Basin, separated only by narrow waterways. Only two years later their existence was cast into doubt

1.24 > Turkish admiral Piri Reis' nautical chart of 1513. There is disagreement as to whether it only shows the coastline of South America or also parts of Antarctica.

by the Dutch seafarer and discoverer of Spitsbergen, Willem Barents. But the idea of an ice-free polar sea persisted for much longer. As late as 1773, two British ships under the commands of Constantine J. Phipps and Skeffington Lutwidge attempted to sail via Spitsbergen to the North Pole – with the firm conviction that the Arctic Ocean must be navigable. Pack ice halted their progress at 81 degrees north latitude.

In contrast to the Arctic, Antarctica was just a theoretical concept in ancient times. The Greeks were convinced of its existence because the world would otherwise be in a state of disequilibrium. In their classical climate-zone model, they assumed that a cold, uninhabitable zone could not exist only in the north, but to satisfy the mass balance of the Earth there must be a corresponding similar zone located in the south.

In the Middle Ages, the Christian Church forbade the idea of a spherical Earth with an icy counterweight at the South Pole. Instead, the Church held the belief that the Earth was a flat disk. A circular map from that time shows the known continents of Asia, Europe and Africa surrounded by a ring-shaped ocean. Beyond this ocean, the Spanish Benedictine monk Beatus of Liébana (circa 730–798) introduced a new unknown continent to the south, with the notation: "Desertta tterra ... incognita nobis".

The southern continent appeared on a world map for the first time in 1508. The Italian Francesco Rosselli drew it in his representation of the Earth. The first known geographical information about Antarctica is seen on the famous Ottoman map drawn by Piri Reis and dating from 1513, although the origins of this information are not known. Some experts suggest that the map shows actual features, including the sub-Antarctic islands south of Tierra del Fuego and islands in an ice-free western region of Queen Maud Land.

During the next two centuries, the still-hypothetical southern landmass became an entrenched feature of maps – usually under the name of Terra Australis Incognita, which awakened images of wealth and prosperity in many Europeans. According to popular legend, the mysterious southern continent promised gold and other rewards to its discoverers. This myth faded, however, when the English explorer and navigator James Cook (1728–1779) sailed around Antarctica for the first time on his second circumnavigation of the Earth (1772–1775), crossing the Antarctic Circle at three points without sighting land. At 71 degrees south latitude he had to turn back because of heavy ice. The explorer concluded that the presumed continent must lie further to the south, and was thus probably hostile and useless. With the Latin expression "nec plus ultra" (to this point and no further) Cook destroyed the legend of a southern land of riches.

New routes to India and China

In the Arctic, the race to traverse the Northeast and Northwest Passages was well under way. The Italian Giovanni Caboto (English name: John Cabot) led the first exploratory voyage in search of a route along the northern coast of America. He was convinced that the shortest passage between India and Europe would be found in the far north, and in 1497 he encountered the North American continent at the latitude of Labrador on an expedition financed by England. His son Sebastiano Caboto, together with his two associates Hugh Willoughby and Richard Chancellor, founded the Company of Merchant Adventurers to New Lands in 1551 to generate funds for the search for a Northeast Passage. The major motivation of the three businessmen was the prospect of new trade relations with Russia and China rather than the possible discovery of previously unknown regions.

In 1553, on their first Arctic expedition with three ships, Hugh Willoughby and his crew froze to death, but Richard Chancellor reached the White Sea and was invited to Moscow for an audience with the Russian Tsar. There, the Englishman obtained special trade concessions. Subsequent attempts by the trading company to advance further eastward by sea, however, all ended on the Arctic island of Novaya Zemlya, which was first visited by an expedition of the company in 1553. Later, the first explorer to travel beyond this point was the Dutchman Willem Barents, after whom the Barents Sea is named.

Bering – "Columbus of the Tsars"

Vitus Bering (1681–1741) had spent eight years at sea as a ship's boy before joining the Russian navy in 1703 as a second lieutenant. There he advanced quickly through the ranks, and near the end of 1724 Peter the Great commissioned him to explore the eastern part of the Russian Empire. At that time Siberia was still largely unexplored, and the Tsar wanted to know what mineral resources could be found in the region, which indigenous peoples lived there, where the borders of the Russian Empire were, and whether there was a land connection between Siberia and North America. Furthermore, there were rumours that the Cossack leader Semyon Ivanovich Dezhnev had already sailed around the eastern tip of Siberia in 1648 and was thus the first to pass through the strait later named after Bering. There was considerable doubt at the time, however, that these reports were true. The Tsar therefore wanted to be sure.

Vitus Bering and his expedition with 33 men set off on the First Kamchatka Expedition in 1725, which did not take them across the sea but over land. After two years of gruelling marches over mountains and rivers, through seemingly endless steppes and swamps, their trek ended in Okhotsk where the men built a small ship. With it, Bering crossed over to Kamchatka. He then crossed to the east coast of the peninsula and had another ship built there in 1728. With it he set off on 14 July 1728 and sailed northward along the east coast of Siberia. Almost four weeks later, on 13 August 1728, he sailed through the strait between America and Asia that is now named after him. There was no trace of a land connection between Asia and America. When the ship was above the Arctic Circle at 67 degrees north latitude, Bering gave the order to turn back. He was now convinced that America and Asia were two separate, unconnected continents.

However, because Bering had not seen the American coast with his own eyes due to thick fog, his reports were questioned in Saint Petersburg. The royal house wanted more scientific facts and gave Bering a second chance. The Second Kamchatka Expedition (Great Northern Expedition, 1733–1743), which he commanded, was intended to eclipse all previous voyages of discovery. Bering commanded an expeditionary team of 10,000 men, subdivided into several individual expeditions, to survey the northern coasts of Siberia and the Pacific, and to scientifically study the expanses of Siberia. Bering himself was commissioned to locate and map the west coast of North America.

After years of research work crossing through Siberia, Bering set sail in 1741 from Kamchatka with two ships heading south-eastward. He held this course until 46 degrees latitude, because he wanted to discover the legendary island of Gamaland with the streets of gold that were supposed to be found there.

Bering and Aleksei Ilyich Chirikov, the captain of the second ship, confirmed that the island was a fantasy that existed only in the imagination of seamen. The ships then changed course to the northeast to sail toward North America. But during a storm the two ships lost contact with one another. Chirikov subsequently discovered several Aleutian Islands and then, due to a dwindling supply of drinking water he turned and set a course for home. Vitus Bering continued to sail the *St. Peter* into the Gulf of Alaska. There he discovered land in July 1741. He had found North America, which earned him the nickname "Columbus of the Tsars", and he continued to sail along the coast to map its course.

The ship then set out for the return voyage to Kamchatka. However, due to bad weather, lack of food and navigation errors, this did not go as planned. The ship beached on an uninhabited island, today known as Bering Island, where the extremely weakened expedition leader died of scurvy on 19 December 1741 at the age of 60. A total of 46 members of his crew survived the winter. In the spring they built a small sailing ship from the wreckage of the *St. Peter* and made it back to Kamchatka, from whence, in the meantime, a search party led by Aleksei Chirikov had already set out.

A more complete exploration of the northwest coast of North America was accomplished in 1778 by the English circumnavigator James Cook. On his third and last major voyage, Cook reached the Bering Strait and mapped the coast of Alaska to 70 degrees north as well as the Chukchi Peninsula. The last large voids on the map of the Siberian Arctic coast were filled in by the Baltic German officer of the Russian navy, Ferdinand von Wrangel. In 1820, he and his followers began exploring the northern coast of East Siberia from land, using dog sledges, and mapping all of the coastal features. In this way, during his four-year expedition, Wrangel filled the remaining cartographic gap between the mouth of the Kolyma River in Eastern Siberia and the Bering Strait.

1.25 > The Danish explorer Vitus Bering drew this map on his First Kamchatka Expedition (1725–1730). After his return, the Russian Imperial Court requested further scientific facts from Bering proving that Asia and North America were separate continents. Bering therefore undertook the Second Kamchatka Expedition (1733–1743).

The first complete crossing through the Northeast Passage, however, was achieved by the Swede Adolf Erik Nordenskiöld (1832–1901) between 1878 and 1879. The polar explorer had already made a name for himself by exploring Spitsbergen and Greenland, and it took three attempts before he was able to realize his dream of a successful passage. On the first two attempts he made it to the mouth of the Yenisei River, and on his return from the second voyage he became the first traveller to transport commercial goods from Asia back to Europe via the northern sea route. On his third voyage, which began on 4 July 1878 in Gothenburg, he headed toward the Yenisei with four ships. Upon arriving at the estuary, he continued eastward with two ships and mapped the coast as far as Cape Chelyuskin on the Taymyr Peninsula, the northernmost point of mainland Asia. He then sent the companion ship *Lena* back with a message of success, but he himself continued heading eastward with his steam-powered vessel *Vega*, and was able to sail along the northern coast of Siberia before the onset of winter. However, a mere 115 nautical miles from his destination of the Bering Strait, the ship became frozen in the ice. Nordenskiöld and his men were trapped on the Chukchi Peninsula and forced to spend the winter there. About 300 days later, on 18 July 1879, the ice finally released the *Vega* again.

Nordenskiöld then sailed through the Bering Strait to Japan. Because the news of the successful voyage had spread like wildfire around the world, his journey home from there was a triumphant one, taking him through the Suez Canal, which was only ten years old at the time.

A shorter route to Australia?

The counterpart to the Northeast Passage, the approximately 5780-kilometre-long Northwest Passage, was first completely traversed 26 years after Nordenskiöld's triumph. After the pioneering expeditions by English and Portuguese explorers in the 16th and 17th centuries, there were no notable ship expeditions to this area for the next 200 years. This lack of interest was partly due to the

1.26 > The English seafarer James Clark Ross discovered the North Magnetic Pole at the age of 31. Ten years later he explored Antarctica and was the first man to advance into the region of the Ross Sea, which bears his name today.

discovery of Lancaster Sound and the Hudson Bay during previous voyages, regions that promised enormous profits for the fur trade due to their great biodiversity. Other potential explorers were distracted by the gold rush in North America.

The desire to find a sea route along the North American Arctic coast was revived only after it became known that the Arctic Ocean was indeed continuous along the northern margin of the continent. Hunters and fur traders had confirmed this by following the Mackenzie and Coppermine Rivers to their mouths. But before a ship could undertake this dangerous voyage three things had to be determined. First of all, there was no known western outlet from Baffin Bay. Secondly, the entryway into the Northwest Passage from the Pacific was not yet known. The Englishman James Cook had advanced into the Bering Strait to 70° 44' North on his third world voyage in 1778, before being blocked by a "12-foot-high wall of ice" to the north of Icy Cape. However, it was completely unknown how the coastline continued beyond that. Thirdly, no one knew whether there would be a navigable sea route through the island maze of the Canadian Arctic Archipelago to the east.

In order to fill these white patches on the map with information, a number of ship and land expeditions to the North American Arctic were undertaken during the first half of the 19th century. The British captain Frederick William Beechey explored the north coast of Alaska from Icy Cape to Point Barrow. The British explorer John Franklin (1786–1847), working on land, mapped the coast around the Mackenzie and Coppermine River Deltas during his first expedition (1825–1827).

An expedition led by John Ross sought to explore the missing area between Melville Island in the east and Franklin's mapping to the west. In the process, Ross' nephew James Clark Ross discovered the magnetic pole of the northern hemisphere in 1831.

Death in the island maze

For the third and ultimate task, the search for a way through the islands of the Canadian Arctic Archipelago, the British admiralty selected a man with previous Arctic experience. In February 1845 they commissioned the polar explorer John Franklin, who had meanwhile been promoted to the rank of Rear Admiral, to find the Northwest Passage. He was to sail with two ships around Greenland through the well-known Baffin Bay, and find a western branch that was believed to exist. The army provided the expedition leader with the two ships best suited for ice at the time: HMS *Erebus* and HMS *Terror*, two converted warships whose bows were reinforced with copper and iron to protect the wooden hulls. Both of the three-masters were equipped with a 25-HP steam engine, which drove a ship's propeller so that the expedition could continue to advance during periods of low wind. In addition, pipes were installed in the ships through which hot water could be pumped to heat the rooms on board. With a crew of 67 men on each ship and provisions for three years, they set sail from London on 19 May 1845.

In the Disko Bay of West Greenland, the crews divided supplies from a third escort ship between the two expedition ships, and set a course for Lancaster Sound, a strait between Baffin Island and Devon Island. After that, they were sighted twice by whalers. Then John Franklin and his men disappeared into the hostile labyrinth of islands, pack ice and rocky coasts, which was largely uncharted at the time.

More than 40 search missions were carried out in the years that followed to determine the fate of the two expedition ships and their crews. In the process, the search parties also made important geographical discoveries and completed Franklin's mission. Finally, in April 1853, two search teams coming from different directions – one led by Robert McClure, the other by Henry Kellett – met in Mercy Bay on the northern end of Banks Island, proving for the first time that the Northwest Passage truly existed.

The first traces of the Franklin expedition had already been found by search teams. In August 1850, shreds of clothing on Devon Island and three graves on Beechey Island were discovered. Four years later, Inuit in Pelly Bay on the Boothia Peninsula reported to the Arctic explorer and physician John Rae about white sailors who had starved to death some distance to the west. In May 1859, another search team, on the west coast of King William Island, discovered a stone marker hiding an expedition report by the ship's crew.

The remains of the two ships were discovered in 2014 and 2016. HMS *Terror* lay on the bottom beneath 24 metres of water in a bay on King William Island. According to reports, the three-master is in such good condition that it would float if it were raised and the water pumped out.

It was more than 50 years after Franklin's disappearance before the Norwegian Roald Amundsen (born 1872, disappeared 1928) became the first to succeed in traversing fully through the Northwest Passage with a ship. But he too was not able to complete the passage within a single year. It took Amundsen a total of three years with his vessel *Gjøa* (1903–1906). He was forced to wait out the winter more than once due to ice conditions. The severe winter ice conditions in the Northwest Passage were also the reason this route did not become a time-saving alternative to the shipping route through the Suez Canal and across the Indian Ocean. With the state of ship technology at that time, the route could not be navigated without spending at least one winter waiting for the ice to recede.

Thirst for knowledge replaces commercial interest

After it had been demonstrated that there was little point in sending merchant ships to Asia and Australia via the Northeast or Northwest Passage, the economic motivation for continued exploration of the North Polar region dissolved. In its place, however, scientific interest in the region increased. Driven by the desire for a more complete knowledge of all earthly realms, many countries intensified their research efforts in the polar regions.

In Germany, the geographer and cartographer August Heinrich Petermann (1822–1878) promoted research in one way by establishing the scientific journal *Petermanns Geographische Mitteilungen* in 1855. In it he published numerous articles and maps on polar research, thus providing scientists with an instrument for sharing their research. In addition, Petermann advocated hypotheses that gave new directions to Arctic polar research at the time. On the one hand, he argued, the Arctic Ocean could not freeze completely over even in winter due to a warm ocean current from the south, an extension of the Gulf Stream, and that an ice-free and navigable Arctic Ocean would be found to the north of the belt of drifting pack ice. Furthermore, he postulated that Greenland, which was still largely unexplored at the time, extended across the Pole to as far as Wrangel Island.

In 1868 Petermann succeeded in initiating the first German North Polar Expedition, led by Carl Christian Koldewey (1837–1908). On board the ship *Grönland* the expedition team was to survey the east coast of Greenland up to 75 degrees north latitude. But the plan did not succeed. Pack ice blocked the ship's path, so Koldewey and his crew changed course and sailed to Spitsbergen. There they carried out meteorological and hydrographic measurements, confirming that a branch of the Gulf Stream carried Atlantic water masses along the west coast of Spitsbergen toward the Arctic.

A second German North Polar Expedition (1869–1870) planned by Petermann also partially failed – due in part to the fact that one of the ships was crushed by the ice. And it was not the last voyage of discovery that would not fully achieve its objective. For example, the Austro-Hungarian North Pole Expedition (1872–1874) led by Carl Weyprecht (1838–1881), which set out to investigate the Arctic Sea north of Siberia, did discover Franz Josef Land but, contrary to plan, the party was forced to spend the winter and later to abandon the ship. Weyprecht, however, learned a lesson from the journey, and based on this experience he developed his basic principles of Arctic research. In his opinion, polar research was only worthwhile if it conformed to his six principles:

1. Arctic research is of the utmost importance to understand natural laws.
2. Geographical discoveries in these areas are only of major importance insofar as they pave the way for scientific research in its strict sense.
3. The detailed topography of the Arctic is of secondary importance.
4. The geographic pole is not of particularly greater scientific importance than any other location at high latitude.
5. Regardless of their latitude, observation stations are more advantageous the more intensively the phenomena for which the study is designed occur at the given site.
6. Individual observation series are of greater relative importance.

1.27 > During the first International Polar Year (August 1882 to August 1883) scientists carried out regular weather observations and measurements of the Earth's magnetic field at twelve research stations in the Arctic. A total of eleven countries participated.

Weyprecht's approach was immediately well received by the research community. It would help to avoid additional costly and less efficient expeditions. He also worked closely with Georg von Neumayer (1826–1909), the director of the German Naval Observatory in Hamburg, on the first international Arctic measurement campaign. Their basic idea of "research stations instead of research voyages" remains one of the cornerstones of modern polar research, emphasising the importance of continuous long-term measurements rather than detailed isolated studies.

Neumayer and Weyprecht's campaign led to the foundation of the first International Polar Commission in 1879, which was chaired by Neumayer. The Commission organized the first International Polar Year (summer of 1882 to summer of 1883), during which eleven countries established a network of twelve meteorological and geomagnetic stations in the Arctic (Russia operated two stations). Two additional stations were set up in the Antarctic. However, to the detriment of science, only the individual results of each of the participating countries were

Two lives under the spell of the ice

Ambitious, meticulous, obsessed with the poles – these traits describe the Norwegian Roald Amundsen as well as the German Erich von Drygalski. Both were pioneers of polar research, but they could hardly have been more different. While one was pursuing a record, the other was striving to understand the larger picture.

Roald Amundsen (1872–1928) – in pursuit of fame

Since the age of 15, South Pole conqueror Roald Amundsen had known only one ambition – to enhance our knowledge of the world's polar regions. He associated the word "knowledge", however, primarily with geographical information rather than a deeper understanding of the nature and climate of the polar regions. On his expeditions, the Norwegian mostly left scientific observations to the specialists, although he himself was competent in various measurement methods. Before his expedition to the Northwest Passage, for example, Amundsen spent several months learning theory from the German Georg von Neumayer, who at the time was a leading expert in geomagnetics. He wanted to learn how to measure the Earth's magnetic field. Furthermore, on a preparatory cruise for the same expedition, he collected oceanographic data for his mentor Fridtjof Nansen.

But science did not excite him. Amundsen was much more interested in the techniques and methods that could contribute to the success of his expedition plans. On the *Belgica* Expedition to Antarctica (1897–1899) Amundsen, as second officer, had learned that details could be crucial in the planning of an exploration cruise. The crew had survived the threat of scurvy, a disease caused by a deficiency of vitamin C, by following the advice of the ship's doctor Frederick A. Cook and eating fresh penguin meat during the winter instead of the stores of canned food.

Amundsen was fascinated by pragmatic solutions. During his voyage through the Northwest Passage (1903–1906), he learned from Eskimos how to build igloos and how to harness dogs to pull sledges. He marvelled at their windproof reindeer-skin clothing and wore it himself from that time on. For his march to the South Pole he successfully used dog sledges and skis as a means of transport, and for his airship flight over the North Pole he had a solar compass built in Berlin, which the pilot could use to accurately navigate northwards.

Amundsen was a born leader and also applied the highest standards in the selection of his team. His crew was always well trained and handpicked, and comprised only as many men as were absolutely necessary for success. Everyone on board was given multiple duties. In this way Amundsen prevented boredom from becoming a problem, and increased the sense of responsibility in his men.

When it came to his reputation and honour as an explorer, however, he could make decisions without regard for the considerations of his companions. In 1910, for example, he informed most of the crew of his research vessel *Fram* at some point after leaving Oslo that he did not intend to sail towards the North Pole as they had all believed, but would instead set a course for Antarctica in order to be the first man to reach the South Pole. Because Frederick A. Cook in 1908 and Robert Peary in 1909 had purportedly already been to the North Pole – two reports which later turned out to be false, as both had only come close to the Pole – Amundsen at least wanted to achieve success in the south. Before their departure he had only revealed their true destination to his brother Leon, who was in charge of the business side of the expeditions, Captain Thorvald Nilsen, and the two helmsmen.

Throughout his life, Amundsen was driven by the desire to conquer frontiers and be the first person to achieve incredible feats. Towards this dream he not only borrowed heavily, he also trained obsessively, endured solitude, and knew better than anyone how to portray his projects in the media. His greatest strength, as described by historians, was his belief in himself. With this attitude, Roald Amundsen not only expanded our knowledge of the polar regions, he also made a name for himself in the history books alongside his role models Nansen and Franklin.

Erich von Drygalski (1965–1949) – in pursuit of knowledge

Erich von Drygalski was not much impressed by the media hype over the race to the South Pole. "For polar research, it is immaterial who is the first man at the Pole", commented the East Prussian and scientific whiz kid in reference to the race between Amundsen and Scott. In 1882, at the age of 17, Drygalski began studying mathematics and physics. Soon afterward, he discovered his passion for geography and ice, hiked through the largest glacial areas of the Alps for eight weeks, and at the age of 22 wrote his doctoral thesis on the distortion of the globe due to ice masses. Ice became the central focus of his life. He wanted to understand the glaciation of the North German lowlands as well as the structure, motion and effects of ice, and to mathematically describe the movements of large ice masses. He decided to address these problems by measuring the movement of glaciers in nature, ideally on a large ice sheet.

The largest and nearest ice mass was the Greenland Ice Sheet. The Geographical Society of Berlin financed a preliminary expedition (1890) and a full-scale expedition (1892–1893) to the Uummannaq Fjord on the western margin of this ice cap. Not only did Drygalski set up a research station there, where he and his two companions spent the winter, he also designed a very modern research programme for the team, which filled their days with a wide range of tasks.

For twelve months the scientists mapped and surveyed a number of glaciers in the region. By marking the ice, Drygalski was able to track its flow as well as its rise and fall. On sledging excursions, he was able to study how the ice formed. The scientists also collected meteorological data throughout the time they were there, including temperature, duration of sunshine, air pressure, humidity and wind, in order to understand the effects of ice on the climate. The team's biologist documented the flora and fauna in order to learn how the ice masses affected the biology of the fjord. In addition, geomagnetic measurements and gravity experiments were carried out. The dataset collected by the team was so immense by the end of the expedition that it took Drygalski four years to analyse it. He published the results in two volumes, advanced a fundamental concept of ice motion, and was named as professor within the top ranks of polar researchers.

Because of his extensive experience, three days after qualifying as professor he was chosen to lead the first German South Polar Expedition (1901–1903). His failure to set any records in his name during this excursion disappointed the German Kaiser and the public, but the scientific data he collected was of excellent quality, and Drygalski again retreated into the analysis of this huge body of data. Personal matters such as family planning were put off for the time being, and could only be addressed again after the analysis had been divided among the scientists, leaving him to deal with the geographical and oceanographic findings. To fail to complete a project he had begun would have been unthinkable for him. Straightforward and determined, he compiled the results of the expedition and published them step by step – a task that kept him busy for a total of 30 years. Roald Amundsen was correct when he assessed the significance of this work. Before his death, he said that Germany had every cause to be proud of the essential scientific results of the South Polar Expedition.

published. An all-inclusive overview, in which all weather data were summarized in monthly maps of air pressure and air temperature, did not appear until 1902 – and then only as a dissertation that received little attention instead of being published as a scientific article in a widely read professional journal.

Drifting toward the North Pole

The First International Polar Year was soon followed by a new era of polar research, in which individual initiative and a desire for knowledge became the primary motivating factors for scientific exploration. In 1888, the Norwegian zoologist Fridtjof Nansen (1861–1930) became the first to cross Greenland, proving that it was covered by a continuous ice sheet from the east to the west coast. Soon thereafter the German geographer and glacier researcher Erich von Drygalski (1865–1949) spent a winter on the west coast of Greenland, primarily to study the movements of small local glaciers and large inland ice flows, but also taking meteorological measurements and collecting biological specimens.

Achieving the next scientific milestone required an investigative instinct and a spirit of adventure. In 1884, Fridtjof Nansen, who had crossed Greenland, learned from a newspaper article that Inuit on the southwest coast of Greenland had found pieces of a ship that had sunk three years earlier north of the Siberian islands 2900 sea miles away. This discovery sparked Nansen's interest. He had a research vessel built with a hull shape that could not be crushed by the pack ice, called it *Fram* and, on 22 September 1893, allowed himself and the ship to be trapped in sea ice off the New Siberian Islands. Locked in the ice, the ship and crew drifted between the Siberian coast and the North Pole for months, travelling hundreds of nautical miles. The ice constantly changed direction, sometimes carrying them northward and then southward again. Although they were able to take many depth soundings of the Arctic Ocean, the men were concerned that they were not making any forward progress. Moreover, the moving ice did not take them as far to the north as Nansen had hoped. Thick pack ice blocked their path.

Transpolar Drift
Transpolar Drift is a wind-driven ice flow and surface-water current in the Eurasian part of the Arctic Ocean. It transports large volumes of Arctic sea ice from the shelf seas off the Siberian coasts across the North Pole toward the east coast of Greenland, where the ice floes generally enter the North Atlantic and melt after one or two years.

The *Fram* reached its most northward position (85° 57' North) on 16 October 1895. By this time, however, Nansen and his companion Hjalmar Johansen had already left the ship and set off for the North Pole on sledges, skis and kayaks. They did not make it very far on this solitary journey, however. The constantly shifting pack ice finally forced the two men to return to Franz Josef Land, where they spent the winter in a shelter made of stones. The following spring, the two explorers saw no other way out of their predicament than to head for home by kayak towards Spitsbergen. Fortunately, their kayak trip ended prematurely at Northbrook Island, which is also part of Franz Josef Land. By chance Nansen and Johansen met a British expedition under the leadership of Frederick George Jackson there, who rescued them and brought them back to Norway. Around the same time, northwest of Spitsbergen, the sea ice released Nansen's ship. On 9 September 1886, Captain Otto Sverdrup sailed the *Fram* back to its home port of Oslo, bringing with him valuable measurements from a region where no one before them had ever been.

Even though Nansen did not reach his desired destination of the North Pole, the scientific findings were still of great importance. For one, Nansen's expedition put to rest the long-debated theory of an ice-free Arctic Ocean. Secondly, his positional data confirmed the existence of the Transpolar Drift. Thirdly, the sounding data documented the depth of the Arctic Basin and proved that the offshore islands were part of the continents. Furthermore, the Norwegian found that the drift direction of the ice was never exactly parallel to the wind direction, rather the ice floes veered slightly to the right, a phenomenon which, in his opinion, was due to the rotational movement of the Earth (Coriolis Effect). Today we know that this assumption was correct.

In pursuit of seals in the south

While the north polar region had been extensively explored by the end of the 19th century, the southern polar region remained an empty patch on the map for many years after. The reason for this was basically a lack of interest. After James Cook had turned back in frustration, another 40 years passed before the next expedition ventured into the deep southern realm. Between 1819 and 1821, the Baltic German captain Fabian Gottlieb von Bellingshausen had circumnavigated the southern continent during a Russian Antarctic scientific expedition and encountered land in two different places. He discovered the present-day Princess Martha Coast, which borders the Weddell Sea, and two islands in the Bellingshausen Sea, which was named after him.

It was his belief that the mythical southern land was a large continent inhabited only by whales, seals and penguins, and was therefore useless in a geostrategic sense. British whalers and seal hunters who learned of Bellingshausen's reports, on the other hand, applying their good business sense, launched their first fishing expeditions to the south in the 1820s and 1830s. According to reports, they wiped out large seal populations within just a few years. One of these men was the mariner and seal hunter James Weddell, who sailed three times into the southern polar region. On his third voyage he had only modest hunting success, but the ice conditions were so favourable that his ship was able to penetrate as far as 74° 15' South and 34° 17' West into the marine area that bears his name today, the Weddell Sea.

The crews of the fishing vessels not only knew how to hunt and fish, they also carried out geographical surveys and mapped newly discovered islands and stretches of coastline. From the beginning of the 1890s surgeons accompanied the whalers and carried out further biological and hydrographic research. All of this mapping and surveying, however, yielded only limited and isolated results, for as long as the whalers and seal hunters could fill their ships' coffers with furs, fat and oil on the Antarctic Peninsula and in other regions north of the Antarctic Circle, they had no need to sail further south for exploration purposes.

The search for the South Magnetic Pole

Relatively early, in contrast to the whalers and seal hunters, scientists sought to venture far beyond the Antarctic Circle. As early as 1836, the German natural scientist Alexander von Humboldt (1769–1859) had given Antarctic research a new impetus by suggesting to the President of the Royal Society in London that simultaneous measurements of the Earth's magnetic field should be carried out in both the northern and southern hemispheres – from the equator to the poles – using the same instruments. Humboldt had supported the founding of the Göttingen Magnetic Society, a working group whose goal was to carry out simultaneous geomagnetic observations worldwide and which soon included 50 observatories.

Humboldt's proposal prompted an international race to locate the South Magnetic Pole, which became known as the Magnetic Crusade and during which many new regions of East Antarctica were discovered. The French polar explorer Jules Dumont d'Urville, for example, claimed the territory of Adélie Land not far from the presumed magnetic pole and extending to the coast, where the French research station Dumont d'Urville, named in his honour, is located today. In 1840, the American Charles Wilkes sailed with his ship along the 2000-kilometre coastline of what is today Wilkes Land. Just a few months later the Englishman James Clark Ross set a new record by crossing the line of 78 degrees latitude during his search for the magnetic pole in an unexplored marine region now called the Ross Sea.

On this voyage (1839–1843) Ross not only determined the position of the South Magnetic Pole, which, according to his measurements, lay at 75° 05' South and 154° 08' East, he also discovered the edge of the immense Ross Ice Shelf (later named after him), Victoria Land, and an island with two majestic volcanoes, which he named after his two ships: Erebus and Terror. Today, unsurprisingly, the island is named Ross Island.

A matter of national interest

After Ross's successful voyages, scientific interest in Antarctica waned. There was a lack of motivation and funds to organize expensive research expeditions to the southern polar region. But there were two exceptions. In 1874, the transit of Venus provided an opportunity to refine measurements of the distance from the Earth to the sun (the astronomical unit). To take advantage of this, England, Germany and the USA set up astronomical observatories on the Kerguelen Islands in the southern Indian Ocean. Eight years later, on the occasion of the First International Polar Year, Georg von Neumayer had an observatory constructed in South Georgia to observe the second transit of Venus during the 19th century. But the primary functions of the station were for weather observations and measurements of the Earth's magnetic field.

The enthusiasm of polar explorers was finally revived shortly before the turn of the century. In 1895, the initial impetus was given by the Sixth International Geographical Congress in London. There, leading scientists proposed the exploration of the still unknown Antarctic region as the ultimate challenge of the late 19th century. At that time, no one could say with certainty whether Antarctica was a continent covered with ice or a gigantic atoll with an ice-covered sea at its centre, which – as in the Arctic – could even be traversed.

This was the motivation for the *Belgica* Expedition (1897–1899), led by the rather inexperienced Belgian polar explorer Adrien de Gerlache de Gomery. For the first time, men spent the winter in the Antarctic pack ice, albeit involuntarily because they did not leave soon enough. Meanwhile, English and German researchers planned a number of major expeditions and divided Antarctica into four equal quadrants. The German area was in the Weddell Sea and the Enderby region, while the English wanted to concentrate on the Victoria and Ross quadrants. In addition, the polar researchers agreed to carry out simultaneous meteorological and magnetic measurements in order to compare the data and thus systematically investigate Antarctica according to Weyprecht's principles.

This close scientific cooperation between Germany and England was remarkable, considering that the two countries were engaged in intense economic competition. The era of colonial imperialism had begun, and international competition for markets and resources had intensified. Germany, as an emerging naval power, desired more international influence and prominence, and the United Kingdom wanted to maintain its hold on these. For this reason, the governments of both countries strongly supported the plans of their scientists. Antarctic research was regarded as a national duty and a cultural mission, the accomplishment of which promised merit and benefit. After prolonged pleading by the scientists, both countries provided state funds – but only for their own expeditions.

1.28 > In March 1902, during the first German South Polar Expedition, the German polar research vessel *Gauß* was immobilized by sea ice. Expedition leader Erich von Drygalski had tents and measurement instruments set up on the ice so that daily research could be carried out.

Scientific results from the five research cruises, in which ships from Sweden, Scotland and France also ultimately took part, were impressive: All the expeditions encountered new territory. Furthermore, it was now certain that Antarctica was a continent and not an atoll. Based on atmospheric pressure measurements the researchers were able to draw inferences regarding the elevation of the ice-covered land masses. According to these, Antarctica has an average elevation of 2000 metres, ± 200 metres.

However, after the scientists returned, fame and honour were bestowed only on the English. In Germany, both the Kaiser and the public viewed the results of the first German South Polar expedition (1901–1903) as disgraceful because the ship, under the scientific direction of Erich von Drygalski, became trapped in ice near the Antarctic Circle, and the scientists were not able to advance as far south as the British expedition under Robert Falcon Scott. In politically charged Berlin at that time, the traditional view still prevailed that the sole purpose of geographical research was to remove white patches from the map or to reach the pole. The value of the meteorological, magnetic, oceanographic and biological data that Drygalski had collected during his expedition was not greatly appreciated at the time. Yet the analyses took three decades and yielded substantial results. Results from the biological collection alone ultimately filled a total of 13 volumes instead of the three volumes that were originally foreseen, and these are still gaining in importance today in the light of modern biodiversity research.

The tragic races to the poles

The turn of the century also marked the beginning of the phase of polar research that has probably been the subject of most books up to now – the era of heroes and tragic losers in the competition for the most spectacular expedition, or for the title "First Man at the North or South Pole". In contrast to the state-organized Antarctic trips from 1901 to 1905, individualists were once again cast into a leading role. This generation of explorers, scientists and adventurers demanded the ultimate physical commitment from themselves and their companions. They were not always well prepared for their journeys, but they were prepared to take enormous risks for fame and honour – a heroic mentality that ultimately led to the deaths of many people, and made experienced polar explorers sceptical of the wisdom of such endeavours.

Fridtjof Nansen, for example, after the failed Spitsbergen expedition by the German officer Herbert Schröder-Stranz in 1912, deeply regretted that he had not been able to prevent the tragedy. He is quoted as saying, "If these people had just had a little experience in ice and snow all this misery could easily have been avoided! Travel to those regions truly entails enough difficulties without having to amplify them with inadequate equipment and an excess of ignorance".

The East Prussian Herbert Schröder-Stranz had sailed to Spitsbergen in August 1912 to obtain polar experience for his planned Northeast Passage crossing. But on Spitsbergen, or more precisely on Nordostland, the second largest island, on the northeast side of the archipelago, he and three of his companions disappeared when they tried to cross the island by dog sledge. A few days later Schröder-Stranz's ship was surrounded by pack ice in the Sorge Bay, and some crew members decided to set off on foot towards the next settlement. This decision also turned out to be a tragic mistake. In the end only seven of the original 15 expedition members survived.

The race to the South Pole, as played out by the Norwegian Roald Amundsen and the British Robert Falcon Scott, also ended tragically. Amundsen, who had sailed to Antarctica on Fridtjof Nansen's ship, the *Fram*, won the race. He and four of his men, all experienced skiers, made their way into the interior of the icy continent on dog sledges and became the first men to reach the South Pole on 14 December 1911 – 34 days ahead of their rivals. They then returned home safely. Their adversaries, on the other hand, were not so lucky. Due to bad weather, Scott and his four companions were not able to make it to their emergency food depot on the way back across the Ross Ice Shelf. The Antarctic winter had overtaken them and the men died of cold and exhaustion.

In Germany, the success or failure of German polar expeditions was analysed in detail in scientific circles. The experts concluded that future expeditions to the Arctic or Antarctic regions would have to meet certain basic requirements. They should be backed by a well-established organization that, in cooperation with institutions and authorities, would raise the necessary funds and develop guidelines for expedition equipment. In addition, the scientists called for a regularly published scientific journal for polar research. Until then most of the papers on Arctic and Antarctic research had appeared in a variety of different periodicals, making it difficult for many interested readers to access the widely scattered articles and reports.

Some of these wishes were fulfilled by new societies established after the First World War. They included the International Society for the Study of the Arctic by Means of Airship, which later became the Aeroarctic Society, as well as the Archive for Polar Research, now called the German Society for Polar Research. Both of these institutions published professional journals. In the Archive, furthermore, material was collected to assist in the preparations for expeditions.

1.29 > A propeller sledge built by the Finnish State Aircraft Factory. The German polar researcher Alfred Wegener had two of these built for his Greenland expedition, but the two vehicles *Schneespatz* (Snow Sparrow) and *Eisbär* (Polar Bear) failed to operate properly during the mission.

Into the ice with Zeppelin and airplane

After the First World War, many forms of modern technology in the fields of communication and transport, such as radiosondes, radios, airships, planes and snowmobiles, were adopted for use in polar research. One of the first to take advantage of these innovations was the discoverer of the South Pole, Roald Amundsen. He had earlier been trained as an aircraft pilot in Norway in 1914, and in May 1925 he departed from Spitsbergen with his crew and two Dornier seaplanes towards the North Pole. However, the adventurer did not reach his goal. When they landed the two aircraft on the sea ice at 88 degrees North so that Amundsen could determine their exact position with a sextant, one of the planes was damaged. Getting the remaining machine airborne again became a struggle for survival for the six expedition members. About three weeks passed before they were able to construct a runway on a large, stable ice floe. They had to spend four days flattening the new snow with their feet. When they were finally successful on their sixth take-off attempt, the expedition team were able to return to Spitsbergen.

But this near catastrophe was no reason for Amundsen to abandon his plan to fly to the North Pole. Just one year later he succeeded in creating a sensation, together with his financial backer Lincoln Ellsworth and the Italian general and aviation pioneer Umberto Nobile. In the airship *Norge*, they not only flew to the North Pole, but also became the first to completely cross the Arctic Ocean, landing in Alaska after a flight time of 70 hours.

Two years later, Umberto Nobile again piloted a self-built airship towards the North Pole in order to carry out extensive scientific investigations on the way. But the *Italia* crashed – an accident that had far-reaching ramifications. During the subsequent search for survivors of the crash, Roald Amundsen, among others, also lost his life.

1.30 > The airship *Norge*, in which Roald Amundsen and his team flew from Spitsbergen over the North Pole in May 1926. It was 109 metres long and achieved a top speed of 85 kilometres per hour.

Not all of the technical innovations of the time would prove to be useful in the polar regions. The propeller sledges that the German polar researcher Alfred Wegener (1880–1930) planned to use for transporting loads on his Greenland expedition (1930–1931) are one example of this. In the freshly fallen snow the heavy vehicles failed, which, due to a tragic chain of events, ultimately led to Wegener's death on the Greenland Ice Sheet.

However, during this period of technological advances, an additional cornerstone was laid for modern polar research. Wegener's Greenland expedition was exemplary in this regard. For it, the scientists had combined three expedition plans into one comprehensive plan, so that all of the participants of the expedition worked on an overarching topic – in this case the inland ice and the weather on the Greenland Ice Sheet – from different scientific perspectives.

As airships began to make more frequent long-distance flights, it became obvious that more reliable weather data from the Arctic region were needed, for example, for transatlantic flights from Europe to North America. At the time, however, these data were only being collected at a few stations and were not sufficient to accurately predict local weather phenomena over the large Arctic islands and over the Greenland Ice Sheet. Scientists and industry therefore called for an expansion of the weather-observatory network, as well as measurements in the higher atmospheric layers of the Arctic.

This demand was addressed during the Second International Polar Year (August 1932 to August 1933), which saw the establishment of a denser measuring network in the Arctic. The scientists launched towed weather balloons with radiosondes attached. Along with these, measurements of the upper atmospheric layers were made by airplanes, whose findings were intended to help understand the influences of polar weather on processes at the middle latitudes.

Over time, the new technological possibilities and improvements in weather prediction made polar research increasingly successful. Expeditions to both polar regions were subsequently well equipped, as technology and participants were tested on preparatory expeditions and thoroughly prepared for operations in the polar regions. The use of aircraft made it possible to leave the ice or land surfaces and investigate large areas from the air. Experience had shown that it was preferable to publish the findings of expeditions through government agencies or similar higher-level institutions. In addition, researchers began to conduct their field research in the polar regions from one or more base stations, for example, from Spitsbergen or the Antarctic Peninsula.

A continent for research

After the Second World War, however, as the number of research stations and the number of winters spent in Antarctica increased, so did the claims to ownership of areas in the region. Bordering and neighbouring countries such as Argentina, Chile, Australia and New Zealand filed claims for certain regions, while Norway, Great Britain and France also wanted pieces of the pie.

Under the politically tense conditions prevalent during the Cold War, Norwegian, British and Swedish scientists carried out joint seismic surveys between 1949 and 1952 in Queen Maud Land, east of the Weddell Sea, to measure the thickness of the Antarctic Ice Sheet in this margin area. To this day, this expedition is regarded as a model for international cooperation in polar research.

Soon thereafter, the international scientific community succeeded in organizing an International Geophysical Year from 1957 to 1958, which historically became the Third International Polar Year. It was the largest meteorological and geophysical experiment that had been carried out up to that time. Twelve nations installed a total of 55 stations in Antarctica – not only on the fringes of the continent, but also directly at the South Pole and on other parts of the ice sheet. With the help of the most modern methods of that time, including the early Russian and American satellites, Antarctica and its overlying atmosphere were extensively studied.

These scientists thus provided the impetus for a peaceful and purely scientific perception of the continent and laid the groundwork for the Antarctic Treaty, which was signed by twelve states in 1959 and entered into force in 1961. The signatories to the treaty not only relinquished their ownership claims, they also agreed that:

- The Antarctic is to be used only for peaceful purposes;
- They support international cooperation in research with the free exchange of information;
- Military activities in the Antarctic are prohibited;
- Radioactive waste may neither be introduced or disposed of here.

To date, 53 states have signed the Antarctic Treaty and committed themselves to permanently protecting Antarctica and using the area south of the 60th parallel exclusively for peaceful purposes. The participating countries include 29 Consultative Parties. These nations actively conduct research in Antarctica and are entitled to vote at the Antarctic Treaty Consultative Meetings, which the other signatories are also invited to attend. At the annual conferences, the principles and objectives of the Treaty are amended and supplemented according to the rule of unanimity.

Since the enactment of the Antarctic Treaty, research activities in the Antarctic region have been coordinated by the Scientific Committee on Antarctic Research (SCAR), which was established at that time. The International Arctic Science Committee (IASC) plays a similar role in the Arctic region. It relies, however, on the voluntary cooperation of all nations conducting research in the Arctic. There are no regulations for the Arctic similar to those laid out in the Antarctic Treaty. The political and economic interests are too divergent for that.

In contrast to the early days of polar research, scientific expeditions today are no longer adventurous journeys into the unknown. Satellite data include the extent of sea-ice cover, enabling the long-range planning of routes. Weather services generally warn of approaching storms well in advance, and automated measuring systems such as ARGO gliders, moorings below the ice, weather stations, and sea-ice buoys transmit data directly to research institutions via radio from many scientifically fascinating regions.

Despite all of the technological advancements, however, the ice cover, extreme climate, and geographical remoteness of many polar regions still represent significant obstacles to scientific work, so that polar research is only possible through international cooperation.

Conclusion

The Arctic and Antarctic – two fundamentally different polar regions

The north and south polar regions are among the most remote and extreme environments for life on Earth. In both regions freezing temperatures, ice, snow and the darkness of the long polar nights make it difficult for plants, animals and humans to survive. Yet the two regions are also fundamentally different from one another. In the south, Antarctica is a vast continent surrounded completely by the Southern Ocean. In the north, the exact opposite applies to the Arctic. Here, the land masses of three continents effectively surround an ocean located in the centre. The only ice sheet in the Arctic covers a large portion of Greenland. But this is still significantly smaller than the Antarctic Ice Sheet, which covers 98 per cent of the continent. On the other hand, the Arctic Ocean possesses a permanent sea-ice cover. Its surface area grows and shrinks in response to the rhythm of the seasons, never diminishing as much as the sea-ice surface in the Southern Ocean, which melts almost completely in summer.

In the geological history of Earth, extensive ice cover over both polar regions at the same time is an exceptional situation. There have only been a few times in the past when the drifting continents have been arranged such that climatic conditions in both the northern and southern hemispheres favoured the icing of the poles. While the climate history of Antarctica is now quite well understood, many open questions remain about the history of ice formation in the Arctic land and marine regions.

The geographical differences between the two polar regions account for their different human settlement histories. Most land areas of the Arctic have been accessible to humans on foot. Coming out of North Africa, they settled in Siberia about 45,000 years ago, and later trekked from there over a land bridge into North America. However, people were only able to settle in Greenland and the northernmost reaches of Europe after the ice sheets of the most recent glacial period had melted. Until then, massive ice had blocked the northward routes in North America and Europe for the hunters and gatherers. Today around four million people live in the Arctic.

In order to reach the more remote Antarctic, it took seaworthy ships and brave seafarers who dared to sail far to the south. The southern continent thus was not discovered until the 19th century and was initially seen only as a seal and whale hunting ground. From the 20th century onward, adventurers and polar researchers explored the icy continent directly, yet in the public eye advances into unknown regions were often more interesting than scientifically relevant data and observations.

After the First World War, modern technology was increasingly applied in polar research. Both the Arctic and Antarctic regions began to be explored from the air. With the establishment of research stations, it became possible to carry out long-term surveys, which improved the ability to predict weather in the polar regions. Furthermore, the significance of the two regions for the Earth's climate was recognized. International scientific cooperation then laid the foundations for the Antarctic Treaty System, which entered into force in 1961 and to this day ensures the protection and peaceful, purely scientific use of the continent. There is no comparable contractual framework for the Arctic region. Despite divergent political interests, researchers from a variety of nations are working hand in hand in both polar regions. The extreme climate and isolated conditions in the two regions present humankind with special logistical and technical challenges that can often only be overcome by working together.

2 The polar regions as components of the global climate system

> The Arctic and Antarctic are the cooling chambers of our planet. Having a very limited supply of solar radiation, they attract warm air and ocean currents from the tropics, cool them down and send them back towards the equator as floating ice. In this way, the polar regions regulate the distribution of heat on the Earth. This mechanism will only continue to function smoothly, however, if the interactions between sea ice, glaciers, ocean and atmosphere do not change.

Why it is so cold in the polar regions

> The climate in the polar regions is the result of a self-reinforcing process. Because so little solar energy is received, the water freezes to ice, which then, like a mirror, reflects the small amount of radiation that does arrive. A multi-layered, complex wind system, which plays a decisive part in the weather and climate on our planet, is driven by differences in temperature and pressure between the warm and icy regions.

It doesn't get any colder

According to the World Meteorological Organization (WMO), the coldest place in the world is the Russian Antarctic research station Vostok. It was established in 1957 in the middle of the East Antarctic Ice Sheet, where it lies at an elevation of 3488 metres above sea level. From the station building it is about 1300 kilometres to the geographic South Pole. On 21 July 1983, at the standard measurement height of two metres above the ice, the station meteorologist measured a low temperature of minus 89.2 degrees Celsius – officially the coldest temperature ever directly measured on the Earth.

But at a height of just a few centimetres above the surface of the East Antarctic Ice Sheet the air temperature drops even further. According to satellite data obtained between 2004 and 2016, in a region of the ice sheet further to the south with a higher elevation, near-surface air temperatures can fall to minus 98 degrees Celsius.

2.1 > Elongated ridges of snow on the East Antarctic Ice Sheet. These are called sastrugi, and they are formed when the wind sweeps over the surface in places with somewhat harder snow, carrying loose snow crystals with it and carving aerodynamic elevations or furrows in the previously higher snow cover.

The thermal engine of the Earth's climate

The singular interplay between sun, ice, humidity and wind is the key to the extremely cold climate in the polar regions. The sun is the primary driving force of weather and climate on the planet. Its radiation warms the continents, the oceans and the atmosphere. The intensity with which the sun's rays impinge upon the outer boundary of the Earth's atmosphere has remained fairly constant since satellite measurements began in 2000. But because of the spherical shape of the Earth, not all locations on its surface receive the same amount of solar radiation. Where the rays intersect with the atmosphere at right angles, the light energy has a strength of 1361 watts per square metre (solar constant). Where the solar radiation strikes the Earth's atmosphere at a much lower angle, as in the polar regions, the incoming solar energy per unit of area is substantially reduced. Moreover, the radiation always falls only on the side of the Earth that is facing towards the sun. Accordingly, the global average solar energy arriving at the upper margin of the atmosphere can be calculated as approximately 340 watts per square metre. The much smaller amount of heat that reaches the polar regions can be illustrated by a simple example: If sunlight falls on the Antarctic continent at an angle of 30 degrees on a cloudless summer day, only half as much energy will arrive there as will fall on the surface near the equator at an angle of 90 degrees.

The major reason for the differences in heat input during the year is the fact that the Earth is spinning like a top in space, and its axis of rotation is not exactly perpen-

The levels of the atmosphere

The Earth is surrounded by a blanket of gas that extends from the surface of the planet to an altitude of about 500 kilometres, and which is held in place by the Earth's gravity. Its name "atmosphere" derives from the Greek words *atmós* and *sfaira* (vapour and sphere). The Earth's atmosphere consists mainly of the gases nitrogen (78.1 per cent), oxygen (20.9 per cent) and argon (0.93 per cent). However, trace gases, also known as greenhouse gases, such as water vapour, carbon dioxide, methane and ozone, with a combined proportion of well below one per cent, are of crucial importance for a climate on Earth that is capable of supporting life. These absorb a portion of the incoming solar radiation as well as a large part of the outgoing heat radiation from the Earth, thus contributing significantly to the warming of the atmosphere. Without the trace gases, the Earth would have an average temperature of around minus 18 degrees Celsius, and the blue planet would more closely resemble a snowball.

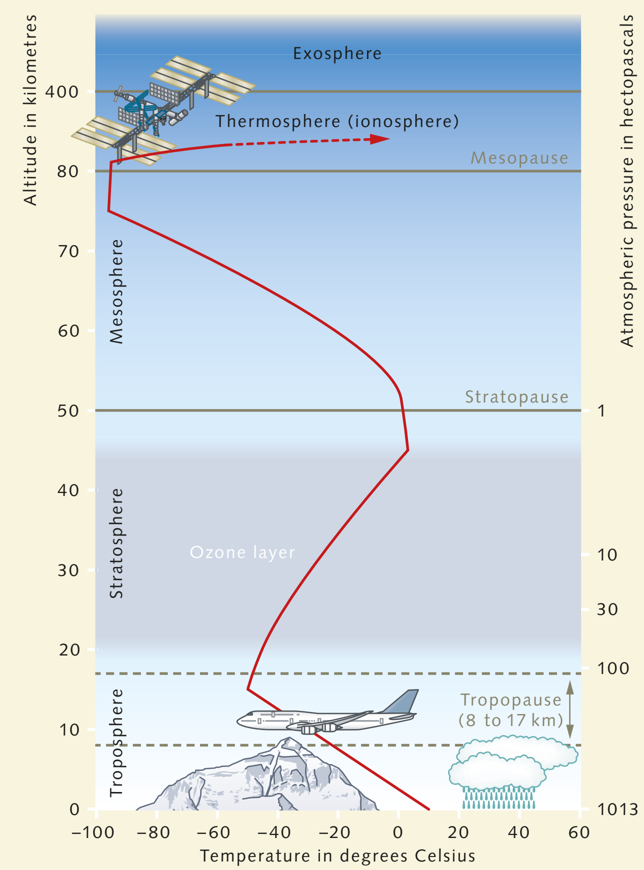
The Earth's atmosphere is composed of several layers, which can be distinguished by their physical and chemical properties. From the bottom upwards it is divided into the troposphere, stratosphere, mesosphere, thermosphere and exosphere.

However, only the two lower layers are important for the weather and climate on the Earth. Weather events occur here, especially in the troposphere, where the temperature decreases with increasing altitude by an average of about 6.5 degrees Celsius per 1000 metres. Above the equator, the troposphere extends to an altitude of about 17 kilometres. In the polar regions, by contrast, it is only half as high, namely eight kilometres.

Above the troposphere lies the stratosphere, which reaches an altitude of around 50 kilometres. In this layer, the temperature gradually increases upwards again because of the heat that is generated when the ultraviolet radiation in sunlight is absorbed in the ozone layer, located 20 to 45 kilometres above the mid-latitudes. Although the stratosphere, unlike the troposphere, contains almost no water vapour, stratospheric clouds with a pearlescent lustre can form under extremely cold conditions, especially in the polar regions.

Overlying the stratosphere is the coldest layer of the Earth's atmosphere – the mesosphere. It extends to an altitude of around 85 kilometres. With increasing altitude, the temperature and air pressure drop significantly, so that the average temperature at the upper margin of the layer is minus 90 degrees Celsius.

In the subsequent layer, the thermosphere, the density of the air is so low that the distance between individual gas molecules can be as much as several thousand metres, so that collisions and the associated exchange of energy seldom take place. The orbit of the International Space Station (ISS) is located in the thermosphere at an altitude of around 400 kilometres. At an altitude of 500 kilometres, the thermosphere transitions into interplanetary space. This transitional zone is called the exosphere. Within this realm the US American satellite SORCE orbits at an altitude of about 640 kilometres. Since 2003 it has been measuring the amount of solar radiation arriving at the outer edge of the atmosphere.



2.2 > The Earth's atmosphere is divided into several layers, of which only the lower two are important for weather processes. Clouds and precipitation form in the troposphere. In the stratosphere ozone absorbs incoming ultraviolet light as well as heat energy radiated from the Earth.

2.3 > Ice and snow surfaces in the polar regions reflect up to 90 per cent of the incoming solar radiation back into space, which results in a cooling of the Earth.

Weather and climate
For meteorologists, "weather" means the current conditions within the lower atmosphere (troposphere) as well as short-term changes at a particular time and place. They use measurements of the temperature, precipitation, wind direction and other parameters to describe these conditions. The term "climate", on the other hand, refers to the statistics of weather. It uses statistical mean and extreme values to describe the weather patterns at some location over a period of 30 years.

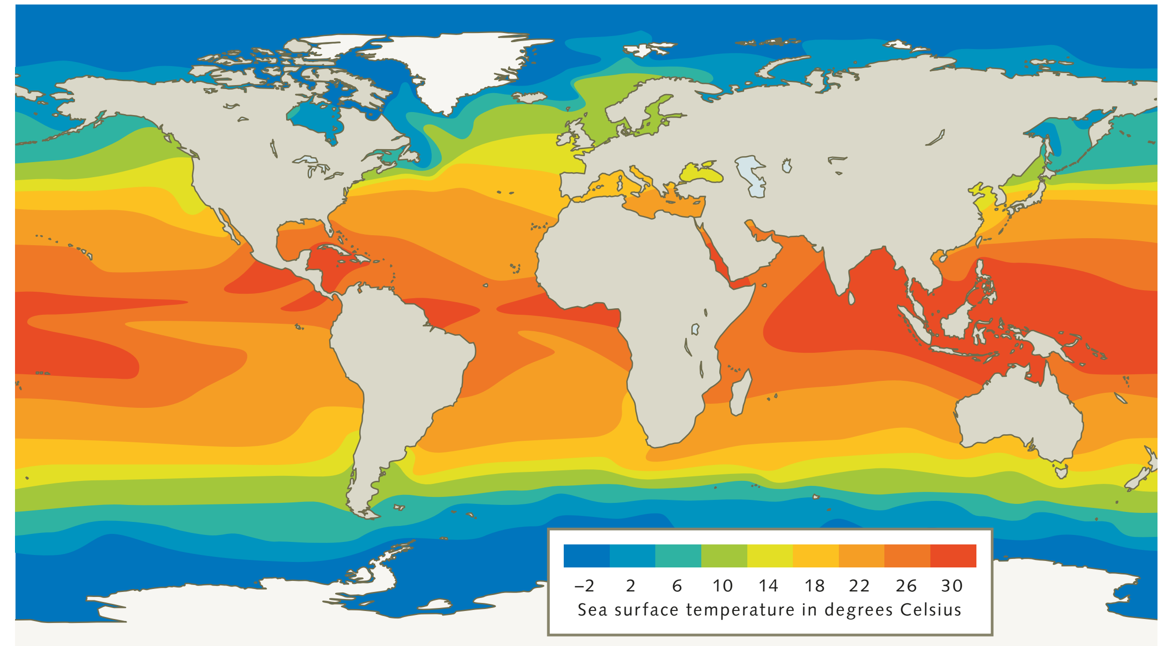
dicular to its plane of orbit around the Sun. Instead, it is presently tilted at an angle of 23.4 degrees. If the Earth's axis were at right angles to its orbit there would be no seasons. Due to its inclination, however, the northern hemisphere faces toward the sun during the northern summer and receives more sunlight, but in the northern winter it is tilted away from the sun and thus receives less radiation. In the southern hemisphere the exact opposite is the case.

The seasons are more pronounced the further one moves away from the equator, but these are not the only phenomena that can be attributed to the planet's inclination. It is also the reason why the sun does not set at all in the polar regions at certain times of the year (polar day) and why it remains hidden below the horizon (polar night) at others. At the geographic North and South Poles, the polar night lasts for almost a half year. If one moves from the Pole towards the Polar Circle, the length of time during which the sun does not rise above the horizon decreases steadily until it is only 24 hours precisely at the Polar Circle.

During its polar night, each polar region is therefore completely cut off from the solar source of heat energy. But even during the polar day, the period of continuous sunlight, only a relatively small amount of solar energy reaches the Arctic or Antarctic regions due to the low angle of incoming rays. These two phenomena thus form the basis for sustained cold conditions in the northern and southern polar regions. There are, however, two other important factors: albedo and water vapour.

White reflects

One of these reinforcing or amplifying factors is the reflective capacity of the Earth's surface, called the albedo effect. It determines how much of the incident solar radiation is reflected by the Earth's surface. As a basic rule of thumb, the darker or rougher a surface is, the less radiation it reflects. A freshly ploughed field may reflect about ten per cent of the sun's energy; green meadows and pastures can account for about 25 per cent. Light-coloured surfaces such as desert sands have an albedo of about 40 per cent, but still do not begin to approach the reflection values of snow and ice. Freshly fallen snow, for example, will reflect up to 90 per cent of the incident solar energy. Depending on its age and surface structure, sea ice



2.4 > Ocean surface temperatures reflect the strong contrast between the warm equatorial regions and cold polar regions. Where the sea and air are warm, greater amounts of water evaporate, and clouds are formed. In colder areas, however, evaporation rates are low.

can have an albedo of 50 to 70 per cent. This rather large range is partially due to the deposition of dust and soot particles on the ice surface over time, which change its colour, particularly in the Arctic. Ice floes from which the wind has blown away the snow layer also have a different surface texture than floes with a hardened snow surface. Snow-free glacier ice, for example, reflects up to 60 per cent of the radiant energy, but with a fresh snow cover the albedo is greater.

Thus, the general situation for the Arctic and Antarctic is as follows: In both regions a relatively small amount of solar energy reaches the Earth's surface for long periods of time because of the spherical shape of the Earth and the tilt of its axis. A large proportion of the energy that does arrive impinges on white ice or snow surfaces and is mostly reflected away. As a result, it is not stored as thermal energy in the ground or ocean, and therefore does not contribute to the warming of the air layers near the land surface or sea. In this way, the high reflectivity of the snow and ice surfaces reinforces cooling in the polar regions. This means that more sea ice is formed in response to the increasing cold, which in turn increases the total albedo levels. This then results in even more solar radiation being reflected. Climate researchers refer to such self-amplifying processes as positive feedback.

Water vapour – invisible regulator of heat

A third factor relating to the origin of cold climate at the poles is water vapour. Water is an extremely versatile element of our climate system. It can evaporate, condense and freeze, and it occurs in nature in three physical states: as a liquid (water), frozen (ice), and as a gas (water vapour).

This odourless and invisible gas is formed when liquid water evaporates. The Earth's atmosphere contains around 13 trillion cubic metres of water. This amount represents about 0.001 per cent of the accessible water on the Earth, whereby the largest proportion of water in the atmosphere is in the gaseous state. If all of the water vapour in the atmosphere were to condense and fall to the surface as rain, it would cover the entire globe with a layer of water about 25 millimetres thick. Still, the proportion of water vapour in the air by mass is on average only 0.25 per cent.

The Earth's heat and radiation balance

The Earth obtains its energy almost exclusively from the sun. With a surface temperature of around 5500 degrees Celsius, it emits a hundred thousand times more energy than the Earth, whose average temperature is around 15 degrees Celsius. The sun's energy impinges on the Earth's atmosphere as extra-terrestrial radiation. This radiation transmits energy in the form of electromagnetic waves. To understand the radiation balance of the Earth, one has to be aware of three physical laws: For one, every body, whether solid, liquid or gaseous, emits electromagnetic radiation as a function of its surface temperature. This is true for the glowing star that is our sun as well as for the Earth. Our home planet has a temperature of 288 degrees Kelvin (14.58 degrees Celsius), and thus also radiates independently without the help of the sun.

Secondly, the wavelengths of radiation emitted depend upon the temperature of the body. The hotter it is, the shorter the waves of the radiation released. The filament in an incandescent bulb, for example, becomes so hot that it glows and emits white light, i.e. visible radiation. When the light is turned off, the filament cools down and continues to glow slightly reddish for a moment. This indicates that its radiation maximum has shifted from the short-wave to the long-wave scale. But it would still be unwise to touch the bulb at this time, because even when the metal filament stops glowing and is no longer giving off visible radiation, it continues to emit invisible heat radiation in the infrared range. It is still hot enough to burn one's fingers. As a relatively cool body, our Earth emits only long-wave heat radiation in the infrared range.

Thirdly, the radiation emitted by one body can be reflected or absorbed by other bodies. This is also the case for the Earth-sun system. The global average solar radiation arriving at the outer edge of the Earth's atmosphere is 340 watts per square metre. About seven per cent of the incoming radiation is UV radiation, 46 per cent is in the range of visible light, and the remaining 47 per cent is in the infrared spectrum.

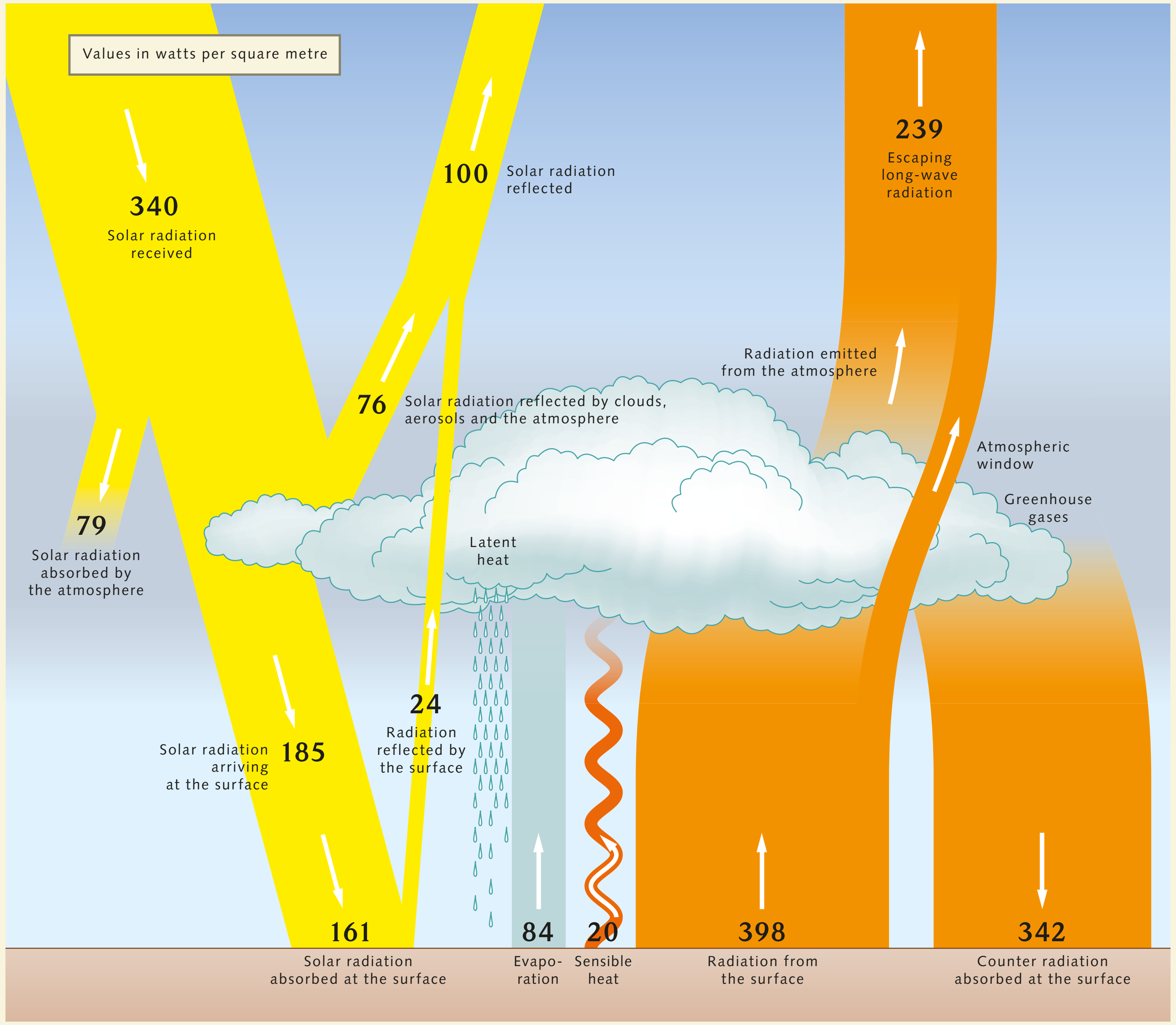
About 30 per cent of the 340 watts per square metre of incoming radiation is reflected directly back into space by the atmosphere and the Earth's surface. This amount, around 100 watts per square metre, is called the planetary albedo. Only 240 watts per square metre remain in the climate system and are available to warm the planet. About one-third of this amount (79 watts per square metre) is absorbed by the clouds, water vapour, dust particles and ozone in the atmosphere. This portion thus warms the atmosphere above us. The gases, in particular, filter within very specific wave ranges. Ozone, for example, absorbs almost all of the incoming ultraviolet radiation and is therefore a very effective UV filter.

It is important at this point to note that the air molecules, water droplets, dust particles and ice crystals present in the atmosphere reflect the incoming radiation in all directions. The portions deflected upwards go back into space, the rays deflected downwards reach the Earth as diffuse sky radiation. Two forms of radiation therefore arrive at the Earth's surface: the direct solar radiation, which only reaches the surface through a cloudless sky, and the diffuse sky radiation.

Almost 60 per cent of the incident solar radiation (185 watts per square metre) actually reaches the Earth's surface. Of this around 13 per cent (24 watts per square metre) is reflected directly back into space. This is a portion of the planetary albedo. The remaining 161 watts per square metre are absorbed by the Earth's surface and provide it with warmth.

The Earth's surface releases its heat in three ways: firstly, in the form of evaporation – called latent heat (84 watts per square metre), secondly through the rising of warm air masses – called sensible heat (20 watts per square metre), and thirdly by radiating long-wave heat rays (398 watts per square metre). However, only a very small amount of the heat radiation is actually lost directly into space. On its way through the atmosphere it collides with the same obstacles that previously hindered the incoming short-wave solar radiation. This time, however, it is primarily the molecules of the trace or greenhouse gases that absorb the long-wave radiation and ultimately emit it again in all directions as heat radiation. They thus trap part of the heat in the lower atmosphere and generate what is called counter radiation (342 watts per square metre). For this reason, the Earth receives a large portion of its emitted radiation back again.

This process is often referred to as the greenhouse effect. But at the same time, the atmosphere does radiate some heat back into space. Comparing the incident solar radiation with the total long-wave radiation emitted at the outer edge of the atmosphere clearly shows that the Earth absorbs slightly more energy than it releases. This fact is of crucial importance, as will be explained later.



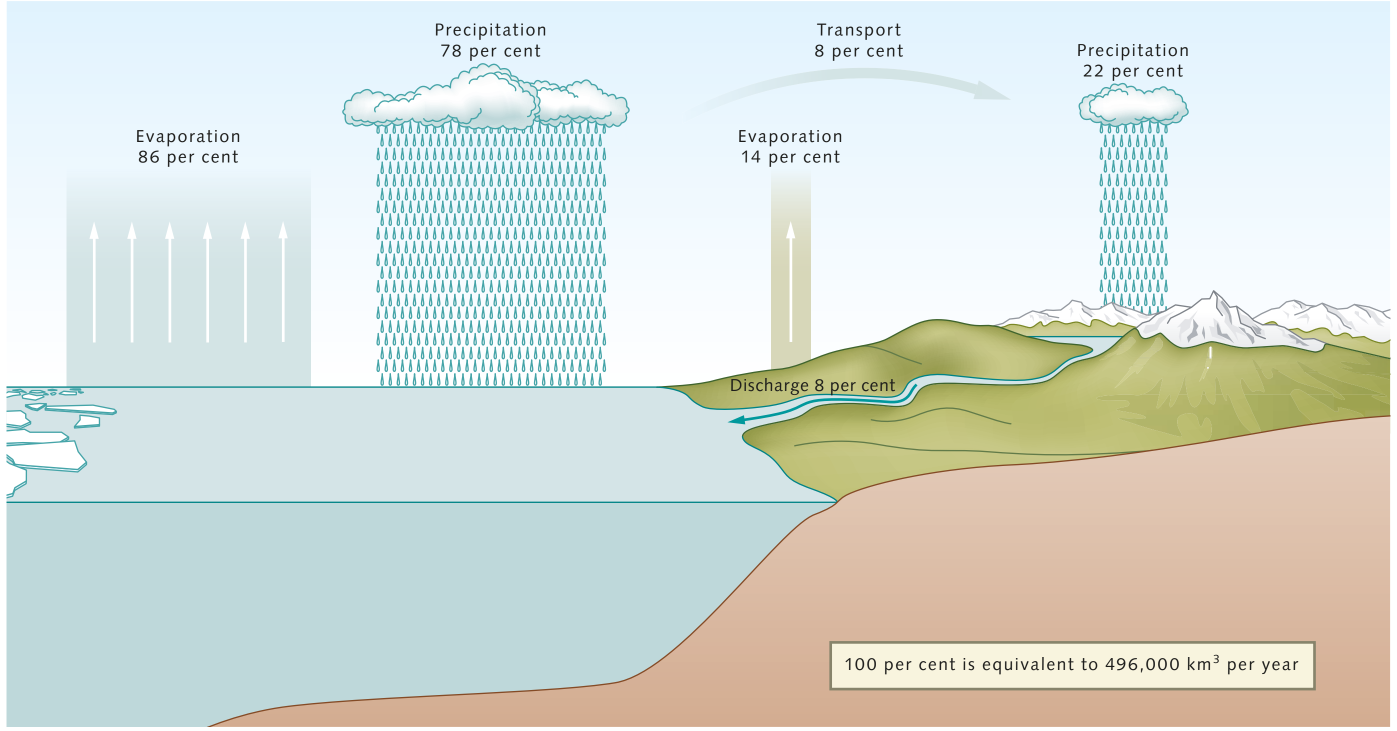
However, this average value is misleading because water vapour is distributed very unevenly throughout the atmosphere. Its concentration decreases rapidly with increasing elevation, due in part to the fact that warm air can hold more water vapour than cold air. Accordingly, large amounts of water can be converted into water vapour in warm regions and less in colder regions. In the polar regions, because of the low temperatures, evaporation and water-vapour content in the atmosphere are very low in winter. The water-vapour capacity of the atmosphere increases with every degree Celsius of air temperature. As an example, one cubic metre of air at a temperature of minus 20 degrees Celsius can hold at most 1.1 grams of water vapour. However, if this volume is heated to plus 20 degrees Celsius, it can contain a maximum of 17.2 grams of water vapour.

The amount of water vapour present in the atmosphere at a given time is commonly referred to as "humidity". When meteorologists report a condition of high humidity, this means that the air contains a large amount of water vapour. The most common measure used is relative humidity in per cent. Because a given volume of air at a given temperature and pressure can only hold a certain maximum amount of water vapour, we refer to a relative humidity of 100 per cent when this maximum amount is reached.

As a general rule, when water evaporates over the sea or on land, no more than ten days will pass before the water vapour leaves the atmosphere again in the form of precipitation. In contrast to carbon dioxide, which may be retained for several centuries, water vapour leaves the atmosphere rather quickly and it is thus referred to as short-lived. Nevertheless, water vapour is regarded as the most important natural greenhouse gas. Firstly, this is because it occurs in higher concentrations in the atmosphere than carbon dioxide, methane or nitrous oxide (laughing gas). Secondly, it contributes two to three times more to the natural greenhouse effect than does carbon dioxide.

The Earth's climate, and particularly the climate of the polar regions, is strongly influenced by the presence or absence of water vapour. The atmosphere has to contain

2.5 > Over the oceans large amounts of water are constantly evaporating, especially in the warmer ocean regions. The moisture does not remain in the atmosphere for long, however. Within ten days it falls to the Earth again as precipitation.



water vapour before fog or clouds can form. However, the water vapour only **condenses** when the air is supersaturated with the gas, i.e. when it contains more water vapour than it can physically retain. This supersaturation occurs when warm humid air masses rise and are cooled, and thus lose their capacity to absorb more water vapour. The gas condenses into small droplets or, in certain circumstances, into small ice particles that waft freely in the air and commonly become visible from the ground as clouds or fog.

There are two ways in which clouds are important for the global climate. The billions of water droplets they contain refract sunlight from above, preventing these rays from striking the Earth's surface directly. Instead, they are deflected in many different directions. A certain portion even escapes back into space. Ultimately, therefore, less solar radiation reaches the ground than it would if there were no cloud cover. As a consequence, the cloud cover effectively cools the Earth. On the other hand, however, clouds also block the long-wave heat radiation rising from the Earth. They absorb a large portion of this heat radiation and release the heat again in all different directions. In this way clouds can also contribute to warming in the atmosphere. Which of the two features is dominant depends upon the type of cloud. Clouds are most commonly differentiated based on their altitude and form. Visibly thick, low-hanging clouds primarily reflect the incoming sunlight and cool the Earth. High thin clouds, on the other hand, let the solar radiation through. They subsequently block the outgoing heat radiation from the Earth and absorb a large portion of the thermal energy. The day-night effect also plays a role. Obviously, a cloudless sky usually means warmer temperatures during the day because the sun's rays are unobstructed. But it becomes cooler at night with no clouds because the Earth's absorbed heat energy can be radiated outward again unhindered.

Freeze-dried air

The Arctic and Antarctic are fundamentally different with regard to the influence of clouds. While dense fog and cloud cover are phenomena often observed during the summer in the Arctic – much to the dismay of polar explorers who usually plan their expeditions for the summer – in Antarctica they normally only form in coastal areas. The air above central Antarctica is simply too cold due to the limited amount of solar radiation, and therefore contains too little water vapour for condensation to form a thick cloud cover. Instead, with increasing cold, all of the residual moisture condenses into ice crystals and falls to the ground as a form called diamond dust. The air is thus essentially freeze-dried, which is why Antarctica is considered to be the world's driest continent.

For comparison: In Germany around 700 litres of precipitation per square metre fall each year. The same amount is also recorded at the weather station on the Antarctic Peninsula. In the coastal area of the Weddell Sea, i.e. near the German Antarctic research station Neumayer III, there are only 300 litres of precipitation per square metre, which is equivalent to a layer of snow about one metre thick. In central Antarctica, on the other hand, annual precipitation rates are less than 50 litres per square metre over vast areas because of the extremely dry air. Only under exceptional conditions have meteorologists reported a thin veil of clouds over the Antarctic Ice Sheet. However, these are not substantial enough to prevent the ice surface from radiating the small amount of incident heat back into space, which leads to further cooling of the air above Antarctica.

In the Arctic, on the other hand, water vapour, clouds and fog can promote warming, especially in summer. One reason for this is the shrinking of the sea-ice cover in the Arctic Ocean during the summer. The white ice floes, drifting in the winter and spring and reflecting a large portion of the sun's radiation, are partially replaced in summer by the much darker sea surface. This absorbs up to 90 per cent of the sun's energy, which causes a rise in the sea-surface temperature. Because this is accompanied by a corresponding warming of the air, the atmosphere can absorb more moisture. The humidity increases, so that only small soot, dust or salt particles in the air are required for the water vapour to condense and form clouds or fog.

In addition to the fact that clouds can be formed from it, water vapour possesses another property that is significant for the heat balance and weather patterns: It stores heat energy. This heat cannot be detected by a thermometer or felt by humans. Meteorologists therefore refer to it as latent heat. It is sometimes referred to as evaporation heat because its value corresponds precisely to the energy originally required to evaporate the water. What is special about the heat storage of water vapour, however, is that as soon as the vapour condenses into water droplets in the atmosphere, the stored heat from evaporation is released again as condensation energy and warms the surrounding air. In regions with high atmospheric water-vapour content, this effect causes additional warming. In areas with low humidity or little water vapour in the atmosphere, this effect is much less significant.

In some small depressions on the southern slope of the East Antarctic Ice Sheet, the paucity of water vapour is one of the reasons that it can get even colder than it does at the Vostok Research Station. In July and August, the air layer directly above the ice sheet becomes so cold that, according to scientific reckoning, it cannot become any colder. Minus 98 degrees Celsius seems to be the coldest temperature possible on the Earth under natural conditions.

For the air in the depressions to become this cold, a number of conditions must be met. Incoming solar radiation has to be absent for several weeks, which can only occur during the polar nights. Furthermore, the air above the snow-covered ice sheet may not contain any water vapour that could give off heat in the case of condensation, or could absorb radiation energy reflected from the snow and then be held in the atmosphere. According to researchers, the air in the region contains so little water vapour in winter that, considered as a water column, its height would be just 0.04 to 0.2 millimetres. Ideally, the water-vapour content has to be less than 0.1 millimetres. Additionally, the wind must be extremely weak and the sky free of clouds for several days.

Under these conditions, the layer of air directly above the snow cools down stepwise. It becomes denser and heavier, slowly flows downslope, and collects in the depressions where researchers have been able to detect it from satellites.

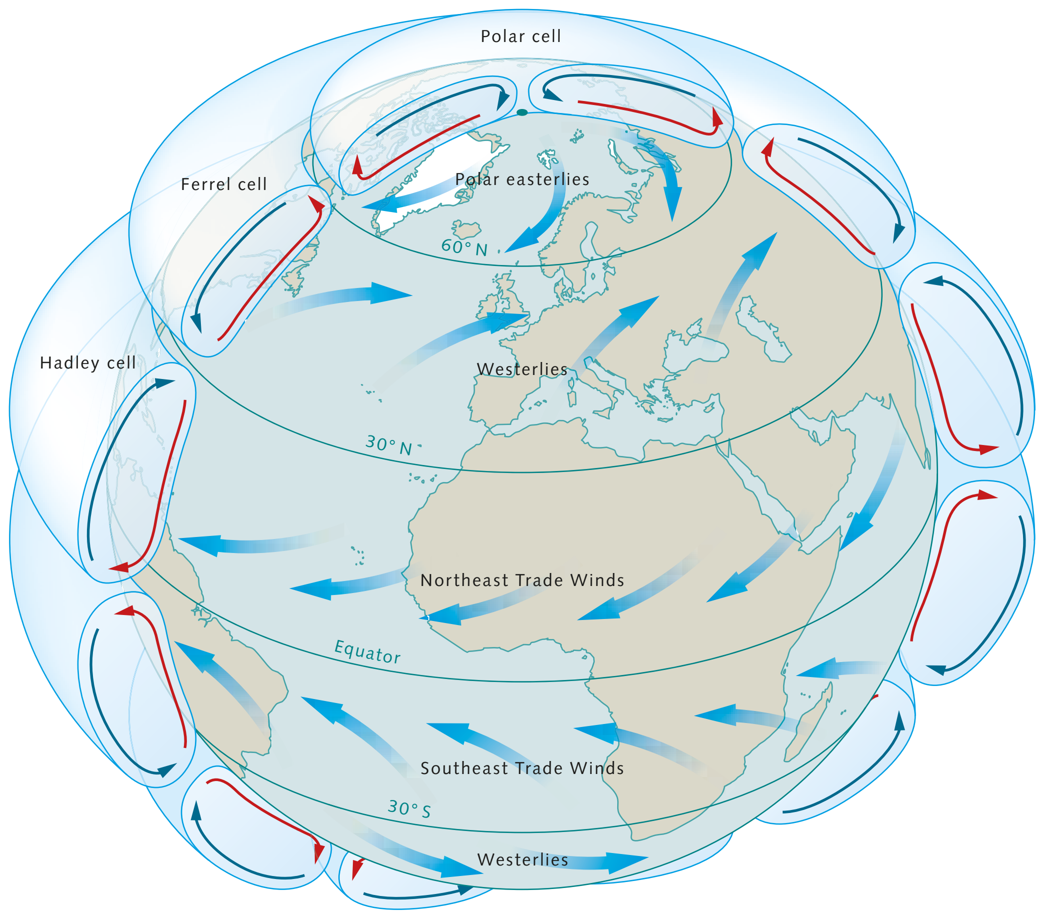
Winds – the driving forces of weather

Looking at the polar regions through the eyes of a physicist, the Arctic and Antarctic are regions where the lack of solar radiation and the high proportion of heat reflection due to the albedo effect result in temperatures that are lower by far than in other regions of the world. Temperature differences are accompanied by density differences; cold air masses are denser and thus heavier than warmer ones. Cold air sinks and warm air rises. These density-differences and resulting air motions are generated by differences in the atmospheric pressure at different locations. Where air cools down and sinks, a high-pressure area develops near the ground, a phenomenon known in both the central Arctic and the Antarctic as a polar or cold high. In low-pressure areas like the tropics, by contrast, warm air rises.

These atmospheric temperature and pressure differences between the warm tropical and the cold polar regions are the true "weather generators" of the Earth. They drive the large wind and current systems of the Earth and thereby also global air circulation. All of the processes in the atmosphere are geared toward equalizing these temperature differences and pressure contrasts. This means that the warm air masses from the tropics migrate poleward at high altitudes, while the cold air masses from the polar regions flow towards the equator closer to the ground.

If the Earth were not rotating on its axis, the paths of the different air masses on a map might be seen as straight lines both near the ground and at higher altitudes. But because the Earth is turning, every air current travelling from a high-pressure to low-pressure area is diverted to the right in the northern hemisphere and to the left in the southern hemisphere. This effect is caused by the Coriolis force – an apparent force arising from the rotation of the Earth. It affects both air and ocean currents, increases with latitude, and is the reason why, for example, the trade winds in the northern hemisphere do not travel in a straight line directly southward towards the equator from the high-pressure area at 30 degrees North. Instead, they are deflected to the right with respect to their flow direc-

2.6 > In late Antarctic spring, the sun rises above the horizon again and marks the end of polar night in Antarctica. In most of the coastal regions of the southern continent this lasts about two months. The nearer one moves to the South Pole, however, the longer the period of darkness lasts.



2.7 > Atmospheric circulation of the air masses surrounding the globe is so complex that researchers sometimes use this highly simplified model. It shows the six circulation cells and wind systems that are formed by deflected air-mass currents, and that are almost identical in the two hemispheres.

tion and therefore sweep across Africa and the Atlantic as northeast winds.

The Coriolis force is also the reason why air high above the equator moving towards the poles is more strongly deflected to the right with every metre that it travels. At about 30 degrees of latitude this deflection is so great that the air current flows parallel to the lines of latitude as high westerly winds, or the subtropical jet stream, and it can no longer perform its actual task of heat balance between the equator and the pole. Instead the air, which has become cooler by this time, descends and flows back toward the equator near the surface as trade winds. This is how the trade-wind circulation, also called Hadley circulation after the British hobby meteorologist George Hadley (1685–1768), is generated between the equator and 30 degrees latitude, both in the northern and southern hemispheres. In simple, idealized descriptions it is referred to as a closed cell.

A very similar circulation pattern, called the polar cell, forms above the northern and southern polar regions. Here, due to cooling, the cold heavy air in the centre descends (high-pressure area) and then flows near the surface toward the polar circle (low-pressure area). Again, the Coriolis force acts so that the air currents become polar easterly winds. On its way towards the Arctic Circle, however, the air warms up enough to rise and return to the pole at high altitude as a counter-current.

Located between the two homologous systems of the Hadley and polar cells, there is room for a third system, called the Ferrel cell, named after the American meteorologist William Ferrel (1817–1891). In this, the air masses circulate in the opposite direction. This means that the near-surface air here is transported towards the pole and is deflected to the right (in the northern hemisphere), so that the winds blow from the west. This zone is therefore referred to as the prevailing westerlies. Unlike the polar cell or the Hadley cell, however, turbulence in the air masses of this zone produce low-pressure cells, which wander back and forth as waves and cause some degree of instability in the circulation. This instability is due to the large temperature contrast between the tropics and the polar regions, which cannot be balanced directly because of the strong Coriolis force. Instead, nature makes use of high- and low-pressure areas, which, like a paddle wheel, shovel warm air to the north and polar air to the south on the opposite side of the depression. For this reason, what meteorologists typically refer to as weather only occurs in the area of the Ferrel cell. In the other cells, the seasons rather than the weather tend to determine meteorological events.

In laboratory experiments scientists have tested how the atmospheric circulation would be different if the planet rotated faster on its axis. The results indicate that the increased Coriolis force would cause five cells to form on each hemisphere. If the Earth were to rotate much more slowly, there would be only one cell between the pole and equator, in which the air masses would then flow directly from the tropics to the poles and back. This kind of single-cell circulation is found, for example, on Venus.

The protective vortices

The wind and current patterns of atmospheric circulation are of great importance for the polar regions. So far, they have been very reliable in preventing warm air masses from reaching the centres of the Arctic or Antarctic regions. In order to understand how the winds protect the polar regions, we have to take a somewhat closer look at the atmosphere in the polar areas.

The air above the polar regions cools down drastically in the autumn and winter (polar night) and descends to the Earth's surface. Whereas a high-pressure area, the polar high, forms near the surface, higher up at an altitude of eight to ten kilometres an area of depression is created. This can extend to an altitude of up to 50 kilometres, and is known as the stratospheric polar vortex. The air masses of this vortex are surrounded and held together by a strong westerly wind called the polar night jet. This develops because the same principles of current flow apply in the stratosphere as in the underlying troposphere.

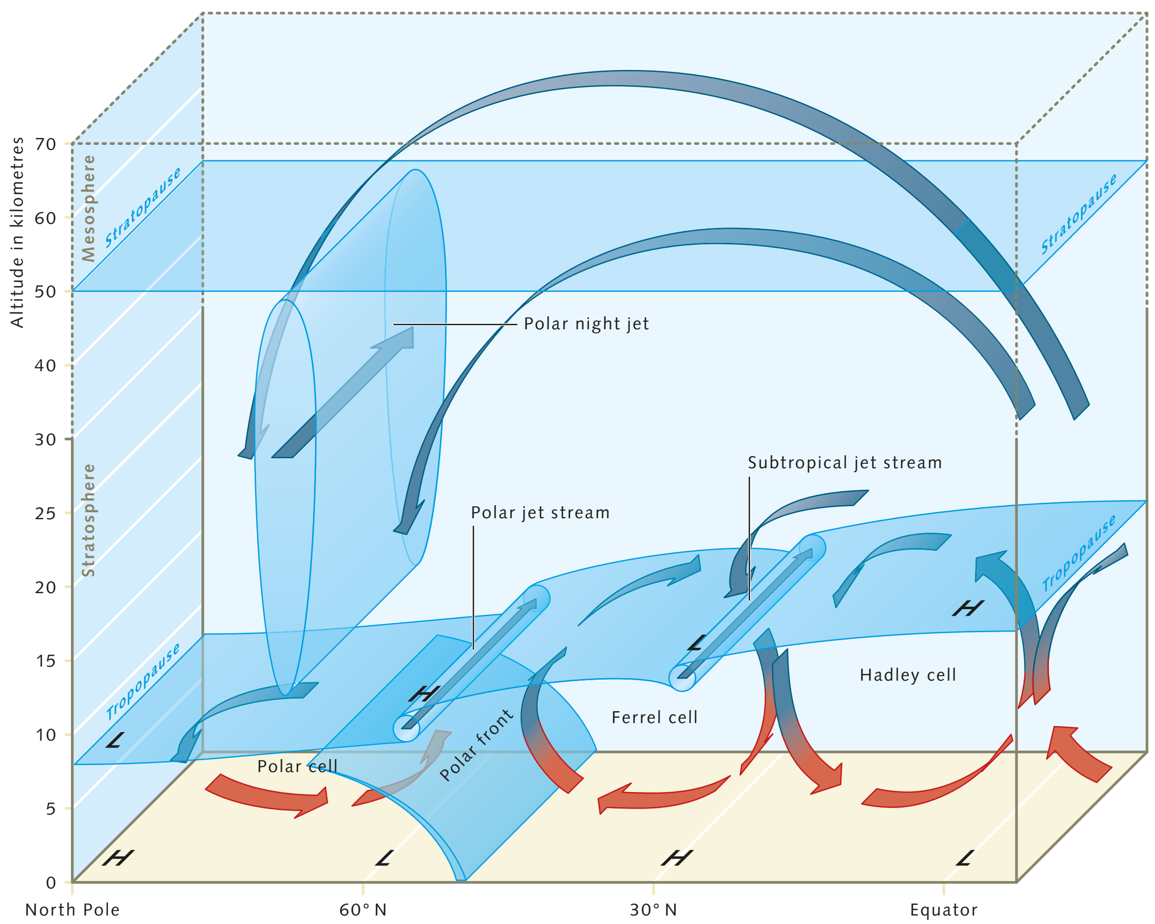
That is to say, air always flows from a high-pressure area, in this case the upper-level high-pressure area above the equator, to a low-pressure area, here the upper-level low-pressure area above the polar regions. However, the air current moving toward the pole is again deflected to the right because of the Earth's rotation, which for the northern hemisphere results in the creation of a westerly wind. The polar night jet is thus located at an altitude above ten kilometres and blows from the west towards the east completely encircling the North Pole. The wind attains its highest velocity at a latitude of about 60 degrees. Here it forms a kind of barrier that isolates the upper-level polar low-pressure area from the air masses coming from the equatorial region, thus preventing the high-altitude warm air masses from advancing further toward the pole.

During the course of the winter, the polar night jet gains strength because, with increased cooling in the stratosphere, more of the air masses in the low-pressure area continue to descend enabling more air to flow in, which boosts the wind strength. However, as soon as the first rays of the sun reach the polar region in spring, the air in the low-pressure area warms up. The differences in density and pressure equilibrate and the wind weakens again.

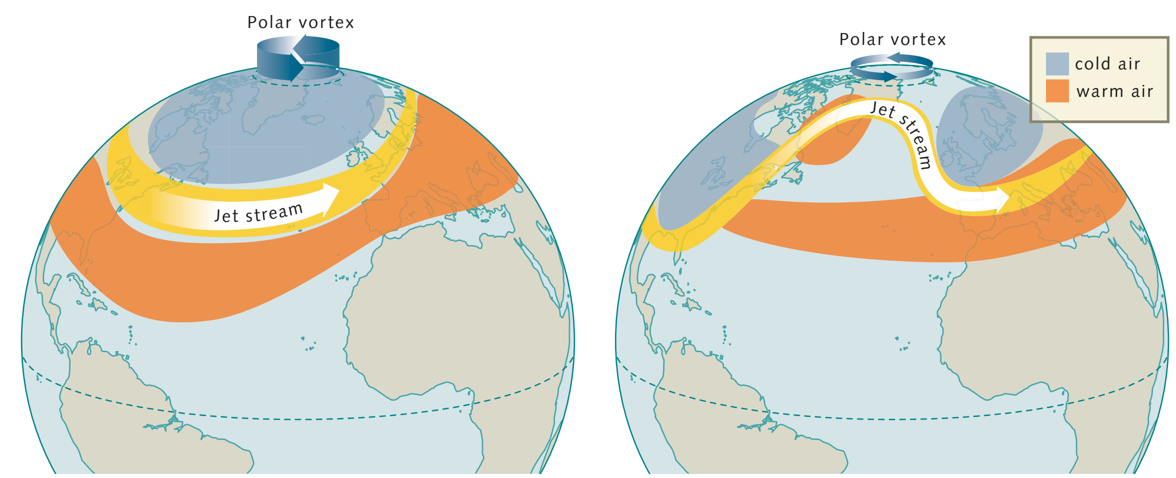
Comparing the stratospheric polar vortex in the Arctic with the one in the Antarctic, it is notable that the wind in the south maintains a more circular path and is significantly stronger than in the high north. On a normal winter day, the winds of the Antarctic polar night jet can achieve velocities of up to 80 metres per second. This is equal to 288 kilometres per hour. By contrast, in the northern hemisphere they blow with an average velocity of only 180 kilometres per hour. In addition, the stratospheric polar vortex over the Antarctic is significantly larger and the temperatures in its interior are lower than those in the north.

The fact that the two stratospheric polar vortices are so different in character is partly due to Rossby waves, which are also referred to in the special literature as planetary waves. These are large masses of air in the troposphere that meander around the globe with the westerlies. This kind of air mass possesses a certain vorticity (spin strength) due to the Coriolis force, which is related to its own rotation. The rotational speed of the air mass depends on the geographical latitude along which it is moving, because the Coriolis force becomes stronger with increasing distance from the equator. Air masses forming at higher latitudes basically rotate faster than those at lower latitudes.

If such a rotating mass of air encounters a mountain or high plateau during its meandering, such as the Rocky Mountains in the USA, or the Urals in Russia, or the high ice sheet of Greenland, it is deflected upwards by the obstacle. When this happens the air mass rises and also forces the overlying air masses to higher altitudes. With this ascent, the vorticity of the air mass changes and it is deflected towards the equator. Here the distance to the Earth's axis is greater than on the original meander path of the air mass. The vorticity of the air mass no longer matches the latitude-dependent vorticity at its new location. As a result, the direction of movement of the air mass changes back toward the pole. It overshoots its original geographical latitude in the opposite direction, then turns back again due to the opposing effect. It thus establishes an oscillating pattern.



2.8 > The polar night jet is a band of wind in the stratosphere that feeds off air masses flowing at high altitudes from the equatorial region towards the high northern latitudes. The polar jet stream, on the other hand, meanders through the troposphere, one atmospheric level lower.



2.9 > The two faces of the polar jet stream: When the polar vortex rotates at full strength in the stratosphere, the winds in the troposphere blow parallel to the equator and effectively block warm air masses from advancing into the Arctic. But if the polar vortex is weaker, the course of the jet stream begins to meander. As a result, cold polar air penetrates southward over North America and Siberia and moist, mild air over the North Atlantic migrates into the Arctic region.

A mass of air that was originally located at 50 degrees north latitude may fluctuate back and forth within the troposphere between 40 and 60 degrees, its path defining a waving line that snakes around the entire globe. This is the Rossby wave, named after the US American meteorologist Carl-Gustaf Arvid Rossby (1898–1957).

Because the Rossby wave also spreads upwards, under certain conditions its effect may extend into the stratosphere and disrupt the polar vortex to such an extent that it is weakened or even collapses completely. If this natural barrier is eliminated, warm air from the mid-latitudes can flow in and lead to a rapid warming of the stratospheric polar region. In the Arctic, scientists observe such a surge and the associated sudden rise of temperature in the stratosphere about every two years. The presence of mountains as well as the stark temperature differences between land and sea surfaces in the northern hemisphere are conducive to the formation of strong planetary waves.

So far, however, researchers have not been able to predict which waves can be destructive to the stratospheric polar vortex or when a surge can be expected. In the southern hemisphere, in contrast, there are no extremely high mountains except for the Andes. Moreover, large portions of the southern hemisphere are covered by seas, which impede the formation of planetary waves. Since observations began there has only been one case of an abrupt warming of the Antarctic winter stratosphere. That was in September 2002.

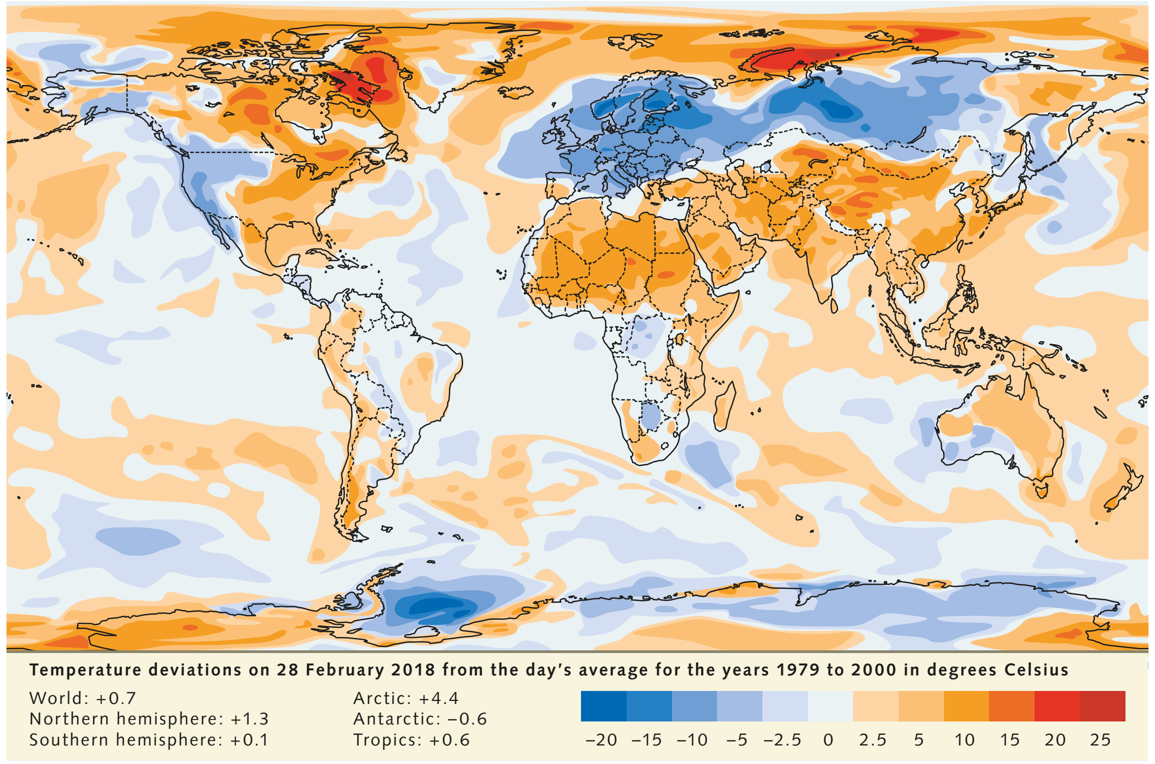
A wall of wind

Besides the stratospheric polar vortex and its associated polar night jet, the polar regions possess another atmospheric protective shield called the tropospheric polar vortex. This also has an accompanying strong wind that is variously referred to as the polar front jet stream, polar jet, or simply the jet stream. Depending on the prevailing weather conditions, this belt of wind lies about eight kilometres above sea level between the 40th and 60th degrees of latitude, i.e. above the zone of westerly winds. In the northern hemisphere the wind speeds here can range from 200 to 500 kilometres per hour and they are sustained throughout the year.

As long as the northern jet stream blows around the Arctic at full strength parallel to the equator, it prevents warm, moist air masses from the south from moving into the northern polar region, just as the polar night jet does in the stratosphere. At the same time, it blocks cold Arctic air from advancing into the mid-latitudes. The jet stream is constantly affected by the Rossby waves. These ultimately contribute to our weekly changing weather conditions, as they are sometimes stronger, sometimes weaker and change their position. The high- and low-pressure areas that define our weather form in the peaks or valleys of the waves.

In winter, the strength and durability of the jet stream in the troposphere depend in part on the stability of the

2.10 > Exceptional atmospheric situation: At the end of February 2018 there was an unusual heat wave in the Arctic. The polar vortex split, causing the jet stream to lose strength, and allowing the penetration of warm air far into the Arctic. In the Labrador Sea and in the Siberian area of the Arctic Ocean the air temperatures rose to as high as 15 degrees Celsius above normal. At the same time, Central Europe was experiencing spells of extreme cold.



polar vortex in the overlying stratosphere. Rossby waves, which can destroy the stratospheric polar vortex and cause an abrupt warming of the polar stratosphere, also change the jet stream in the troposphere. The wind in the troposphere weakens and assumes a meandering course over the northern hemisphere. The result is that over North America and northern Europe the tropospheric vortex expands to the south, and cold polar air can penetrate deeper into North America and Central Europe. Over East Greenland it retreats back to the far north, allowing damp, warm air to migrate into the Arctic region.

In February 2018, for example, the northern hemisphere experienced this kind of exceptional atmospheric situation. At that time, Rossby waves were able to split the polar vortex, which caused a rapid warming of the stratosphere above the Arctic region to temperatures as high as 50 degrees Celsius. This, in turn, caused a weakening of the polar front jet stream in the underlying troposphere, which had far-reaching impacts. While Central Europe suffered from extreme cold in February, with snowfall even in Rome, mild spring temperatures were predominant in the Arctic in spite of the polar night. In Siberia the temperatures at times reached values up to 35 degrees Celsius above the normal average for February. The weather station at Cape Morris Jesup, the northernmost point of Greenland, recorded ten winter days in a row in which the temperature did not drop below the freezing point. And off the west coast of Alaska, one-third of the sea ice that is normally present at this time of year melted within a period of eight days.

Home of the blizzards

Antarctica is not only the coldest continent in the world, it also tops the list of windiest regions. At the French research station Dumont d'Urville, for example, scientists recorded a peak wind speed of 327 kilometres per hour in July 1972. This is more than double the strength of hurricane winds. A hurricane is defined as winds with average speeds of 120 kilometres per hour or more.

2.11 > The French research station Dumont d'Urville on Pétrel Island in Adélie Land is one of the windiest places in Antarctica. Particularly in winter, air masses that have cooled over the East Antarctic Ice Sheet gush down onto the sea as descending (katabatic) winds.

The documentation of such high wind speeds in the coastal region of Antarctica is not a coincidence. Apart from the global wind systems, the icy continent produces its own local wind system, which forces researchers to remain confined inside their stations, especially in winter, and which is largely responsible for the formation of sea ice in the Southern Ocean.

Winds normally develop when air masses flow from a high-pressure area into a low-pressure area to compensate for the difference in pressure. However, an air mass can also begin to move due to its own weight – for example, when it becomes colder and heavier than the surrounding air masses and sinks as a result. The near-surface air layer above the Antarctic Ice Sheet is particularly dense and heavy due to its altitude, low solar radiation input and high radiational cooling from the ice. The cooled air masses form a heavy 300-metre-thick layer above the central ice sheet. Because the ice sheet does not have a flat surface, but falls away at the edges, this extremely cold and heavy air from Central Antarctica at some point begins to slide down the slopes toward the coasts. It gains velocity exclusively through its own weight and the steepness of the slope.

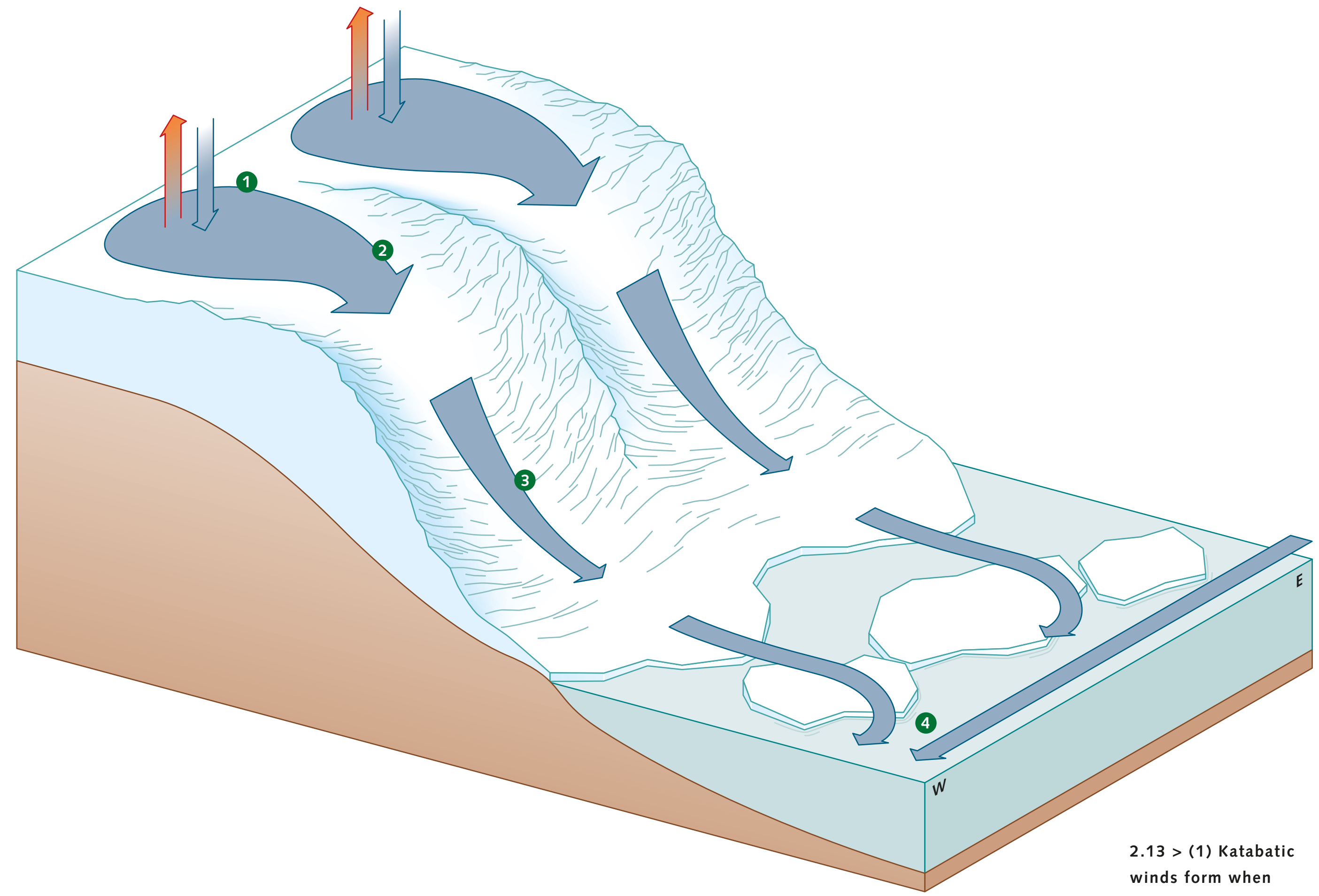
However, the cold rushing air really begins to gain speed when its path toward the coast is partially blocked by mountains. When this happens the total air mass has to squeeze through narrow valleys, which accelerates the air current enormously. In extreme cases, when these winds, called katabatic winds, reach the coast they can attain storm or even hurricane strengths. This technical term derives from the Greek prefix *kata*, which means "descending" or "downwards".

Polar researchers report that katabatic winds can arise unexpectedly from nowhere. At one moment the working conditions on a glacier or ice shelf can be totally windless and five minutes later, with no warning, a hurricane can sweep across the ice and lead to a condition known as whiteout.

Just as abruptly, however, the wind can again subside – depending on the area of the ice surface above

Whiteout
Polar scientists refer to "whiteout" as the condition where fog, clouds or a snowstorm restrict visibility to such an extent that neither contours nor the horizon can be recognized in any direction.

2.12 > A Piteraq blows through the Greenland settlement of Tiniteqilaaq. Gusts of this katabatic wind can reach speeds of up to 300 kilometres per hour.



2.13 > (1) Katabatic winds form when near-surface air above an ice sheet cools and thus becomes denser and heavier. (2) The air mass then slides down the slope due to its own weight, (3) gains speed along its way through narrow valleys, and (4) pushes loose ice floes off the coast into the sea, where the air mass is deflected and slowed by coastal winds.

which the cold air formed. In extreme cases, however, this kind of wind can persist for several days with sustained high velocities.

These exceptional winds occur most notably in the coastal region of Adélie Land, the windiest part of Antarctica and location of the French research station Dumont d'Urville. This is due to the topography of the region. Here the cold air from a large area of Eastern Antarctica flows down the ice sheet, and newly formed cold air masses can flow down at any time, especially during the winter. In addition, mountains channel the air currents through narrow valleys, which amplifies their strength each time.

Katabatic winds, incidentally, also occur in regions outside Antarctica – for example, at the margins of the vast Greenland Ice Sheet, where the near-surface air layer above the high plateaus is cooled to a temperature between minus 20 and minus 40 degrees Celsius in winter. Greenland's strongest winds occur on the southeast coast, in the region near the town of Tasiilaq. Storm winds can gust at speeds up to 300 kilometres per hour, and because of the great danger they are called "piteraq" by the natives, which in their local language means „that which attacks you".

On 27 April 2013 a wind like this not only blew snow from large areas of the ice sheet. Blasting through the 85-kilometre-long Sermilik Fjord, the piteraq also pushed all of the sea ice and glacier ice floating in the fjord out into the sea, so that the fjord was virtually ice-free after the storm.

Ice floes, ice sheets and the sea

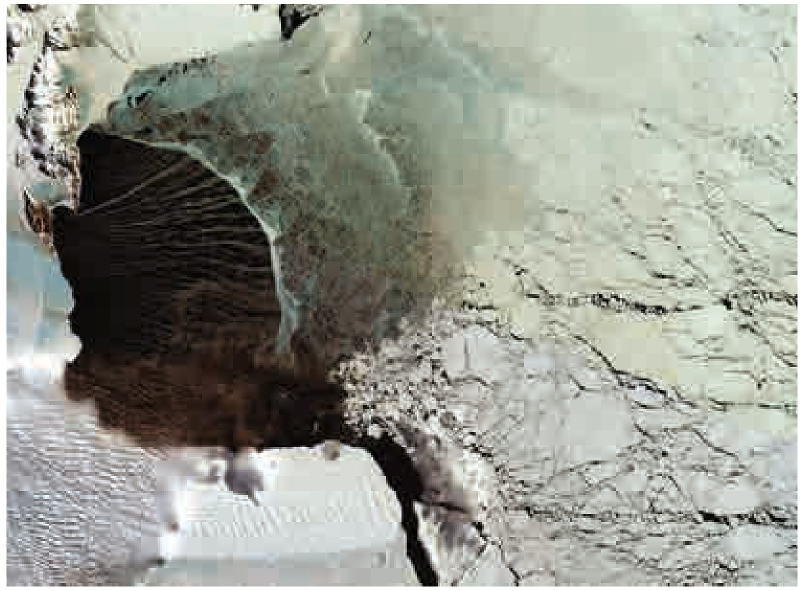
> There are large areas in the polar regions where water occurs predominantly in its frozen state. It either falls as snow to contribute to the growth of ice sheets and glaciers, or it drifts on the sea as ice floes. In both cases the fate of the ice depends largely on the ocean and its currents. The water masses can provide protection or accelerate melting, depending on the path that heat follows.

Sea-ice nurseries

When strong winds in the Arctic and Antarctic regions force icebergs and sea ice away from the coasts and out to sea, areas of open water remain where air and water are in direct contact with each other. These areas are called coastal polynyas, and they are the places where sea ice is created. Scientists sometimes refer to them as ice factories. Especially in winter, when the air temperature sinks far below zero degrees Celsius and offshore winds blow constantly, sea ice is produced in the Arctic and Antarctic polynyas in assembly-line fashion.

Sea-ice production follows the same routine everywhere. First, frigid winds cool down the areas of open water so intensely within a short time that the surface freezes over. Because seawater contains salt, its freezing point lies below zero degrees Celsius. In the Arctic and Antarctic, seawater has to be cooled to minus 1.9 degrees Celsius before the first ice crystals begin to form. For comparison, in the Baltic Sea, where the salinity is lower, the water begins to freeze at minus 0.5 degrees Celsius.

2.14 > Terra Nova Bay in the Antarctic Ross Sea is an example of a coastal polynya. Sea ice is created there. The light streaks are a result of the cold offshore winds blowing over the water from the Ross Ice Shelf, forming an icy sludge on the surface. This freezes to form thin ice, which is then pushed offshore by the wind where it ultimately develops into pack ice.



The first sea-ice crystals look like small, delicate needles or discs. They increase in number as more heat is removed from the water. At this point, the new ice resembles a fine slurry of needles and discs. Under calm wind conditions, a contiguous cover of thin ice forms from this still relatively transparent ice sludge. In the presence of strong winds, however, a typical structure called pancake ice forms in the wake of the rolling waves. This is composed of round, plate-sized ice slabs whose edges are curved slightly upward as a result of the wave impact. The ice therefore actually looks like an agglomeration of freshly baked pancakes before it freezes into a thin ice cover.

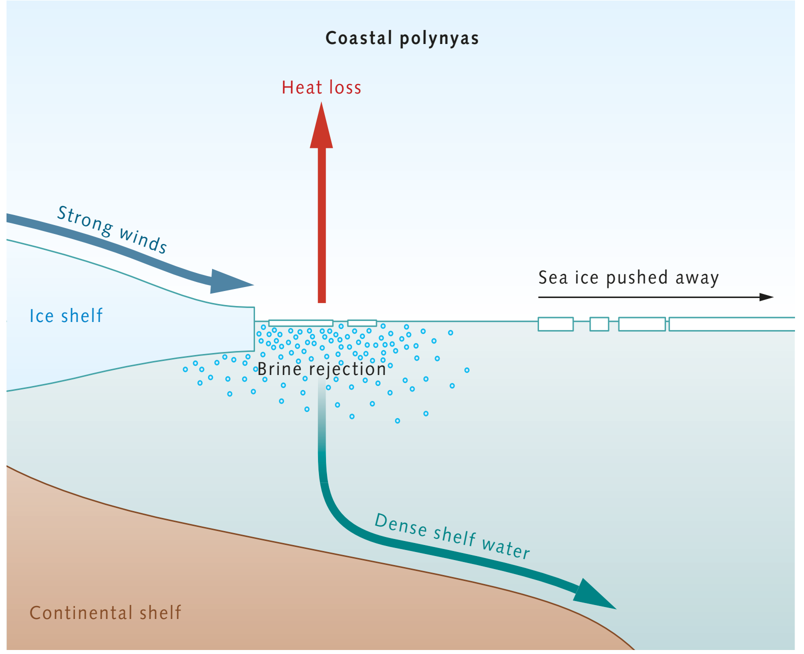
This young sea ice has a distinctive quality that distinguishes it from ice cubes, or from the ice on frozen freshwater lakes. Instead of forming a compact solid ice block, it is interspersed with small channels and cavities. The salt contained in seawater collects in these spaces because it cannot be incorporated into the lattice structure of the ice crystals during the freezing process. Instead, the salt flows as a highly concentrated brine through the small cavities, eventually seeping into the sea on the underside of the ice.

Because the density of frozen water is lower than that of liquid water, ice always floats on the surface. In the polynyas it thus presents a solid face above the sea surface for the wind to strike. The wind propels the young, thin ice out to sea where it collides with the older and thicker pack ice that is already floating off the coast. This compresses the young ice. It becomes thicker, breaks into individual floes depending on the conditions, and is pushed out ever further by the wind. Meanwhile, ice production in the coastal area of the polynyas starts over again from the beginning.

The coastal polynyas in the Antarctic can be from ten to a hundred kilometres wide, whereby scientists are not in complete agreement as to whether the term "polynya" should only refer to the completely ice-free water surface, or if the zone with new thin ice should be included. Satellite surveys show that Antarctic polynyas are almost completely frozen over in winter. The only exception, depending on the location of the polynya, is a strip of water about one kilometre wide directly off the coast or ice-shelf margin, which is kept free of ice by the offshore winds. Similar observations have been made in the Arctic. When air temperatures there drop to minus 40 degrees Celsius in the winter, the shallow-water polynyas (water depths less than 50 metres) off the coast of Siberia freeze up so quickly that a strip of water only a few hundred metres wide remains free of ice due to the wind. But as spring approaches the air becomes warmer. The surface waters are not cooled as intensely, and they freeze more slowly. Because the wind can now push the ice further out to sea, the polynya expands again to a width of several kilometres.

The most productive sea-ice factories in the Southern Ocean are the polynyas off the Ross Ice Shelf (producing 253 cubic kilometres of sea ice per year), the Cape Darnley polynya in the East Antarctic (127 cubic kilometres), and the polynya offshore of the Mertz Glacier (125 cubic kilometres). The Arctic Ocean sea ice is mostly formed in polynyas off the Siberian coast. The main suppliers of new ice are the Russian shelf seas, especially the Kara and Laptev Seas. This new ice is transported towards the Fram Strait by the wind and by the transpolar drift. But some sea ice is also produced off the coasts of Greenland and North America. However, because the wind on many segments of these coasts blows onshore instead of offshore, it pushes the sea ice toward the coasts, where it can become particularly thick.

Sea ice can also become thicker when seawater freezes on its underside. However, this can only happen when a sufficient amount of heat is somehow dissipated from the water on the underside of the ice into the atmosphere.



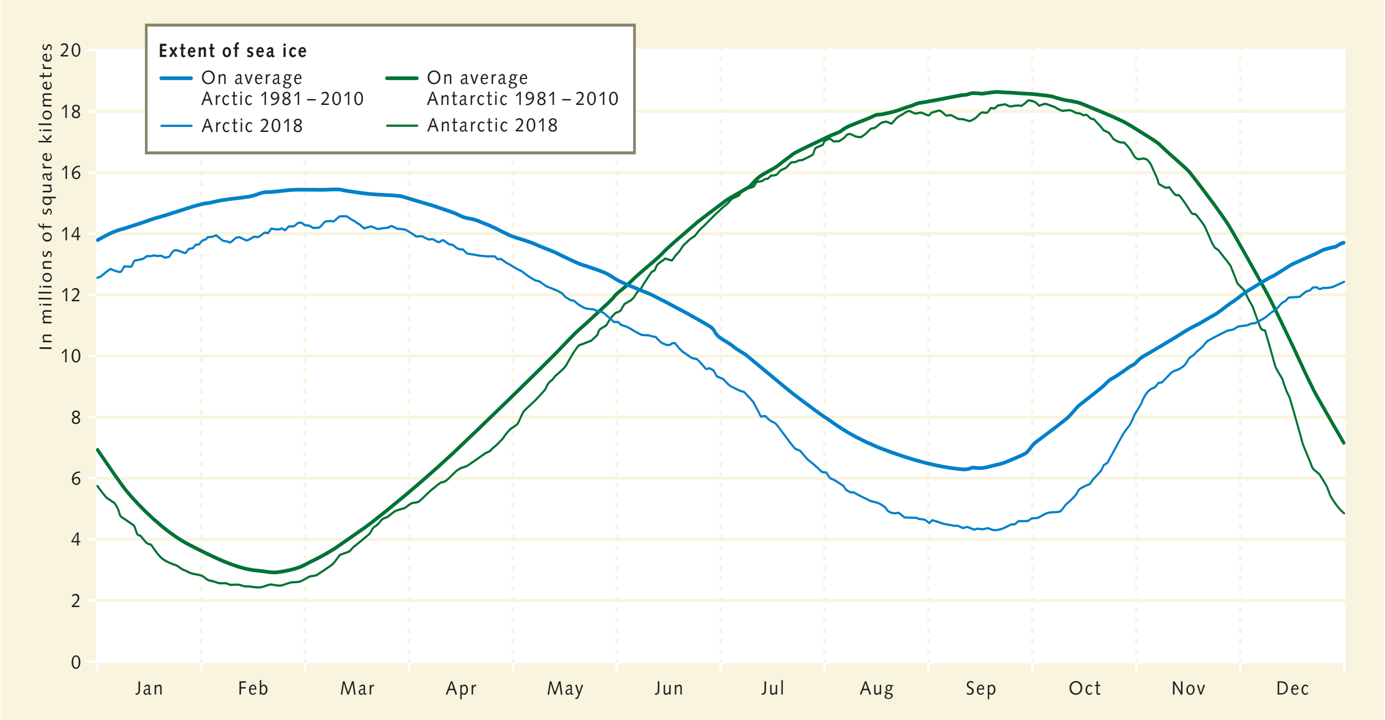
2.15 > When sea ice forms in Antarctic coastal polynyas, heat dissipates into the atmosphere and brine is released, creating cold, heavy water masses. These sink to greater depths where they feed the deepest layers of the world ocean as Antarctic Bottom Water or Circumpolar Deep Water.

This process is called thermodynamic growth. The heat lost by the water has to actually be transported through the ice from below and up into the atmosphere. This heat transmission works very well initially, when the ice is still relatively thin. Arctic sea ice, for example, can grow to a thickness of one to two metres within a single winter. As the ice becomes thicker, however, heat conduction is less effective and the ice floes grow more slowly. Thick, multi-year pack ice therefore acts in a way similar to a lid on a cooking pot: it inhibits the heat in the sea from escaping upward into the atmosphere.

Location matters

Adding all of the sea-ice areas in the world will give an annual average total of around 25 million square kilometres, which is about two-and-a-half times the area of Canada. The global distribution of this total sea ice, however, is not limited to the Arctic and Antarctic regions. During particularly cold winters the sea also freezes off the coast of China. From the Bohai Gulf, for example, thin ice floes drift on the sea at least for a short time to as far south as 38 degrees latitude. The distance to the equator

2.16 > Calving on the front of Lamplugh Glacier in the US state of Alaska. When ice masses weighing many tonnes break off and fall into the sea, fountains of water soar upward. When the blocks melt, the resulting water mixes with the surface water of the sea, reducing its salinity and density.



2.17 > The extent of sea ice expands and shrinks with the changing seasons both in the Arctic and Antarctic, whereby a greater proportion of sea-ice in the Southern Ocean consistently melts than does the ice cover of the Arctic Ocean.

from here is shorter than to the North Pole. In the southern hemisphere, seawater only freezes in the regions south of 55 degrees latitude. Due to the geographical situation (a large ocean surrounding a continent), Antarctic sea ice differs in a fundamental way from sea ice in the Arctic Ocean (continents surrounding a small ocean). It drifts much faster, for example, in part because the vast Southern Ocean offers more open area for the ice, allowing it to move more freely than it can in the Arctic. For the same reason, however, the sea ice in the Southern Ocean is less likely to form metres-high pressure ridges. These walls of ice, often kilometres-long, are common in the Arctic because the wind piles up the densely packed ice floes to heights of 25 metres or more, particularly near the coasts. These thick barricades of ice represent impregnable barriers, even for modern icebreakers.

Because of the great breadth of the Southern Ocean, the air masses coming from the northwest are also able to collect a great deal of moisture on their way to the Antarctic continent. This ultimately falls along the coast of the Antarctic continent, which is why the Antarctic sea ice is often covered by a thick blanket of snow. In the Arctic, by contrast, the incoming air masses pass over large areas of land before reaching the ocean in the centre. This air is therefore relatively dry and rarely produces snow.

Because ice floes in the Southern Ocean have room to drift into areas of warmer water, almost all of the freely moving ice in the Antarctic melts during the summer. The only exceptions are the sea-ice areas that are frozen along the coastline, or areas where icebergs have run aground and block the path of the sea ice to the open sea. This grounded sea ice, which is found both in the Arctic and Antarctic, is also called land-fast ice or bay ice. It provides, among other things, resting places and nursery areas for seals and penguins.

The migration of Antarctic sea ice to warmer northern latitudes means that it rarely survives for more than a year, and it is therefore thinner on average than Arctic sea ice. The ice cover in the Southern Ocean is usually one to two metres thick. In the Arctic, on the other hand, scientists often measure thicknesses of four to five metres, especially in regions with multi-year ice.

New sea ice is mostly produced during the winter months. Sea ice in the Arctic Ocean attains its greatest areal extent in March. When satellite measurements began in 1979, it amounted to slightly more than 16 mil-

2.18 > Researchers have set up camp on an ice floe to investigate the meltwater ponds. These often form on ice floes in the Arctic where meltwater collects. Because the dark water surfaces absorb more solar energy than the sea ice around them, the ice below the ponds melts especially rapidly.

lion square kilometres – an area about one-and-a-half times the size of the USA. This figure has since dropped to around 14.5 million square kilometres. The Antarctic sea ice freezes between March and September. At the end of the Antarctic winter it covers an area that averages more than 18 million square kilometres.

When spring comes

By the beginning of spring at the latest, however, the growth of sea ice comes to an end in both polar regions. Because of the increasing air temperatures, the formation of new ice begins to slow down and then at some point it stops completely. Now the sea ice begins to melt. There are a number of basic processes involved in this. When the air temperature rises above freezing, the sea ice begins to melt first on the upper surface, so it becomes thinner. In the summer of 2018, on an expedition to the central Arctic Ocean, German sea-ice researchers investigated the rates of surface melt there. After weeks of observation, they were able to confirm that, by the end of summer, the original two-metre-thick ice floes had lost up to 60 centimetres in thickness due to melting processes at the surface alone.

The water produced by surface melting can either seep through the porous sea ice or run off the edge of the floe into the sea. In the Arctic, the meltwater often collects on top of the ice to create meltwater ponds. Because the dark water surface absorbs more solar energy than the sea ice around the pond, the ice at the bottom of the pond melts more quickly.

In the Antarctic, on the other hand, researchers have rarely observed meltwater collecting on the ice. There are two reasons for this. For one, the snow cover on the Antarctic sea ice is much thicker than that on Arctic floes. The meltwater therefore seeps deeper into the snow and often refreezes to form an intermediate layer of ice. For another, the cold offshore winds in the coastal regions of the Antarctic generally prevent the sea ice and its snow cover from melting as quickly at the surface as on the ice floes in the high northern latitudes. Instead, a certain amount of snow in the Antarctic evaporates in the cold, dry air without ever melting. Scientists refer to this direct transformation of a substance from a solid to a gaseous state as sublimation.

Ice floes, however, do not only melt on the upper surface. The solar radiation absorbed there is also transferred through the ice. As a result, the floe becomes warmer overall and also begins to melt in the centre. The small brine channels become larger and the ice becomes more porous and brittle. Thus, at a certain point in this process, sea-ice researchers refer to it as “rotten ice”, because these ice floes can disintegrate or crumble like a very rotten log.

Finally, sea ice can also melt from below. This is primarily caused by warm water masses that flow directly under the ice. In the Southern Ocean, these may well up from greater depths, or wind and ocean currents can transport the mobile pack ice northward into areas with comparatively warm water. Conversely, in the Arctic Ocean, the sun warms the surface water, which can then release its heat to the ice and accelerate the melting process.

In the past, melting on the upper surface was the primary cause for the summer shrinking of sea-ice cover in the Arctic. But in recent years the amount of melting on the underside of the ice has increased significantly because, due to its long-term decrease in sea-ice cover, the Arctic Ocean is absorbing more solar energy and the surface waters are getting warmer. The heat supply is not yet sufficient for the sea ice in the Arctic Ocean to disappear completely. But even now, well over half of the winter ice cover is already melting in summer.

Standing on the Antarctic sea ice in winter, one might easily imagine that one is on a gigantic white land mass. Ice covers the Southern Ocean as far as the eye can see. There is usually a blanket of freshly fallen snow on the ice that increases the reflectivity of the surface to as much as 90 per cent. However, the reflection of incident solar energy is not the only critical function of sea ice within the Earth’s climate system. It is also, in a sense, a driving force behind the conveyor belt of the world’s ocean currents, because the brine that enters the ocean when the ice freezes plays an important role in a gigantic chain reaction.

What drives the ocean currents

The temperature differences between polar regions and the tropics effectively drive not only the air currents in the atmosphere in the global wind system but also, to a large degree, the worldwide system of ocean currents. These, in turn, influence the Earth’s weather and climate in two important ways:

- The ocean currents transport an immense amount of heat energy and distribute it around the world.
- Variously warm air currents and water currents regulate the Earth’s water cycle through the evaporation of seawater and the absorption or release of heat at the sea surface, depending on whether the overlying atmosphere is colder or warmer than the water.

Vertical transport of water in the oceans is involved when water from great depths reaches the surface at upwelling areas, while elsewhere surface waters sink to greater depths. The descending currents carry heat, oxygen and dissolved trace gases down from the sea surface with them. As a result of this process, the world’s oceans have become our planet’s most important heat-storage reservoir. In the past 50 years, they have absorbed 90 per cent of the excess heat that has been retained in the Earth system due to rising greenhouse-gas concentrations.

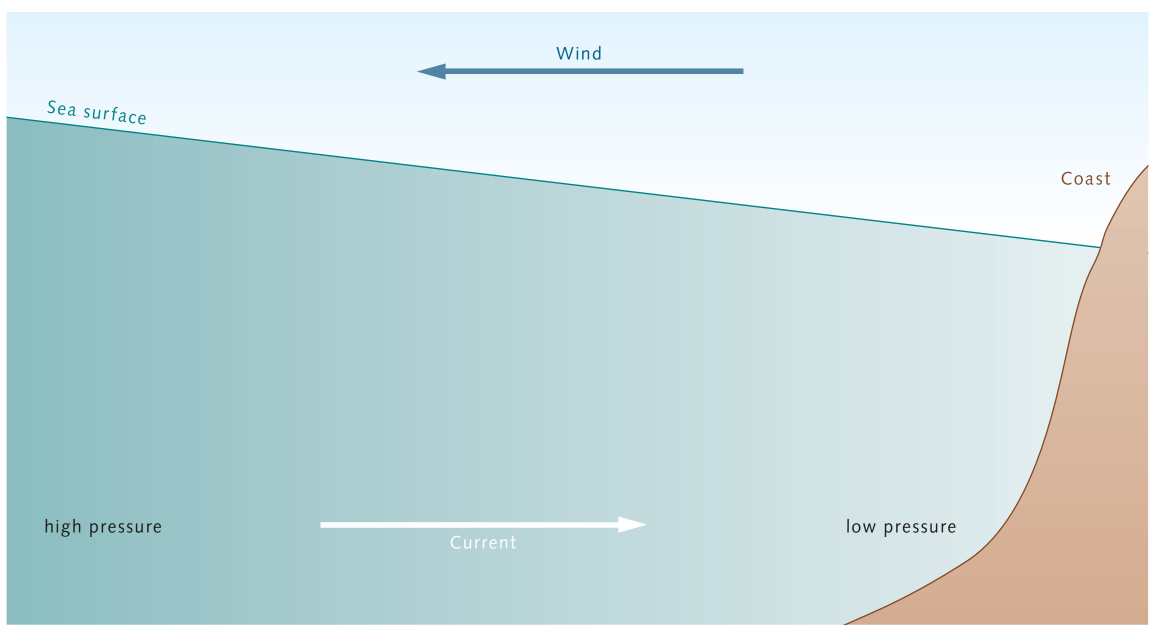
At right angles to the wind

Ocean currents generated by the motions of high and low tides are a familiar phenomenon around the world. But the large marine currents around the world are primarily driven by the density differences between water masses or by the power of the wind. When the wind blows over the water surface, friction is produced. The wind energy is transferred to water particles near the surface and sets them in motion. This produces waves and turbulence. The energy is distributed within the upper several metres of the water column, and a wind-driven surface current is created.

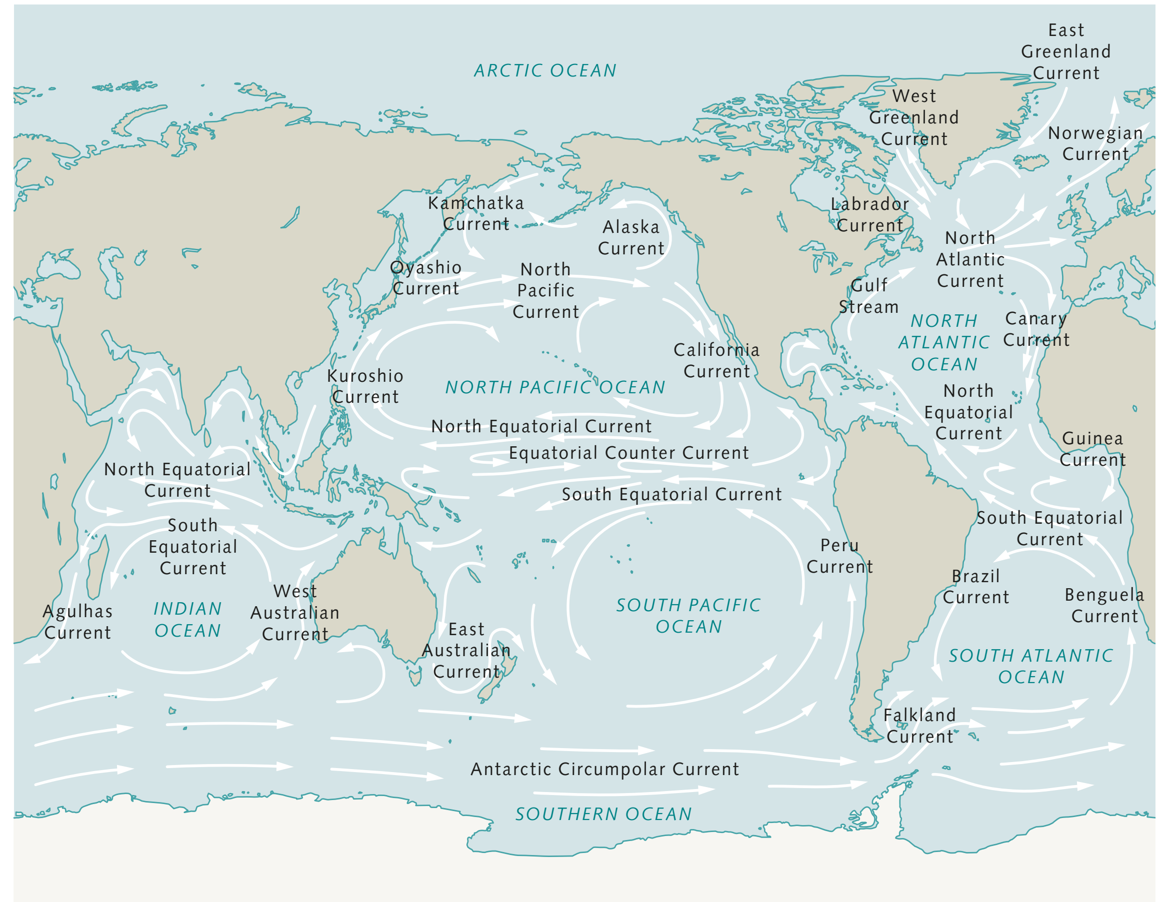
Contrary to reasonable expectation, perhaps, this current does not flow in a straight line parallel to the wind. Because the Earth is turning, the Coriolis force operates here to deflect the current. The total deflection, however, is only 45 degrees because the surface water driven by the wind pulls the immediately underlying, more static water layer with it to some extent. This means that the deeper water masses likewise sheer off and are diverted. With increasing depth, therefore, the flow angle with respect to the surficial wind direction increases and the flow velocity decreases. A schematic drawing, with the flow direction and speed of each of these successively deepening water layers represented as arrows, reveals a spiral-shaped, vertical velocity profile that resembles a corkscrew and is called the Ekman spiral. It was named for the Swedish oceanographer Vagn Walfrid Ekman (1874–1954). He was the first to recognize that the wind-driven near-surface water layers flowed more slowly with increasing depth and that their flow direction deviated increasingly from the wind direction. When all of these progressively changing flow directions in the water column are combined and the mean value is calculated, the result is that, for purely wind-driven ocean currents, the overall water transport is at right angles to the wind direction.

This phenomenon is known as Ekman transport, and it helps to explain, among other things, how water rises from great depths in upwelling areas such as the Benguela Current off the west coast of South Africa. This kind of upwelling occurs in coastal areas where the wind blows parallel to the coast and the Ekman transport it generates forces the near-surface waters out to the open sea at a right angle. Deep waters then flow in from below, replacing these surface waters.

Such upwelling currents are of crucial importance for life in the sea and for the climate in the coastal regions where they occur. For one, nutrients brought up with the deep water promote the growth of algae and microorganisms, which in turn become food for many larger marine organisms. That is why the most important worldwide fishing grounds are always in upwelling areas. For another, the cold water masses at the surface flow toward the equator as a part of the eastern boundary currents of subtropical gyres, and have an effect on the air temperatures and amounts of precipitation in the coastal regions. Worldwide, there are five of these currents. They are the California Current, the Peru Current, the Canary Current, the Benguela Current and the West Australian Current.



2.19 > When winds at the sea surface push water masses in one direction and pile them up, a counter current develops at depth due to the changing pressure conditions.



2.20 > All of the ocean currents and gyres illustrated here are part of the surface circulation of the world ocean, and are driven by winds.

The five subtropical ocean gyres are among the most prominent surface currents in the world ocean. They are driven by the trade winds and the west winds, and they differ only by the fact that, due to the Coriolis force, the water masses in the gyres in the northern hemisphere rotate clockwise and those south of the equator flow in a counter-clockwise direction. A piling up of water masses on the western side of these ocean gyres results in the formation of western boundary currents. These include, among others, the Gulf Stream off the east coast of the USA and the Agulhas Current in the southern Indian Ocean. The western boundary currents, as a rule, are significantly narrower than the boundary currents on the eastern side of the gyres, and they also flow faster.

Density changes – ascending or descending?

In addition to the wind as a driving force, there is another mechanism that sets enormous currents into motion: a global-scale overturning circulation that transports the water masses on a kind of conveyor belt through all the world's oceans. The motion along this conveyor belt is maintained by differences in the temperature and salinity of the water masses, which is why scientists also refer to it as thermohaline circulation (*thermo*: driven by temperature differences; *haline*: driven by differences in salinity). To understand the mystery of its function, one has to know two things about the world oceans in general and about water specifically, because water behaves differently from most other chemical substances. In almost all other substances, the atoms and molecules move closer together the colder it gets, but this is not strictly the case with water. Normal freshwater exhibits its maximum density at a temperature of four degrees Celsius, because at that temperature the water molecules are closest together.

When it contains dissolved salt, however, the chemical and physical properties of water are different. The density of saltwater continues to increase steadily with falling temperature, and reaches its maximum at the freezing point. For this reason, saltwater at two degrees Celsius is significantly more dense and heavier than freshwater at the same temperature.

There is another important factor: the saltier the water is, the heavier it is. This means that the actual density of seawater is determined by a rather complex relationship between temperature and salinity. In principle, the water masses of the ocean are layered one above the other according to their density. The heaviest and usually the coldest water is found in the deep sea, while the lightest water is found at the surface.

As a rule, winds and waves are only capable of mixing the upper 200 metres of the water column. The deeper water masses, on the other hand, remain virtually unmixed. This is why scientists can speak in terms of the stable stratification of the oceans. Similar to the way that horizontal density differences between high- and low-pressure areas in the atmosphere cause winds, the horizontal pressure differences in the ocean, with a small intermediate step, are responsible for the creation of currents.

A question of salinity

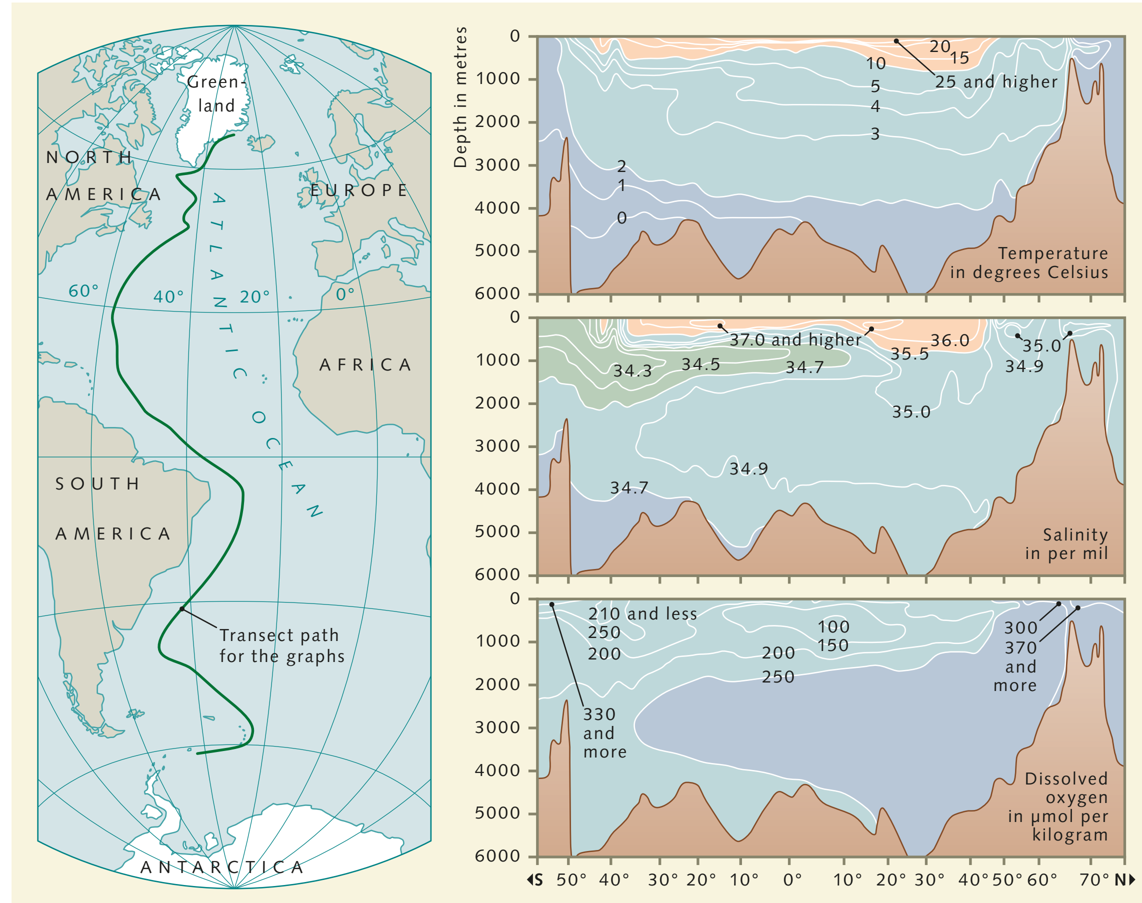
The temperature and salinity of the water, and therefore its density, are determined by processes at the sea surface. When water cools, its density increases. It becomes heavier and sinks to a greater depth. This process is called thermal convection. But when the surface water warms up, it becomes less dense. It becomes lighter, and the difference between its density and that of the underlying water increases. As a result, the warm, light water remains at the sea surface unless a mixing of the two water layers is induced by the wind.

A similar case is observed for salinity. It increases when water evaporates at the sea surface. But when it rains, or where rivers or glaciers deliver fresh water into the sea, the salinity of the surface water decreases along with its density. In this case again, the light water remains at the sea surface. If a water mass becomes more saline, however, and thus heavier, then haline convection commences. The heavier water sinks. In this way, immense amounts of water are overturned to depths of several kilometres.

The salinity of surface water also changes when sea ice forms. For example, when the coastal regions of the Southern Ocean freeze in early winter, salt is effectively spread over large areas in the sea, as the brine that collects in the small channels and chambers of the porous sea ice gradually seeps out into the water.

Scientists have found that 70 to 90 per cent of the salt contained in the surface water is released into the underlying water layer during the freezing process. With decreasing temperature or increasing salinity of this layer beneath the sea ice, the water becomes heavier. It sinks to the sea floor, collecting there as dense shelf water. It then spreads out and, at some point, flows down the continental slope into the deep sea. There, at a depth of several kilometres, it feeds the Antarctic Bottom Water, which is the lowest level of the world ocean. Above this flows the somewhat warmer, and thus lighter North Atlantic Deep Water coming from the north.

There are presently four known regions in which Antarctic Bottom Water is created: in the Weddell Sea, the Ross Sea, off the coast of Adélie Land, and in the Cape Darnley polynya west of the Amery Ice Shelf. The heavy, cold water is an important component in the worldwide conveyor belt of ocean currents. In somewhat simple terms, the cycle functions as follows: Warm water from the tropics flows into the polar regions. There it releases its heat into



2.21 > The individual water masses of the Atlantic Ocean can be distinguished by their temperature as well as by their salt and oxygen content. The vertical cross sections show how the water masses are layered one above the other, following the course of the line drawn on the map on the left, from the Antarctic to East Greenland.

the cold polar atmosphere. As a result, the water cools, becomes heavier, and descends to greater depths, whereupon it flows back toward the equator. At the sea surface, new warm water continues to flow in and cool down so that the overturning motion continues uninterrupted.

Even from this simplified explanation it is clear that the polar seas play a key role in the global water-mass circulation. They are the driving force behind the global conveyor belt, although the processes controlling the turnover of water masses differ greatly between the Arctic and Antarctic.

Overturning in the wild Southern Ocean

As a sea that circles the globe, the Southern Ocean connects the world's three large ocean basins and thus facilitates the global circulation of water masses. Hydrographically, it can be broken down into the Antarctic Circumpolar Current in the north, the coastal current on the continental margin in the south, and the three large subpolar gyres situated in between. These gyres, rotating clockwise, are located in the areas of the Weddell Sea (Weddell Gyre), the Ross Sea (Ross Gyre) and the Australian-Antarctic Basin (Kerguelen Gyre).

The sea-surface characteristics of the individual water masses are primarily controlled by conditions in the atmosphere. The air temperature over the oceans in the southern hemisphere drops strongly toward the south, which has an impact on the air pressure and thus on the wind conditions. Over the near-coastal parts of the Southern Ocean, easterly winds blow as well as offshore fall winds in some areas, which are known as katabatic winds. The zone of circumpolar west winds is located further to the north. These loosely defined bands are known as the "roaring forties", the "wild fifties", and the "howling sixties", and they provide the driving force behind the marine currents in the Southern Ocean. Like the air temperature, the temperature of the water also falls to the south. In the subtropics the water temperature at the surface is a warm 25 degrees Celsius. In the Antarctic coastal waters it is near the freezing point of salty seawater, which is minus 1.9 degrees Celsius.

The Antarctic Circumpolar Current is driven by a large-scale band of west winds. It transports water masses more than one hundred times greater than all the world's rivers combined, and is the most powerful current system on the Earth. Immense amounts of water are involved here because the Circumpolar Current is up to 2000 kilometres wide and extends far below the surface. While other wind-driven currents move the water to maximum depths of only 1000 metres, the Circumpolar Current can extend down to depths of 2000 or even 4000 metres. The current velocity in many places, however, is only 20 centimetres per second or less. This makes it a comparatively slow ocean current.

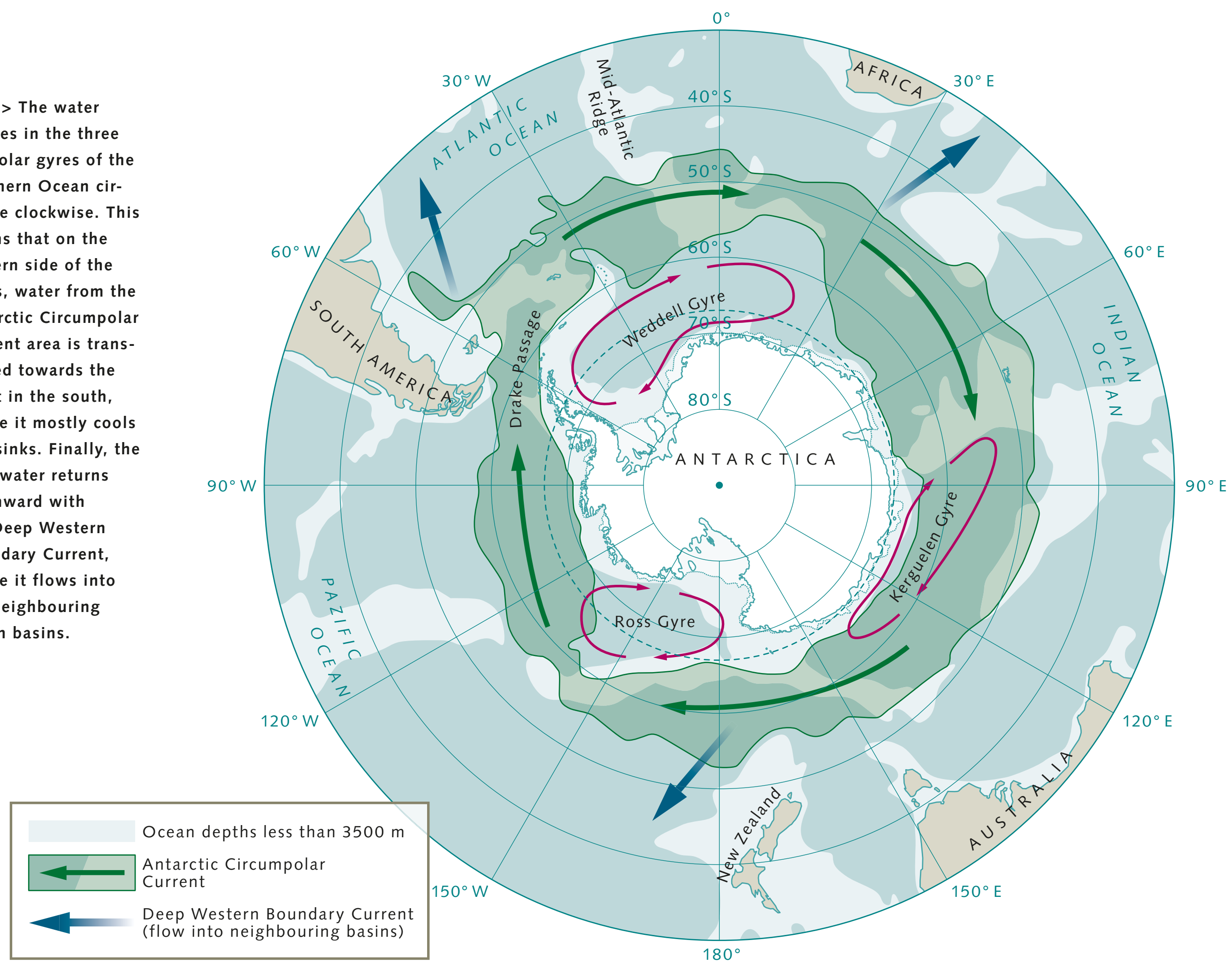
The Circumpolar Current is not a unified cohesive belt, but is subdivided into a number of smaller segments connected by what are known as fronts. To a large extent, it prevents warm surface water from the Tropics from penetrating directly into the Antarctic region. But this barrier is not completely impregnable. Eddies with diameters typically around 100 kilometres repeatedly break away from the fronts, migrate a bit to the north or south depending on the direction of rotation, and then dissipate again after a few weeks. The eddies thus allow for a certain amount of horizontal mixing of the water-mass properties by permitting deep water coming from the north to penetrate southward beyond the Circumpolar Current at a depth of 2000 to 3000 metres.

Here, scientists distinguish between the Upper Circumpolar Deep Water, which has average temperature and salinity values and contains little oxygen because it has been circulating for centuries through the deep Pacific Ocean with no surface contact, and the high-salinity Lower Circumpolar Deep Water, which originates from the North Atlantic Deep Water and is not as old.

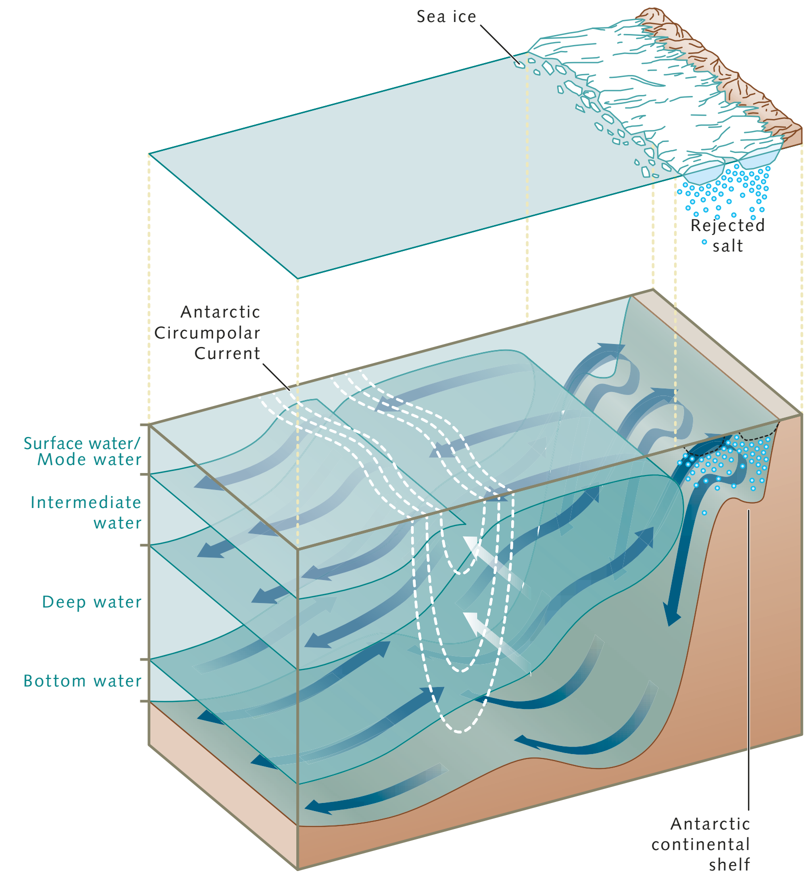
Both of these deep water masses are initially carried along with the Circumpolar Current. They make a couple of revolutions around the continent of Antarctica, slowly rise upward, and are eventually able to break away to the south with the help of the subpolar gyres. Upon reaching the sea surface, the water masses release their heat to the atmosphere. At the same time, snow, rain and melting icebergs all contribute to reducing their salinity. A portion of this ascending water subsequently flows to the north and sinks to intermediate depths again as Antarctic Intermediate Water on the northern flank of the Circumpolar Current. The remaining portion is transported southward to the coast by the subpolar gyres. There the surface water freezes and, through the process of ice formation, it is again enriched with salt.

Its subsequent path back into the depths is thereby predestined. The cold, heavy water sinks and thus triggers a convective mixing. The more intensive the cooling and salt enrichment process is at the sea surface, the deeper the heavy water sinks. In some situations, it can even flow beneath the relatively warm Circumpolar Deep Water lying on the continental slope.

While the Circumpolar Current is driven by westerly winds in the northern part of the Southern Ocean, the near-coastal easterly winds further to the south propel a counter current, the Antarctic Coastal Current. This flows westward above the Antarctic continental slope as a boundary current and includes the southern segments of the subpolar gyres. The Antarctic icebergs drift with the Coastal Current. One reason why researchers are interested in this current is that warm, relatively salt-rich Circumpolar Deep Water lurks on its underside and, in the course of climate change, this is becoming increasingly threatening for the Antarctic ice masses.



2.22 > The water masses in the three subpolar gyres of the Southern Ocean circulate clockwise. This means that on the eastern side of the gyres, water from the Antarctic Circumpolar Current area is transported towards the coast in the south, where it mostly cools and sinks. Finally, the cold water returns northward with the Deep Western Boundary Current, where it flows into the neighbouring ocean basins.



2.23 > With the overturning in the Southern Ocean, the deep water coming out of the north wells up just off the coast, cools down almost to the freezing point at the surface, and then, saturated with brine, it sinks to the deepest level of the ocean as heavy bottom water. Further to the north, on the other hand, upwelling water flows back toward the equator, changing to lighter mode water or intermediate water underlying the surface waters.

Overturning in the Arctic Ocean

The formation of deep water in the Antarctic is not the only process that keeps the global conveyer belt of ocean circulation in motion. A second driving force, the Atlantic Meridional Overturning Circulation (AMOC), acts in the

2.24 > The current system of the Arctic Ocean is controlled to some extent by the influx of warm, salt-rich water from the North Atlantic Current. In addition, some cold water masses form in the Siberian marginal seas and in the Norwegian Sea, especially in winter, and subsequently flow out of the Arctic region toward the Atlantic Ocean.

northern part of the Atlantic Ocean. Simply put, this is a mechanism that transports warm surface water from the tropics to the North Atlantic, where it cools, sinks, and then flows southward again as cold North Atlantic Deep Water at a depth of two to three kilometres. At the surface it is continuously replaced by water flowing in from the subtropics.

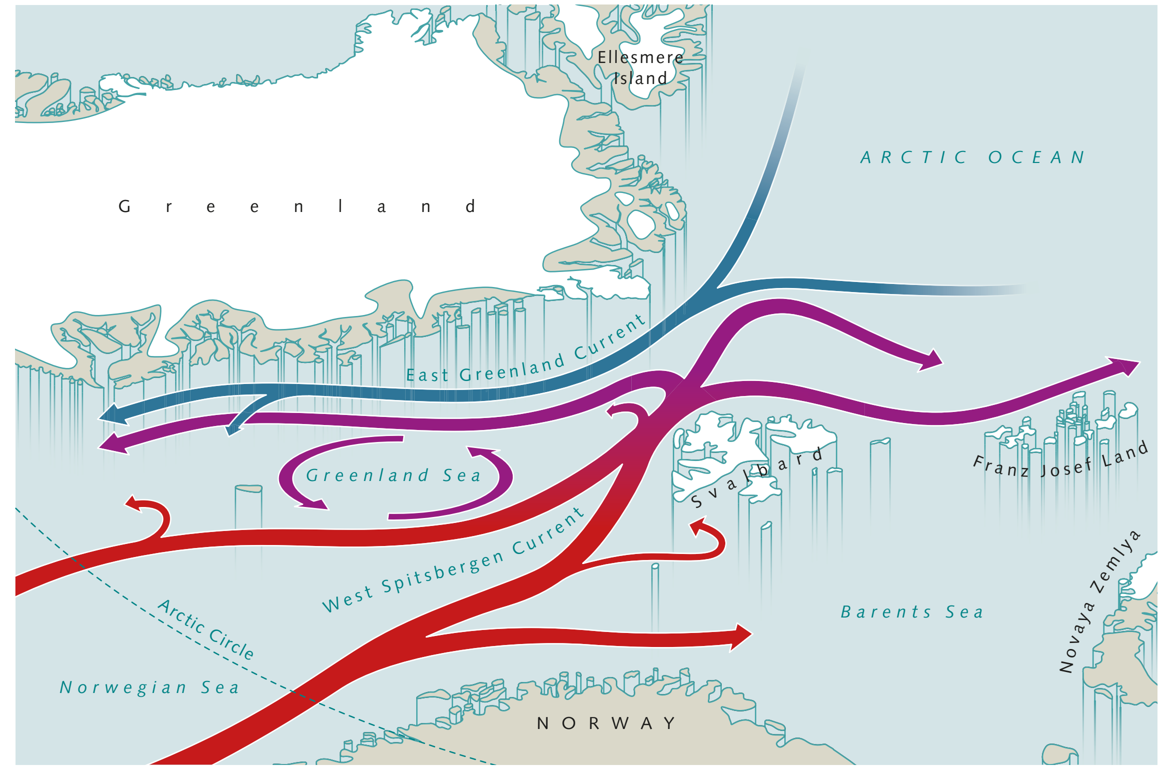
In order to understand the decisive role that the Arctic plays in this overturning process, it is helpful to take a closer look at the individual steps involved. The warm surface water is transported to the west coast of Ireland by the northern branch of the Gulf Stream, which scientists call the North Atlantic Current. There the current divides and about one-third of the water is entrained by the subpolar gyre. As the Norwegian Current, this flows along the west coast of Scandinavia, then from the Norwegian Sea into the Barents Sea, a marginal sea of the Arctic Ocean. The remaining water branches off toward Greenland, then divides again into the West Spitsbergen Current, which flows into the Fram Strait, and another arm that transports the warm water into the Labrador Sea between Greenland and Canada.

On their northward pathways, all of these currents cool down and are diluted by rainwater. With the release of heat energy into the atmosphere, they significantly influence the climate of northern Europe. Without the heat transport of the Gulf Stream and its extensions the climate would be much colder in northern Europe, especially in the winter.

The water loses particularly large amounts of heat in the Barents Sea. As an Arctic marginal or shelf sea it is only 50 to 400 metres deep, and therefore cools down fairly rapidly. Furthermore, there is a great extent of mixing of the inflowing water masses here. A number of rivers, the Russian Kola, for example, transport large amounts of freshwater into the Barents Sea. The water masses flow back and forth with the tides, which causes the entire water column to lose a great deal of heat energy, especially in winter. If the water also freezes to form sea ice, and the brine created increases the density of the shelf water, three different kinds of water are formed:

- cold, low-salinity surface water that is driven by the wind and distributed into the central Arctic;
- cold, high-salinity water that sinks to intermediate depths and spreads out there; and
- very salty, heavy water masses that either flow directly through the Norwegian Sea back to the Atlantic or take the longer route as Arctic Bottom Water through the Arctic Basin and the Fram Strait.

The tides play a less important role In the Fram Strait, but even here the three- to six-degrees-Celsius warm Atlantic Water cools down by large increments. The current system of the Fram Strait can be envisioned as a major road with a turning lane. In the right lane to the



2.25 > The Fram Strait is one of three marine regions in the Arctic where water is overturned. Here the West Spitsbergen Current transports warm, salt-rich water northward where it first cools and then eventually sinks to a depth of 200 to 800 metres. One part of the current then flows into the Arctic Ocean. The other part reverses direction and flows southward as North Atlantic Deep Water beneath the cold East Greenland Current.

east, the warm, saline Atlantic Water first flows northward on the surface in the West Spitsbergen Current. The colder it becomes, the heavier it becomes. At a certain point the current sinks to a depth of 200 to 800 metres, where it splits. One branch of the current continues on its path into the Arctic Ocean. The remaining water turns to the west, making a 180-degree-turn, and moves into the opposing lane, where it flows back to the south as North Atlantic Deep Water on the eastern edge of the Greenland shelf. However, along this opposing lane, called the East Greenland Current, there is also a second current that flows one level higher at the sea surface. It comes from the Arctic and transports cold, minus 1.8-degree-Celsius water with relatively low salinity and abundant ice floes into the North Atlantic.

Together, these water masses cross the shallow thresholds, only 800 metres deep, between Greenland, Iceland and Scotland, and then flow downward like giant waterfalls into the deep basin of the North Atlantic. A third current, with deep water from the Labrador Sea, now flows above them. During its winter cooling it has sunk to a depth of about 2000 metres and now completes the Arctic cold-water stream, which flows as deep water along the east coast of America toward the South Atlantic.

A comparison of the overturning circulation in the North Atlantic with deep-water formation in the Southern Ocean reveals an important difference. The water masses in the north sink because they lose heat to the atmosphere in ice-free marine regions like the Labrador Sea, the Norwegian Sea and the Siberian shelf seas, and thereby become colder and heavier. At the same time, in the central Arctic Ocean hardly any convection takes place. Here the sea-ice cover insulates the ocean too well for it to be able to release much heat into the atmosphere.

In the Antarctic, on the other hand, deep-water formation is mainly driven by the freezing of sea ice and the associated release of brine. Although the prior heat loss of the water also plays a role, the formation of sea ice is more significant here.

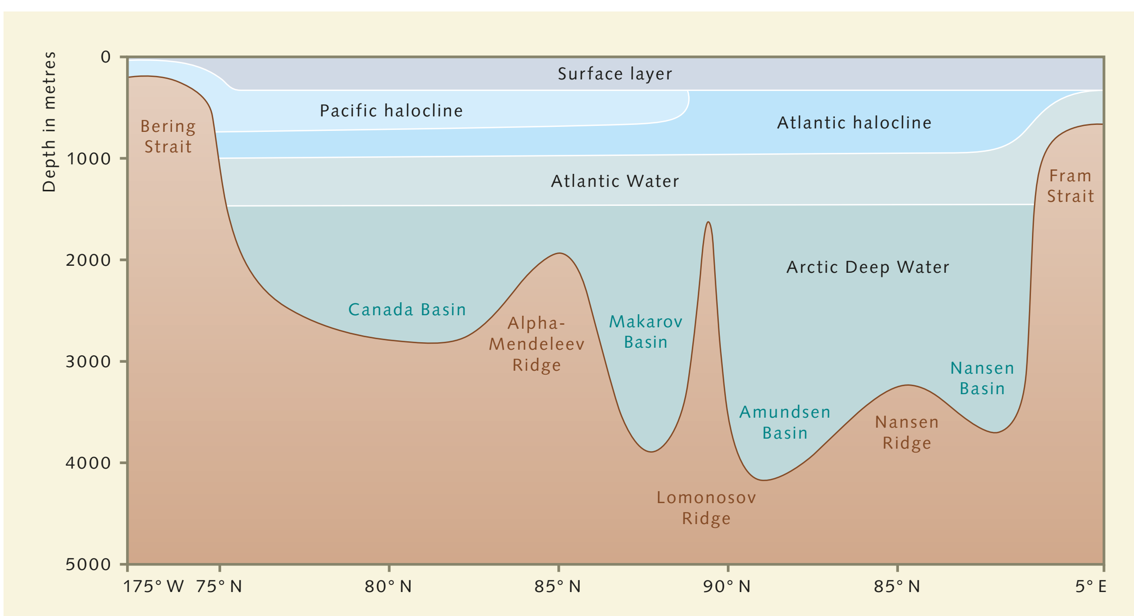
A protective layer for the sea ice

Overturning of the Atlantic Water, however, is not the only role played by the Arctic Ocean in the global conveyor belt of ocean currents. It also represents an important link between the Pacific and Atlantic Oceans. Through the Bering Strait, only 85 kilometres wide and 50 metres deep, relatively warm, low-salinity Pacific water flows into the Arctic Ocean. The inflow is only one-tenth of the amount that enters through the Fram Strait and the Barents Sea from the North Atlantic, but it definitely has an influence on the course of events here. The water masses from the Pacific transport heat into the high north, which has an impact on the formation of sea ice in the Chukchi Sea north of the Bering Strait. Because of its low salinity, the Pacific water reinforces the stratification of the Arctic Ocean. Looking at a profile of its water column, the following characteristic features can be recognized from top to bottom:

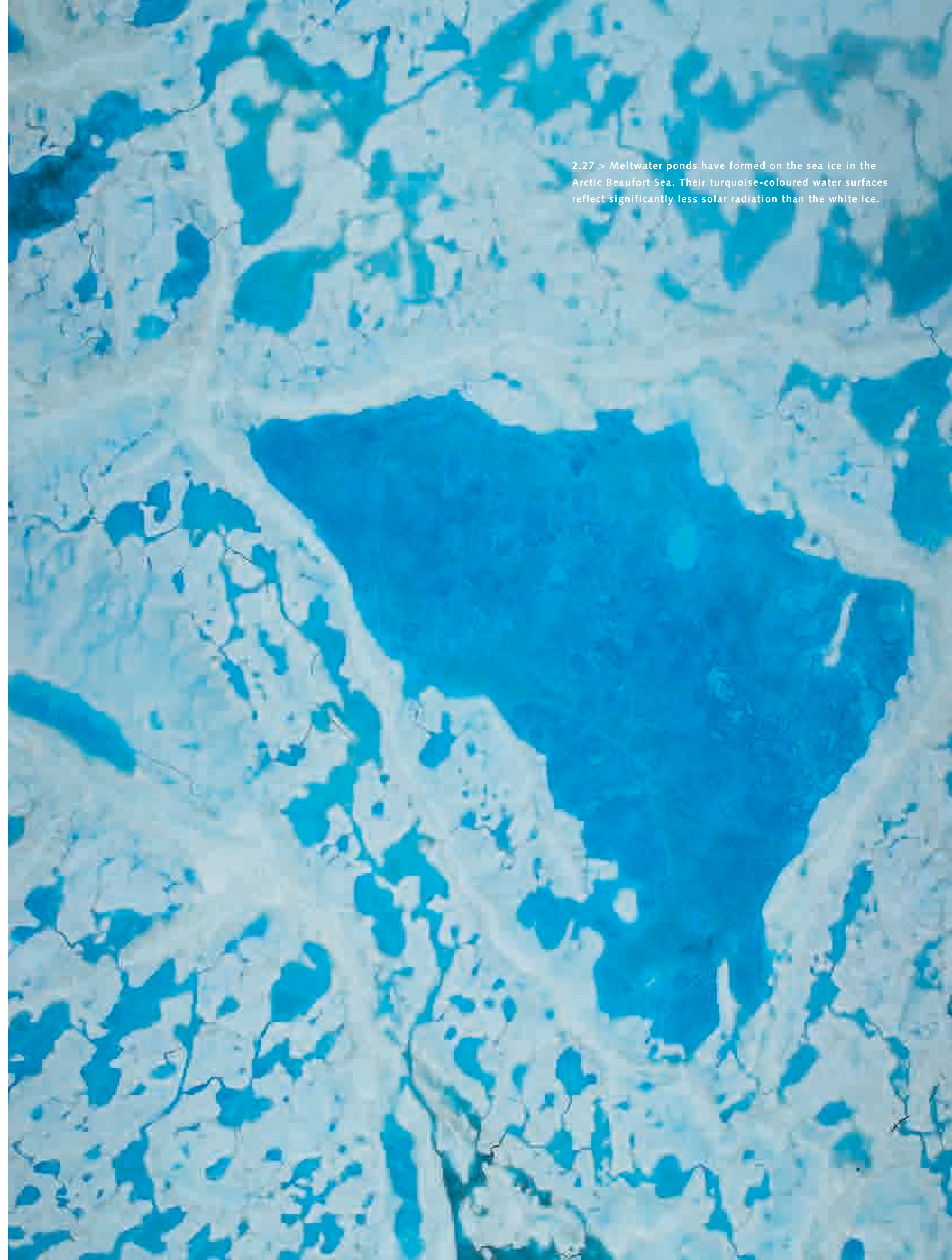
The surface layer

Wherever sea ice floats on the Arctic Ocean, it is underlain by a 5- to 50-metre-thick layer of low-salinity water. This uppermost water layer is fed by freshwater that primarily comes from the many rivers that empty into the Arctic Ocean. The northern European, Siberian and North American rivers alone transport around 3300 cubic kilometres of water into the Arctic Ocean annually. This is equal to about eleven per cent of the world's continental runoff, and explains why the water of the Arctic Ocean contains significantly less salt than, for example, the water masses of the Atlantic Ocean.

The freshwater carried in by rivers mixes with seawater in the shallow shelf seas and then, driven by the wind, spreads into the central Arctic. In the shelf seas, as well as in the central Arctic Ocean, this surface layer can be relatively warm in summer, especially where the ice cover has broken up into individual floes or even completely melted. Where no sea ice is present the solar radiation can warm the surface water, which in many places leads to more enhanced melting of the remaining floes from below. As a consequence of melting and the associated freshwater input, the surface layer becomes less saline and thus more stable as the summer progresses. As a result, this water tends to mix less readily with the underlying, higher salinity water masses. The incoming heat radiation thus remains trapped within the uppermost water layer. In the autumn and winter,



2.26 > Schematic representation of the water masses in the Arctic Ocean. Warm water masses from the Atlantic circulate above the Arctic Deep Water. Above these, in turn, are the cold Atlantic and Pacific Haloclines, which, together with the surface layer, protect the floating sea ice from the heat of the Atlantic Water.



2.27 > Meltwater ponds have formed on the sea ice in the Arctic Beaufort Sea. Their turquoise-coloured water surfaces reflect significantly less solar radiation than the white ice.

however, the surface layer again cools down and, with the initiation of ice formation, becomes more saline.

The halocline

Beneath the surface layer, especially in the deep basin of the Arctic Ocean, lies a second well-defined layer called the cold halocline. The term “halocline” comes from the Greek and indicates a transitional zone between water layers that have different salt contents, which is why the halocline is also sometimes called the salinity discontinuity layer. The salinity of the water increases from the base of the surface layer to a depth of around 200 metres, until it has the same value as the underlying Atlantic Water. This kind of salinity layering is not at all unusual in the world’s oceans. A special feature of the Arctic Ocean, however, is that, although the salinity of the water in the Arctic halocline does increase with depth, the water temperature remains fairly close to freezing throughout, despite the fact that the Atlantic Water below the halocline is significantly warmer, with a temperature of approximately one degree Celsius.

The temperature in the Arctic halocline is relatively low because its water originates in the shelf seas, where the surface waters cool down considerably in winter, and large amounts of ice are formed in the coastal polynyas. Furthermore, numerous rivers dilute the shelf water with freshwater, which is why its salinity is very low. During the winter, however, the salt content increases as a result of the constant formation of sea ice.

This cold water, which is still fairly low in salinity at the beginning of winter, flows from the shelf seas into the central Arctic. There it spreads in all directions, flows beneath the even lower-salinity surface layer because of its density, and provides an additional layer of insulation against the deeper warm Atlantic Water.

Together, the surface layer and halocline provide a degree of stability in the stratification of the Arctic Ocean, such that neither the wind nor convection are able to produce the turbulence necessary to transport significant amounts of warmer Atlantic Water up to the sea surface from below.

The water masses from the Pacific Ocean flowing through the Bering Strait into the Arctic Ocean have a fate similar to that of the shelf water. They are also relatively low in salt content, and experience a similar development in the shallow Chukchi Sea as the water masses from the other shelf seas. Ultimately, the ocean water from the Pacific, because of its density, is integrated into the layering scheme of the central Arctic as the Pacific Halocline.

The Atlantic Water

The Atlantic Water, which has already been mentioned numerous times, flows into the Arctic through the Fram Strait and the Norwegian Sea. It originates in the Gulf Stream far to the south, but cools down markedly on its northward journey. By the time it has reached the central Arctic, its temperature is only about one degree Celsius, but it is still by far the warmest water there. It circulates counter-clockwise through the Arctic as a narrow boundary current. One part of this boundary current flows along the continental slope throughout the entire Arctic. Additional portions branch off at the three submarine ridges that divide the central Arctic into the Canada, Makarov, Amundsen and Nansen Basins. If this Atlantic Water were to rise to the surface, the days of the sea ice would be numbered, because its heat energy would be sufficient to melt great volumes of ice.

The Arctic Deep Water

Beneath the Atlantic Water, at the greatest depths of the Arctic Ocean, flow the coldest and most saline water masses of the Arctic Ocean: the Arctic Deep Water. This is heavy water that has travelled down the continental slope in narrow, shallow channels from the shelf seas, and along its way mixed with the salty Atlantic Water. These descending streams are also affected by the Coriolis force. It deflects the water to the right so that it travels through the entire Arctic Ocean along the continental shelf on its way to the deep sea. The upper part of these water masses, in turn, ultimately leaves the Arctic Ocean through the Fram Strait.

The relatively stable stratification of the water masses in the Arctic Ocean has so far prevented the heat coming in from the Atlantic from rising to the sea surface, where it would present a serious threat to the Arctic sea ice. In the course of climate change, however, researchers expect to see far-reaching changes in the interactions between the ocean and sea ice.

Continental-scale ice sheets

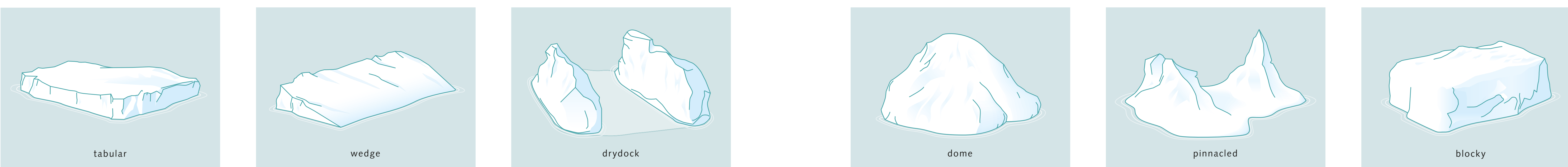
The amount of ice incorporated in the ice sheets of Greenland and Antarctica is difficult for the human mind to conceive. The polar ice sheets are the largest contiguous ice masses on the Earth. In order to illustrate their magnitude, impressive statistics of their mass are often cited. They incorporate around 99 per cent of the Earth’s total ice mass and, with a total area of 15.6 million square kilometres, they cover around 9.5 per cent of the land area of our planet. For illustration, the entire area of Germany could be covered almost five times by the Greenland Ice Sheet and almost 39 times by the inland ice of Antarctica.

The ice sheet of Greenland is up to 3300 metres thick and that of Antarctica as thick as 4900 metres. Together they store a volume of ice that, if completely melted, would cause global sea level to rise by around 65 metres. The ice sheets of West and East Antarctica have a combined ice volume of 26.37 million cubic kilometres, and the inland ice of Greenland around three million cubic kilometres.

Each of the ice sheets is surrounded by glaciers, through which the ice formed in the continental interior flows towards the sea. Researchers have counted 13,880 glaciers in Greenland alone. Many of them culminate in fiords, where icebergs can break off at the glacier’s leading edge, called the calving front. By contrast, in Antarctica the ice masses of multiple glaciers often converge on a coastal segment to form a large ice tongue that protrudes out into the sea. These floating extensions of the glaciers are called ice shelves. Icebergs also break off at these calving fronts, but as a rule they are considerably larger than those in Greenland. Because of their shape, Antarctic icebergs are commonly referred to as tabular icebergs.

The significance of the ice sheets for the climate of the polar regions is primarily due to the high albedo effect of the seemingly endless white ice surfaces. In regions

Tabular iceberg
A freshly calved tabular iceberg has a flat, level surface and nearly vertical flanks. In the Antarctic these icebergs can be up to 160 kilometres long and tens of kilometres wide. As a rule, they are 200 to 400 metres thick and rise 30 to 50 metres above the water surface. Similarly shaped icebergs in the Arctic are generally much smaller.



2.28 > No two icebergs are the same, largely because waves and winds always affect the ice masses in different ways. Nevertheless, six fundamentally different types of iceberg can be distinguished.

2.29 > At the centre of every snow crystal there is a small dust particle, around which water vapour from the air condenses and freezes to ice. Snow, however, does not usually fall in the form of single crystals, but as flakes that are composed of several interconnected snow crystals.

where freshly fallen snow lies on the ice sheet, up to 90 per cent of the incident solar radiation may be reflected. Even without a snow cover this value is still around 55 to 60 per cent. Through the glaciers and ice shelves, continental ice sheets also have an impact on the oceans. Where glaciers are calving, where meltwater is flowing into the sea, or where ice shelves and floating glacier tongues melt on the underside, fresh water is released directly into the ocean. Conversely, the growth of ice sheets and glaciers also removes large amounts of moisture from the water cycle. In the Antarctic, for example, the amount of snow that falls on the inland ice annually would be enough to raise global sea level by six millimetres. In the Southern Ocean, the floating glacier tongues and ice shelves also play a decisive role in the formation of deep water, and thus also in driving the global ocean currents. And finally, the growth and shrinking of the ice masses on land can serve as an indicator of developments in the global climate. Shrinking of the ice sheets and glaciers is a fairly certain sign of global warming, while an increase in their masses would suggest cooling of the world climate.

From snow to ice in three steps

Ice sheets and glaciers form in polar or high-altitude regions where more snow falls in winter than melts, evaporates, or is otherwise lost, such as through the breaking-off of icebergs, in the summer. However, in order for compacted glacial ice to form from a loose powder of snow, pressure and a fairly large amount of time are necessary, as is illustrated by the formation of ice in Greenland.

When new snow falls on the inland ice of Greenland, it has a density of 50 to 70 kilograms per cubic metre. This is because new snow is a relatively light material that contains a great deal of air compared to water in its liquid

form. Freshwater, for example, has a density of 1000 kilograms per cubic metre. As soon as the snow falls its metamorphosis begins, which proceeds in a similar way through three phases everywhere in the world.

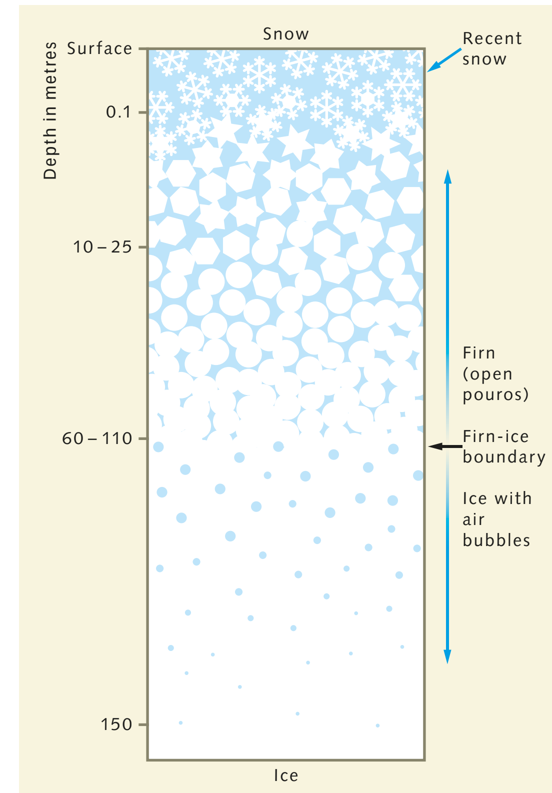
1. Snow compaction

First, the snow crystals are transported or blown about by the wind, which tends to break off their fine crystalline branches. In this, and other ways, every snowflake transforms to a granule of snow that resembles a tiny ball. This is driven by the physical principle of the minimization of surface energy. Spherical bodies have the minimum surface energy, and snow crystals, too, take on a spherical shape with time. Because of this shape, the snow can now also settle and be compacted. Many more spherical snow granules can fit into a given volume than fine-structured branching snow crystals. However, at this point the snow grains are not yet sticking together. If a shovel were used to dig into this top layer of snow, the individual snow grains would roll loosely off the blade.

2. Firn formation

Because the inland air temperature of Greenland rarely rises above zero degrees Celsius, even in the summer, the snow of a single winter generally remains unmelted. The following winter, when new snow falls onto the old snow, the weight of the new snow slowly compresses the underlying layers. The loose snow granules lying adjacent to one another now begin to bond with and adhere to their neighbouring grains. It almost appears as though the larger snow grains are consuming the smaller ones, because they continue to grow over the years. If one were to dig a pit in the snow at this point and repeat the shovel test at a depth of about one metre, the snow would remain on the shovel as a fairly solid block. Specialists call these coherent snow layers firn.

In the upper part of the firn layer the compressed material has a density of around 350 kilograms per cubic metre. In this phase it is still porous as a sponge, and air can circulate freely through it. But the more snow that falls on the surface of the ice sheet above, the greater the pressure on the deeper layers becomes. The ice crystals

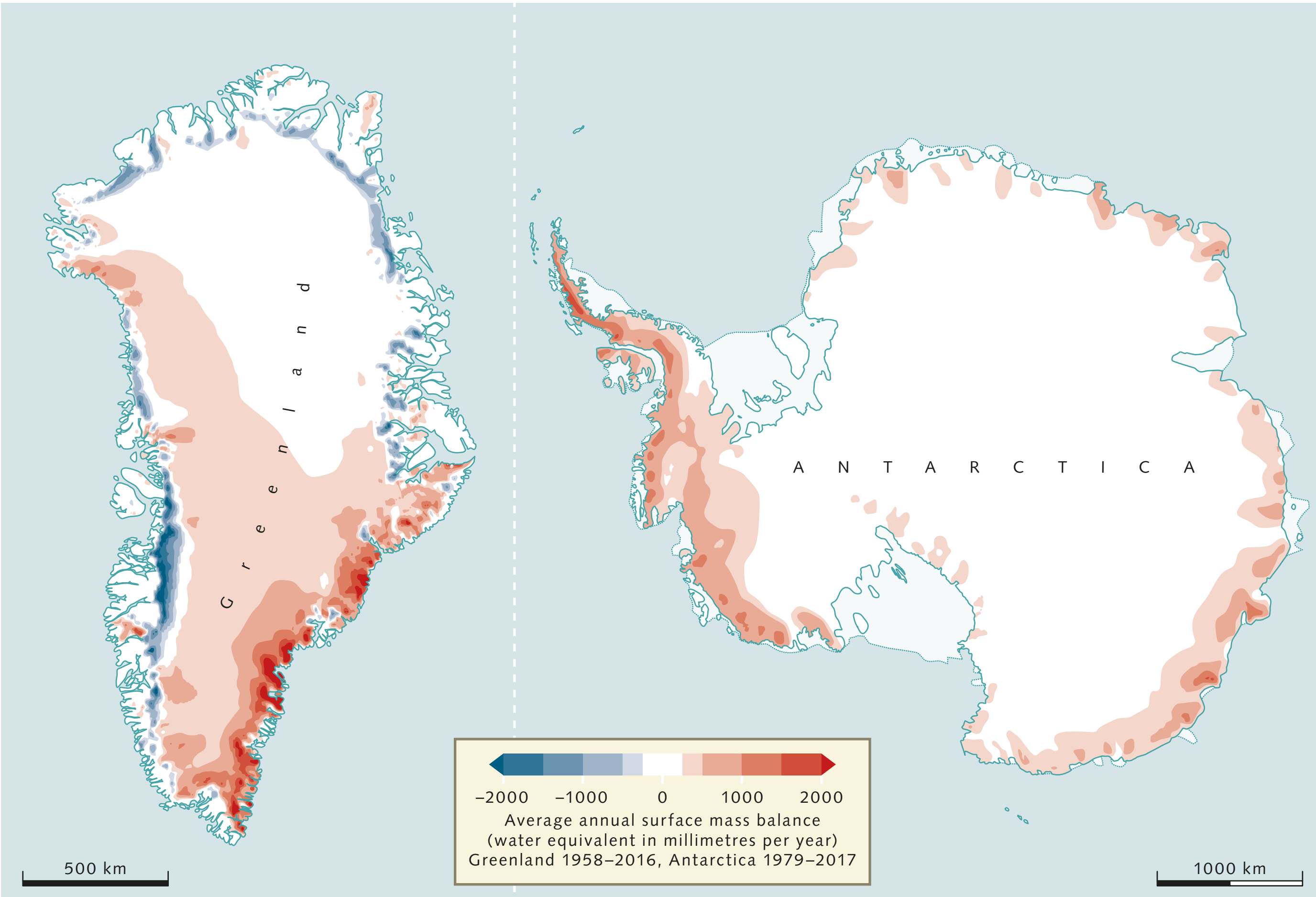


2.30 > Glacial ice forms from snow, which initially compacts to firn and with continued compaction becomes ice. The speed and depth at which this process occurs depends, among other things, on how much new snow falls on the glacier's surface to increase the pressure on the underlying layers.

in the firn grow and press closer together, and the pore spaces become narrower.

3. Ice formation

The compaction through settling processes and the growth of ice crystals ultimately produces a maximum density of 550 kilograms per cubic metre. However, as the snow load and resulting pressure from above continues to increase, pressure sintering commences. This means that the ice crystals fuse with each other. The pores close off and are sealed so that all of the air that was not able to escape is trapped in small bubbles. The point in time that this blockage of air flow occurs, and at what depth it occurs, depends on both the amount of annual snow accumulation and the temperature of the firn. In regions with higher snowfall, pore closure generally happens sooner than in areas with less snowfall. The same applies to firn that is warmer. The ice grains are cemented together more readily than they are in a very cold firn. In Greenland, as



2.31 > Whether there is a positive or negative surface mass balance in an ice sheet depends on how much snow has fallen and what portion of it is lost through melting, wind transport or sublimation.

a rule, sealing occurs at a depth of 60 to 110 metres. At this point the material has a density of around 830 kilograms per cubic metre.

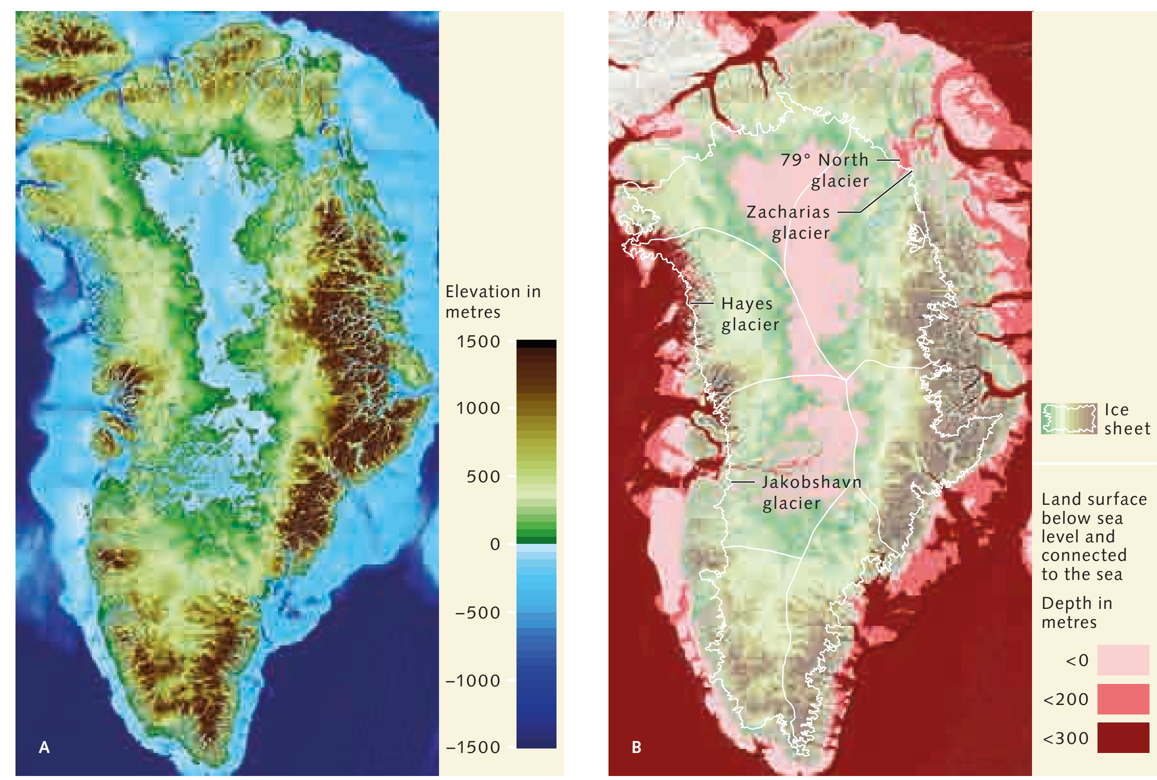
When the air can no longer escape, the state of ice has been reached. On the sub-Antarctic islands, researchers can recognize the firn-to-ice transition zone by a thick layer of refrozen meltwater in the ice body. During the summer there, snow on the glacier surface melts and the meltwater seeps down into the firn as deeply as the pores in the material allow. At the firn-ice transition it is blocked and then freezes again.

But the formation of glacial ice does not end with the sealing of the pore spaces. When the sheet of snow, firn and ice is several hundred metres thick, there is so much weight on the lower layers, and especially on the air bubbles, that the air within them crystallizes out. This means that all of the molecules contained in the bubbles are incorporated into the crystal structure of the ice. This applies to the gas molecules as well as to dust particles or other impurities in the air. Ultimately, a very dense, bubble-free ice forms that is characterized by its blue colour. When natural light shines on this ice, it absorbs a small portion of the red light, so that humans perceive the ice as having a slightly bluish hue. Glacial ice that appears to be more white, on the other hand, generally still contains many air bubbles.

How rapidly a glacier or ice sheet grows depends, among other things, on the amount of precipitation that falls on it. In West Antarctica up to four metres of new snow fall annually, with as much as six metres in the

northern Antarctic Peninsula and on the coast of Wilkes Land, although these are only approximate values. Researchers always specify the amount of precipitation in terms of water equivalent (WE). This refers to the height of a water column that would result if the snow were to melt. In West Antarctica the precipitation would have a water equivalent of up to 1200 millimetres, or that same number of litres per square metre, while on the Antarctic Peninsula and in Wilkes Land it would come to 1800 millimetres (or litres). In order to derive the precise snow thicknesses from this, one would have to accurately know the density of the snow, which is seldom possible for large areas. Therefore, an estimate is commonly applied. One cubic metre of fresh snow yields a water column with a height of about 300 to 350 millimetres. The snow depths for the coastal areas of West Antarctica and Wilkes Land given above are derived by applying this approximation. In the centre of the continent, on the other hand, only a few centimetres of new snow fall each year. At the US American Amundsen-Scott South Pole Station, for example, between 1983 and 2010, meteorologists documented an annual snow accumulation of 27.4 centimetres, whereby this value also includes snow that was blown by the wind into the measurement field.

Most of the snow in Greenland falls on the southeast coast. Satellite data indicate that the new snow there drifts to heights of up to ten metres. The northern part of the island, by comparison, is very dry. Here, for the most part, less than 30 centimetres fall annually. The question then immediately arises as to how much of this new snow melts or evaporates during the summer and how much remains. Up until 30 years ago, this was just under half of the total snow in Greenland. Of the 750 gigatonnes of snow that fell during the winter about 350 gigatonnes survived to the end of summer. Today only around 200 gigatonnes remain through the summer. On the continent of Antarctica, excluding the ice shelf, around 2236 gigatonnes of snow fall each winter, of which about 50 gigatonnes are lost due to melting, particularly on the Antarctic Peninsula. An additional 84 gigatonnes of snow



2.32 > The topography of the land surface beneath an ice sheet has a great influence on how the ice masses flow and whether warm sea water can pose a threat to them. These two ice-free depictions of Greenland illustrate that the central region of the island actually lies below sea level (A) and it is directly connected by fiords to the sea (B). Also clearly recognizable are the deep channels through which the warm Atlantic Waters can encroach onto the shelf and into the fiords.

evaporate by sublimation. Most of the remaining snow compacts into ice.

Why does ice flow?

When a glacier or ice sheet has reached a certain size, the ice masses begin to move. Alpine glaciers, which are found in high mountainous areas such as the Alps or the Rocky Mountains, always travel down towards the valleys, a phenomenon that every skier and sledge rider can confirm from personal experience. But why do ice masses that lie on level terrain or in a valley also move? The Greenland Ice Sheet, for example, largely rests in a kind of basin, as the map of the island's underlying land surface shows. Still, its ice masses flow toward the outer margins.

The explanation for this is rather complex. Basically, large masses of ice move because the glacial ice either deforms under its own weight or because it glides on a slick subsurface. Usually it is a combination of the two processes. A key difference between them, however, is that gliding always requires a thin film of melt water on which the ice can slide, while the deformation can occur in a completely frozen state.

To help in understanding the deformation process, an ice sheet can be compared to a huge, viscous mass of cake batter piled onto a flat working surface, to which more dough is added one spoonful at a time. With the initial additions, the shape of the mound will not change substantially. Over a longer time, however, the mass in the centre will become so great that the dough begins to flow away towards the edges.

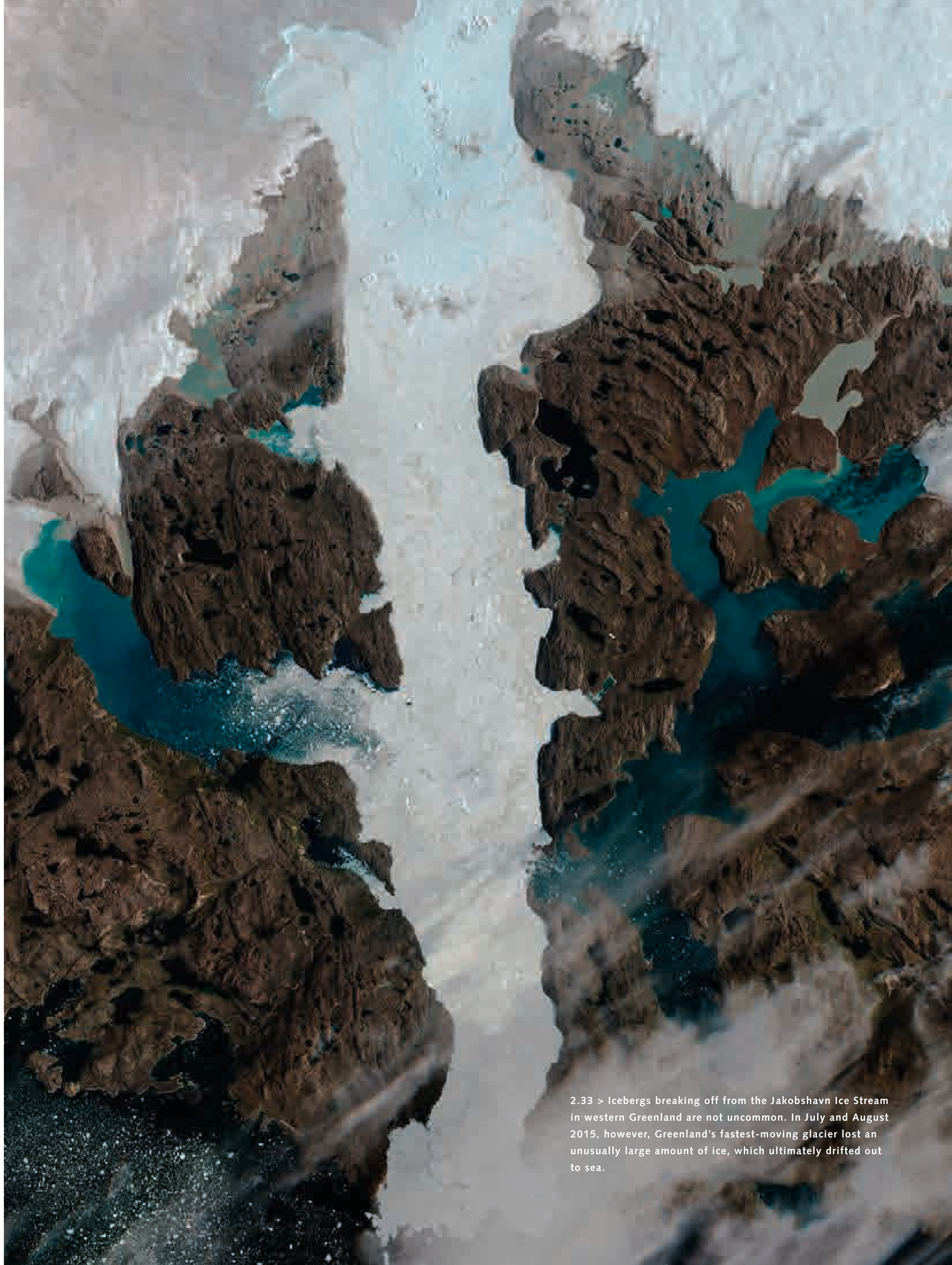
A large ice sheet responds in a similar way. With every new layer of snow the total amount of material increases. The pressure on the underlying ice masses increases, causing them to deform and flow toward the edges. As the deformation progresses, shear heat is generated within the ice sheet. This warms the ice and thus further accelerates the flow, because warmer ice deforms more easily.

The deformation processes alone, however, are not sufficient to cause ice streams, and especially glaciers, to move at the rapid speeds that scientists are observing today. The ice masses primarily gain speed by basal sliding. On a thin film of lubricating meltwater they glide down an incline like a sledge. In Greenland, under certain conditions, this meltwater can originate from the ice surface. In the summer it collects there in large meltwater lakes. In some of these lakes, the water then drains through cracks, crevices or tunnels in the ice down to the underside of the glacier, where it becomes the gliding film responsible for acceleration. As a rule, however, melting at the base of the ice sheet primarily occurs due to geothermal heat from the Earth below. This does not require a large amount of heat because, beneath thousands of metres of ice, the melting point at its base is reduced due to the high load pressure. It can therefore melt at a temperature of around minus two or minus 1.5 degrees Celsius. Still, however, the ice sheets only lose a few millimetres of ice on their underside each year due to melting.

Ice streams

To date, scientists are only beginning to understand the processes of gliding glacial ice. On the one hand, movement is influenced by the nature of the underlying landscape. On the other hand, sliding generates frictional heat, which melts a small amount of ice and warms the lower ice layers. As a result, these ice layers deform more easily, which can further accelerate the flow of ice.

In the Antarctic, about 30 outlet glaciers and ice streams transport ice into the sea. Researchers refer to large bands of flowing ice within an ice sheet as ice streams. These are generally distinguished from the surrounding ice by their flow velocity and direction, and they flow into glaciers at the outer margins of the ice sheet. Science still has no clear explanation as to why ice streams form or what mechanisms regulate their ice-mass transport, because hardly any two streams are alike. Some flow constantly, for example, and others only intermittently. Ice streams can also change their flow direction, abruptly increase their speed, or slow down significantly. There must therefore be a number of influencing factors. Researchers have identified the following seven parameters:



2.33 > Icebergs breaking off from the Jakobshavn Ice Stream in western Greenland are not uncommon. In July and August 2015, however, Greenland's fastest-moving glacier lost an unusually large amount of ice, which ultimately drifted out to sea.

1. Topographic constraint

The presence of a valley in the underlying bedrock restricts the ice masses at depth. In order to maintain speed with the upper layers, the ice masses at depth have to flow faster. Furthermore, the total friction surface at the base is larger. This generates more heat, which causes the ice on the underside to melt, and likewise increases the speed of flow. The best-known example of an ice stream whose origin can be related to topographic constriction is the Jakobshavn Ice Stream in western Greenland. At depth, its ice masses flow through a valley that is up to 2000 metres deep in some places, facilitating a velocity of the ice stream of as much as 17 kilometres per year.

2. Topographic steps

When an ice sheet flows across a steep cliff or similar abrupt topographic step, the deformation and acceleration of the ice is especially enhanced because of its great weight and the pull of gravity. At the same time, it is warmed, which further facilitates the amount and rate of deformation. The total flow speed of the ice thus increases. Well known glaciers that accelerate in this manner include the Byrd and the Thwaites Glaciers in West Antarctica.

3. Unevenness of the bedrock

There is still very little known about the topography below the large ice sheets. Researchers assume with some confidence, however, that various surface features such as rock outcrops, hills and small ditches can have a considerable influence on the flow velocity and direction of an ice stream. The more of these that are present, producing an uneven gliding surface, the slower the ice masses flow. In other words, the ice masses can flow more easily on a smooth bedrock surface than on a coarse one. This effect is observed in the Möller Ice Stream in West Antarctica.

4. Break-off of icebergs

When icebergs break off at the calving front of a floating glacier or ice shelf and ice is lost, a self-sustaining process is initiated. First, the ice masses in the stream behind the front accelerate. With this motion the ice of the entire stream warms up so it deforms more easily. Furthermore, on its underside, due to the increased friction, more lubricating meltwater is produced on which the ice masses can glide. These two processes result in an increase in the speed of the ice stream. The Jakobshavn Ice Stream in West Greenland again shows how effective this self-reinforcement can be. After an unusually high number of icebergs calved at its head between 1992 and 2004, such that the glacier tongue barely reached the fiord, its flow speed tripled to 17 kilometres per year.

5. Deformable sediments beneath the ice sheet

The ground below the ice sheet is not composed of hard bare rocks everywhere. In many places the upper ground layer is predominantly made up of gravel or other fine-grained sediment deposits. On this kind of soft ground the ice masses of an ice sheet glide much more easily than on a hard surface for three reasons:

- Firstly, the sediments, as a covering layer, smooth out existing irregularities in the subsurface and thus reduce its unevenness.
- Secondly, a sediment layer saturated with melt water creates an optimal sliding surface. Anyone who has slipped in the mud as a child knows that this sliding effect is not experienced on a dry, paved or asphalted surface.
- And thirdly, sediment deposits are easily deformed under the weight of the ice. Under some circumstances, they may even slip themselves and thus clear the way or accelerate the ice flow.

Researchers have found evidence for these three explanations in the Whillans Ice Stream in West Antarctica. Its ice masses lie atop a five-metre-thick unfrozen sediment layer that separates the ice stream from the rocky substrate below and accelerates its flow speed in the ways described above. Some scientific opinion now even suggests that a soft subsoil is one of the basic prerequisites for the generation of ice streams. According to one hypothesis, only where the ice sheets are underlain by sediment deposits, usually in basins, can ice streams originate and their ice masses glide at great speeds. This, however, is not consistent with the fact that there are also ice streams overlying bare rock that still carry large amounts of ice with them. The true role of the subsurface will therefore remain an object of research for some time to come.

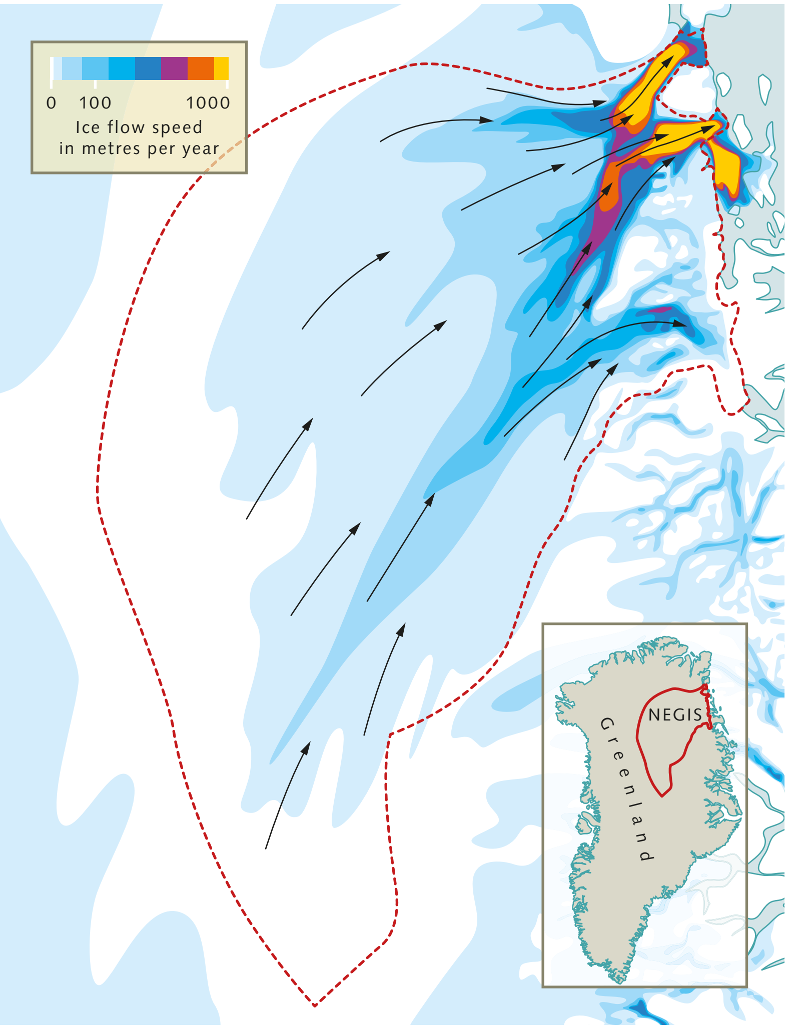
6. Geothermal heat

The larger the meltwater film is on its underside, the faster glacial ice moves. Meltwater, in turn, is produced by heat, which can also originate from within the Earth. This geothermal heat plays an important role, particularly in regions where active volcanoes are located beneath the ice sheet, or where the Earth's crust is especially thin. Scientists have found evidence for both of these phenomena in West Antarctica. Geothermal heat has also been suggested as a possible explanation for the origin of the Northeast Greenland Ice Stream (NEGIS). This is Greenland's only ice stream. Its catchment area covers twelve per cent of the total area of Greenland's inland ice and it is the connection between the ice and the ocean. In the area of its origin, the Earth's crust releases almost 20 times more heat than Greenland's overall average.

7. Meltwater lakes and rivers

As more details about the topography of the land surface beneath the ice sheets in Antarctica and Greenland are discovered, it is becoming clear that some ice streams originate in regions where the subsurface gradient alone is not sufficient to initiate the flow of ice. The area where the Recovery Ice Stream begins in East Antarctica is just one example of many. Theoretically the ice in this part of East Antarctica should hardly move at all. In fact, however, the stream transports its ice masses at a speed of ten to 400 metres per year from the high plateau of the East Antarctic Ice Sheet down towards the Weddell Sea. Its catchment area spreads inland for about 1000 kilometres from the Filchner-Ronne Ice Shelf on the coast, and is equal to an area almost three times as large as Germany. It is an enormous ice stream that researchers previously thought might be receiving the decisive impetus for its formation from overflowing meltwater lakes beneath the ice sheet. The basic idea was that these lakes occasionally overflow, creating a lubricating film on which the ice sheet slides like an aquaplaning car.

The existence of subglacial lakes in Antarctica is known from Russian and British research projects at Lake Vostok and Lake Ellsworth. Both of these water bodies formed in depressions beneath the ice sheet. Over the course of many millennia, so much melt water has accumulated in them that, as a rule, they are larger than Lake Constance. But the assumption that these kinds of huge lakes are present in abundance beneath the Antarctic Ice Sheet, and that they are responsible for initiating the ice streams could not be confirmed by German polar scientists in a field study of the Recovery Ice Stream. Every-

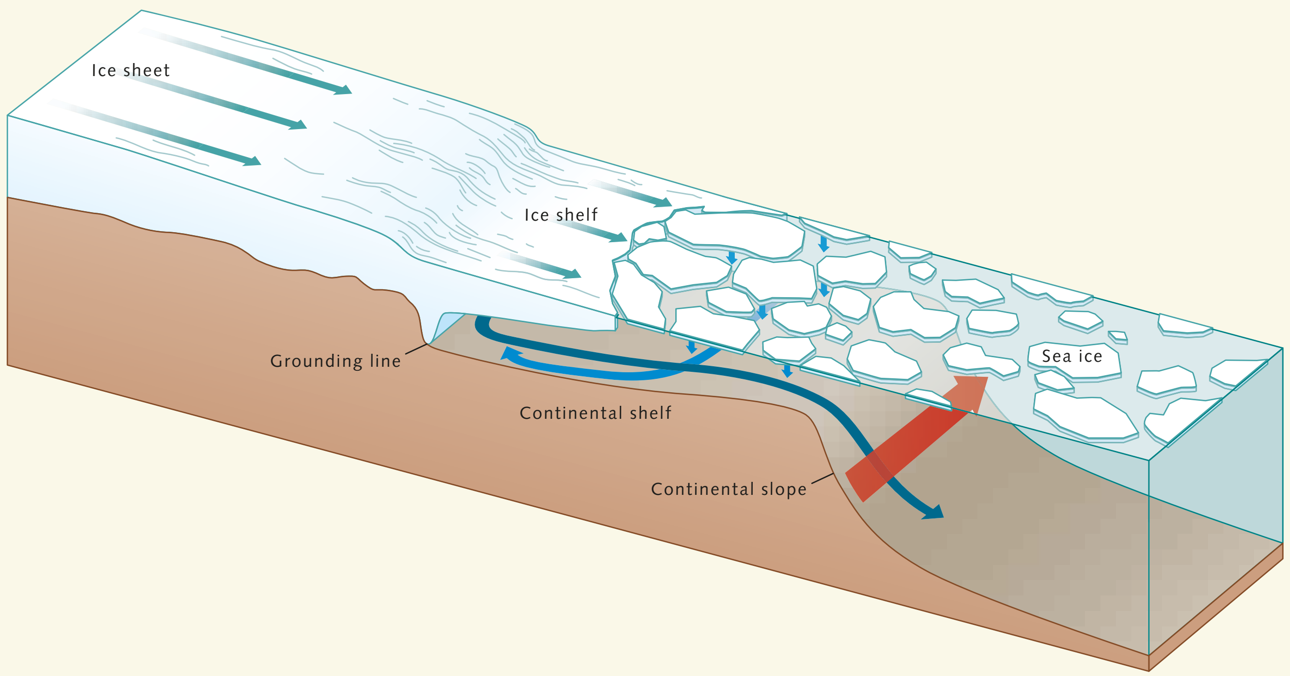


2.34 > The NEGIS catchment area extends far into the interior of Greenland. From there it transports the ice masses towards the northeast where they reach the sea through three glaciers.

Ice shelf and ocean – a give-and-take relationship

By definition, ice shelves come into large-scale contact with the sea. The Southern Ocean water masses have a decisive influence on the stability and mass balance of the ice sheets. As an example, on the continental shelf of the southern Weddell Sea, where the sea floor slopes towards the land, highly saline, cold shelf water with a temperature of about minus 1.9 degrees Celsius flows just above the seabed for a distance of up to a thousand kilometres, reaching far under the Filchner-Ronne Ice Shelf. The further the water masses penetrate under the ice sheet, the more destructive they are for the ice. This is because the water sinks deeper with every metre that it travels towards the coast. The water pressure under the ice shelf therefore increases and, correspondingly, the freezing point of the water drops from minus 1.9 degrees Celsius to minus 2.5 degrees Celsius. The result of this change is that the cold shelf water deep under the ice sheet does not freeze, but releases its residual heat to the ice and cools down even further. The loss of heat has two consequences: First, the coldest water masses in the world, known as ice-shelf water, form underneath the ice shelf. Its initial temperature is minus 2.5 degrees Celsius. Second, the ice shelf melts from the bottom (basal melting) because of the heat released by the inflowing water. When the ice melts, freshwater is released, thus diluting the super-cold ice-shelf water. Its density decreases and it rises up to meet the underside of the ice shelf. It then flows back to the shelf-ice margin.

On its way there, the freezing point of the ice-shelf water continues to rise due to decreasing pressure. As a result, salt-free ice crystals form in the super-cold ice-shelf water, which then rise to attach to the underside of the ice and freeze there. Scientists refer to this new ice as marine ice. The remaining water masses continue to drift further. Measurements at the shelf-ice edge have revealed that the ice-shelf water flows out from beneath the ice with a temperature below minus 2.2 degrees Celsius, and that it ultimately becomes a part of the Antarctic Deep Water. Ice shelves are therefore intimately interconnected with the deep ocean. While the ocean regulates the thickness of the ice shelf, the ice shelf cools the migrating water masses of the shelf sea and contributes to driving the thermohaline circulation.



2.35 > When sea ice forms in the Weddell Sea, cold, highly saline shelf water is created that flows beneath the Filchner-Ronne Ice Shelf where it cools still further. It ultimately flows down the continental slope as super-cold ice-shelf water.

where the researchers predicted the presence of water under the ice they were unable to detect it.

The exact role of subglacial lakes is thus still uncertain, as is the question of the general distribution of meltwater under the ice sheets. The paths of presumed streams and rivers beneath the ice have so far only been predicted by computer simulations. Initial efforts have also been made to derive this information from satellite data. However, measurement methods for detecting and mapping large-scale lake chains or river networks are not yet available.

How ice shelves retard glacial flow

More than half of the Antarctic coast is bounded by ice shelves. The more than 300 floating glacier tongues are all extensions of one or more glaciers that slowly push their coherent ice masses out into the Southern Ocean. The leading edge of the Larsen C Ice Shelf in the western Weddell Sea, for example, moves at a rate of around 700 metres annually. Expansion of the ice sheet is limited only by the loss of ice due to icebergs breaking away from the calving front at regular intervals. On large ice shelves, it can take more than a thousand years for an ice crystal to travel through the entire ice shelf and commence the final stage of its journey aboard an iceberg.

Ice shelves in the Antarctic are, as a rule, between 300 and 2500 metres thick, although they become thinner the further they extend out into the sea. They are thickest at the grounding line, the furthest seaward point where the ice is still in contact with the bottom and where it begins to float. In the Antarctic region ice shelves cover a total area of 1.3 million square kilometres. The largest ice shelf, the Ross Ice Shelf in the Ross Sea, is almost as large as Spain.

Ice shelves are fed primarily by the ice of the glaciers and ice streams behind them. However, their volume can also increase when snow falls on the ice shelf or the offshore sea ice and subsequently condenses in some areas to form firn and ice. In other places seawater can freeze onto the underside of the ice shelf and contribute to the growth of the ice tongue. Ice shelves lose ice through the calving of icebergs, but warm water masses can also melt the ice tongues from below. Researchers refer to this process as basal melting of the ice shelf.

The ice shelf is considered to be in a state of equilibrium if it loses the same amount or less ice than flows in through the glaciers. In this state, the floating ice tongues can survive for several millennia. But if the rate of ice loss increases abruptly there is reason for concern, because the ice shelves perform a critical and elementary function in the Earth's climate system. They inhibit the flow of further ice masses from the interior and thus also slow the rise in sea level.

To clearly understand this role, one has to look again at their formation. As floating extensions of one or more glaciers, the ice masses of the ice shelf have a long journey behind them, from the high plateau in the Antarctic interior, through ice streams and glaciers down to the sea. Then, extending out from the coast as large floating sheets and pushed out into the sea, the ice can get caught up on islands or rocks. Ice shelves can sometimes skim over flat obstacles, or they may collide with an island that abruptly applies the brakes to the ice flow. The thicker the ice shelf is, the more effective it is at holding back the inland ice masses.

The amount of pressure the ice shelves have to withstand is perhaps best illustrated by the fact that, through the glaciers and ice shelves, 74 per cent of Antarctica's inland ice reaches the sea. When the Larsen B Ice Shelf on the Antarctic Peninsula broke into thousands of icebergs in 2002, which led to a loss of its braking function, the flow rate of the glaciers behind it increased by a factor of three to eight times within the following 18 months.

Floating glacier tongues are also found in the Arctic, of course, especially in Greenland and on the coast of Canada's Ellesmere Island. These ice areas, however, which are firmly attached to the land, are not usually referred to as ice shelves because they primarily occur in fiords and the width of their expansion is thus limited by land. For this reason, specialists refer to this floating ice from the land as ice tongues. The Ward-Hunt Ice Shelf off the coast of Ellesmere Island is an exception. It is made up of consolidated sea ice, onto which snow fell and was compacted into ice. This ice mass is therefore not land ice and so it is distinctively different from the large ice sheets of Antarctica.

The drifting paths of icebergs

The calving of substantial icebergs at the leading edge of a glacier or ice shelf is a completely natural process. At regular intervals, ice shelves in the Antarctic release tabular icebergs with surface areas that can be as large as cities such as Hamburg or Berlin. The size of an iceberg also determines its subsequent fate, at least in the Antarctic. Icebergs that are less than two kilometres long or wide drift away from the edge of the ice shelf or glacier and out of the coastal region within a few months. Thereupon, offshore winds force them out onto the open sea, where they break into smaller pieces and melt within one to two years.

But the offshore winds play a less important role for icebergs that are larger than two kilometres in diameter. Their movement, in contrast to their larger siblings, is primarily driven by their own weight. To understand this phenomenon, one needs to realize that the Southern Ocean is not actually a flat surface. Because of the prevailing winds, its surface may be as much as 50 centimetres higher near the coast. Large, freshly calved icebergs can slide down this incline of the sea surface. Their path does not follow a straight line, however, but forms an arc due to the Coriolis force. So the icebergs are deflected towards the coast. This means that they remain within the cold coastal current for a long time and often do not reach the warmer, more northerly waters until years later, when they finally break apart and melt.

The speed at which the icebergs travel along their paths can be influenced by the topography of the sea floor. Large icebergs may often run aground and remain trapped for an indeterminate length of time. In addition, the giant icebergs often freeze onto sea ice, so that the waves can no longer strike their flanks and the effect of erosion is reduced. Scientists have tracked the pathways of drifting Antarctic icebergs and produced computer models to calculate them. Depending on the marine area in which the giant icebergs have calved, they take one of four major routes that all drifting ice follows, both sea ice and icebergs, into warmer climes. GPS data have shown that one large iceberg has even been able to completely circumnavigate Antarctica. It started in the Weddell Sea, was driven northward along the east coast of the Antarctic Peninsula, then turned back to the east and drifted once around the continent before finally melting north of the Antarctic Peninsula.

From the Arctic glacier tongues, it is more common for a fleet of numerous smaller icebergs to calve instead of a few large ones. The winds drive them out of the fiords onto the open sea where they normally drift southward with the coastal current. Many of the icebergs that reach the shipping lanes off the southern coast of Newfoundland originate from the Jakobshavn Ice Stream in western Greenland. In 2018 alone, more than 500 icebergs from the west coast of Greenland drifted into the coastal areas of Newfoundland and Labrador. In the record year of 1984 there were 2002 icebergs. For most of them this journey lasted from one to three years.

Researchers believe that there is a correlation between the prevailing atmospheric current conditions over the North Atlantic and the number of icebergs drifting so far to the south. If onshore winds blow along the coast of Labrador in winter, warmer sea air reaches this region. That air prevents the formation of sea ice. As a result, the drifting icebergs are exposed to greater levels of destructive wave power. In addition, the onshore winds push them the into shallower waters where the ice masses run aground.

If the large air-current patterns reverse, a strong cold westerly wind blows over Labrador. Icy air reaches the region in its wake. Sea ice forms from the seawater, protecting the icebergs from extensive destruction. In the following summer, they then begin their southward journey unhampered and in large numbers. But icebergs also calve on the east coast of Greenland. On 22 June 2018, for example, the Helheim Glacier lost a six-kilometre-long strip of ice in a single stroke. Greenland-wide, it was the largest iceberg to break off in the past ten years.

Conclusion

A chain reaction with an icy end

It is so extremely cold in the polar regions because of a self-reinforcing process that involves several factors. Fundamentally, it is due to the fact that much less solar energy reaches the Earth's surface in the polar regions than it does, for example, in Central Europe or at the equator. The reasons for this are the low angle of incoming sunlight, the tilt of the Earth's axis and the orbit of our planet around the sun. This combination of factors results in the polar regions being generally undersupplied with energy compared to the rest of the world, and being completely cut off from the sun's heat during the polar nights.

While the polar regions receive sparse solar radiation, the tropics receive a great deal, which results in a marked temperature contrast between the two regions. The large air and ocean currents that we see today are generated as responses to compensate for this difference. They distribute heat from the tropics around the globe and thereby determine the weather conditions throughout the world. Without the cold regions in the far north and south, these global circulation patterns of air and water masses would not exist. It is also important to note that strong bands of wind form in both hemispheres that act as protective walls to prevent heat from the tropics from reaching deep into the polar regions.

However, the freezing conditions in the Arctic and Antarctic also mean that precipitation in these regions is primarily in the form of snow, and that large areas of the polar surface waters freeze over in winter. Because the white snow and ice covers have a high reflective capability, called the albedo, a large proportion of the solar radiation is not absorbed, and thus cannot contribute to warming the surface of the Earth. In this way, the snow and ice surfaces amplify cooling in the polar regions. To scientists this kind of effect is known as positive feedback.

The fact that cold air cannot hold large amounts of water vapour is another factor that facilitates the low temperatures. Especially over central Antarctica, the air masses lack this important heat reservoir, and thus also the capability to form a thick cloud cover. This could otherwise help to limit the cooling. Instead, the dry air amplifies the cooling effect and, in concert with the other factors, helps to create the ideal conditions for the formation of immense ice sheets, glaciers and areas of sea-ice.

The various forms of polar ice and their strong albedo are fundamental components of the cooling and climate system of our Earth. They regulate chemical and biological cycles and interact very closely with the ocean, the atmosphere and the land. However, there are numerous geographical differences between the Arctic and Antarctic regions. In the Arctic Ocean, with its shallow shelf seas, the water masses circulate in a completely different way than they do in the Southern Ocean, a ring ocean that surrounds a large continent. These regional differences likewise affect the polar ice masses. In the Antarctic the conditions result, among other things, in large-scale melting of the Southern Ocean sea ice in summer. In the Arctic, on the other hand, slightly less than half of the sea ice survives the summer, and researchers there refer to a permanent sea-ice cover. The amounts of precipitation that fall in the Arctic and Antarctic are also different, resulting in different rates of growth on the ice sheets of Greenland and Antarctica. There is, however, one thing that the ice masses of the two regions have in common – they both react very sensitively to increasing temperatures.

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

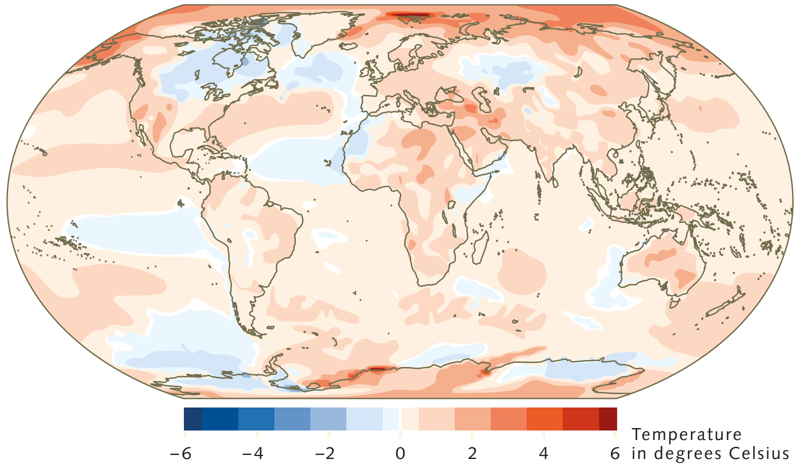
> Climate change produces more visible traces in the polar regions than it does on other parts of the Earth. This is due in part to the special sensitivity to heat of these icy worlds. But another factor is that the warming due to greenhouse gas emissions is more strongly amplified in the Arctic by a 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 refrozen 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

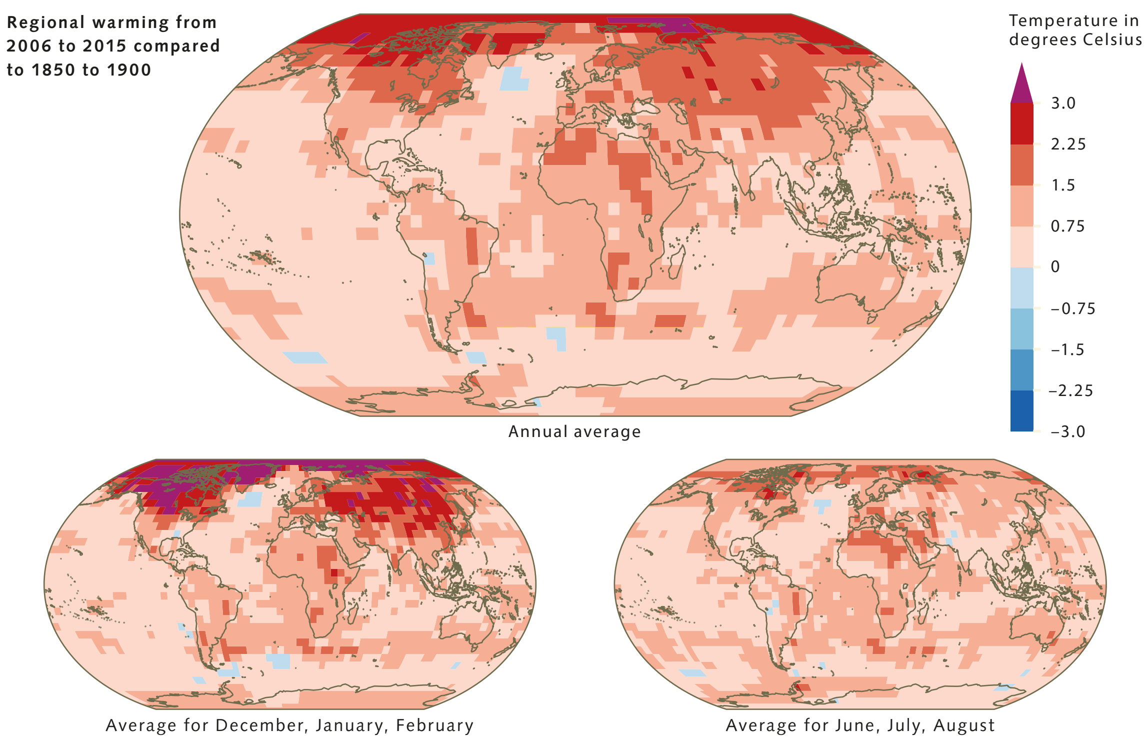
The year 2015 drew to a close with a sensational meteorological event in the Arctic. On 29 December, in the middle of the Arctic winter, the surface temperature at the North Pole rose within a single day from minus 26.8 degrees Celsius to minus 0.8 degrees Celsius. It presumably rained at the northernmost 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.

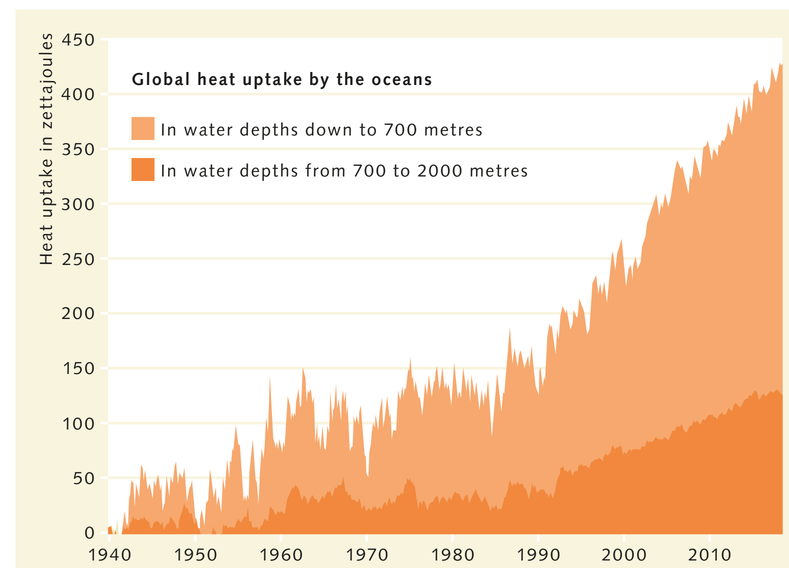
Over the remainder of the world, with the exception of central Antarctica, global warming has been developing at full force since the beginning of the 21st century. Since then, reports of record temperatures have been increasing, and major climate research institutions have begun to rank the warmest 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.

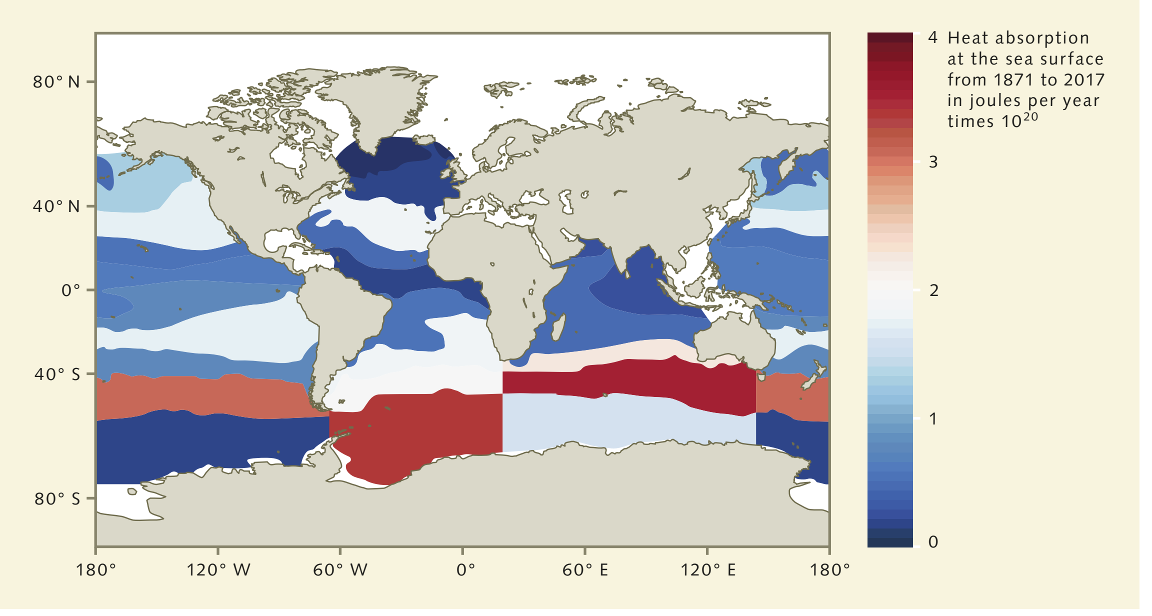
The oceans are warming

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.

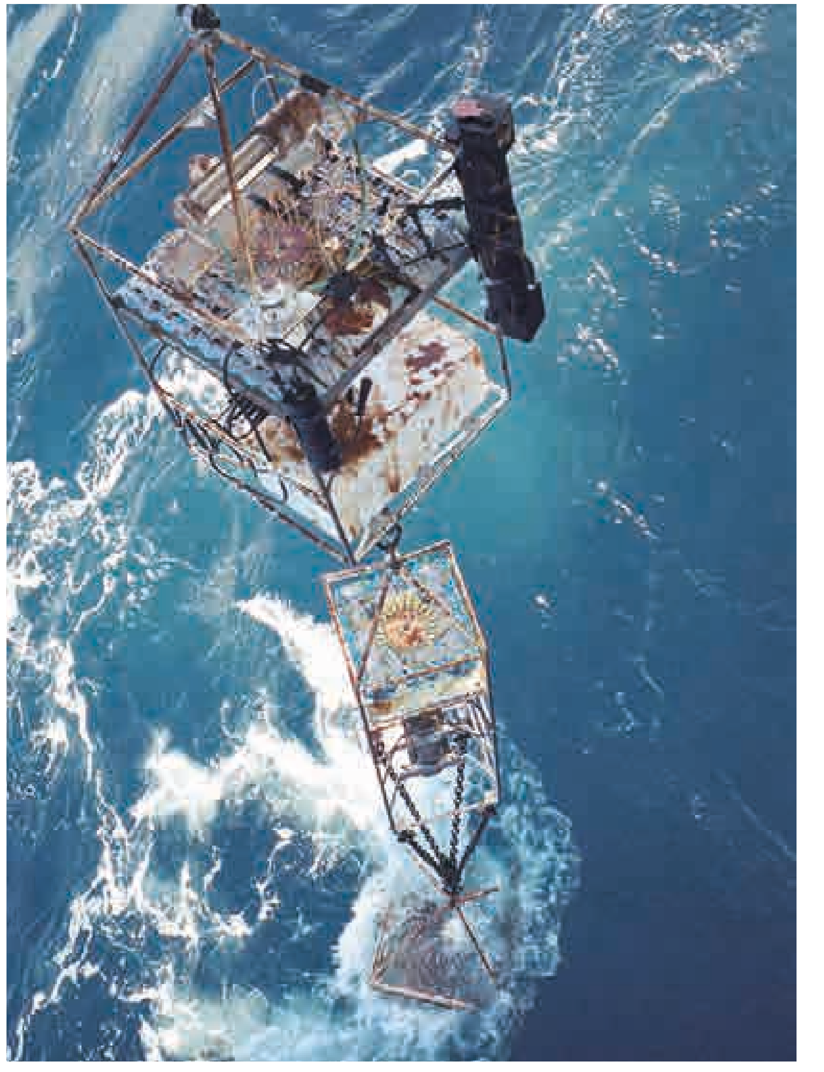
Tracking heat in the polar seas

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.

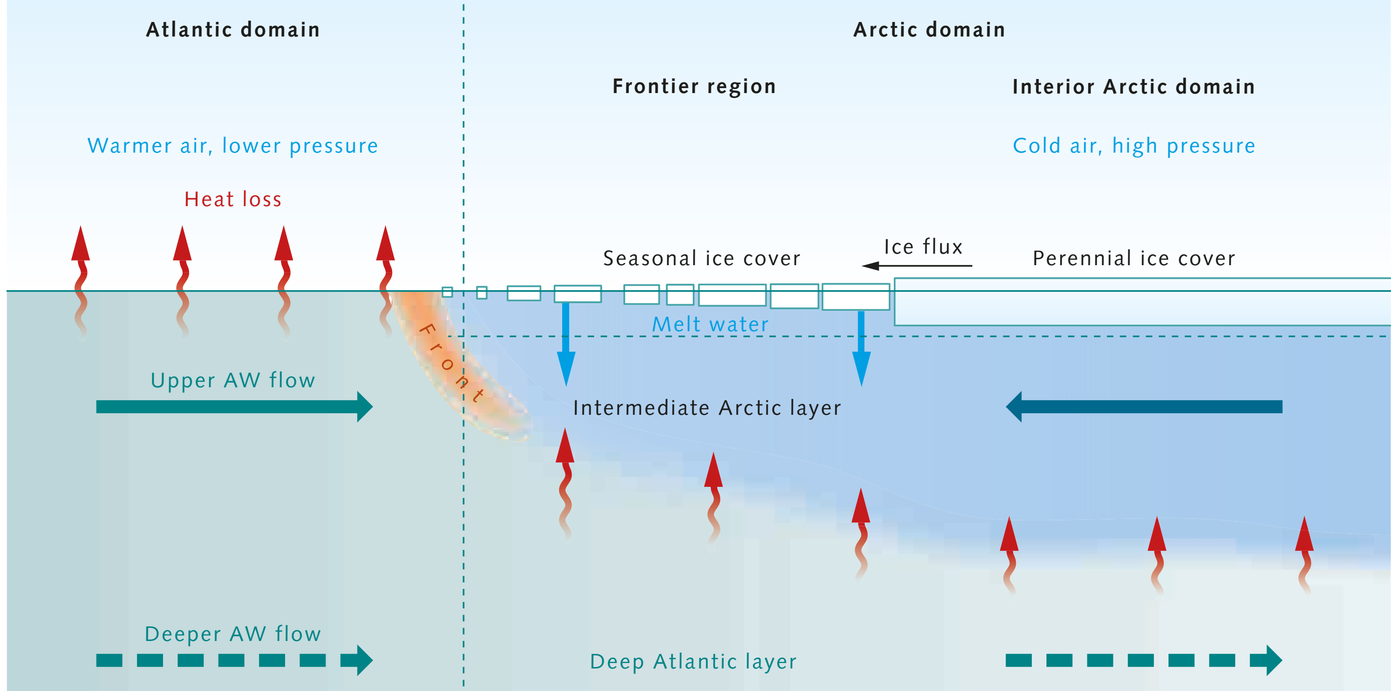
The water masses in the northern part of this sea are vertically layered in typical Arctic fashion. This pattern is characterized by sea ice floating upon a surface layer of cold, rather low salinity water, below which lies another cold but more saline layer called the halocline. These two layers protect 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.

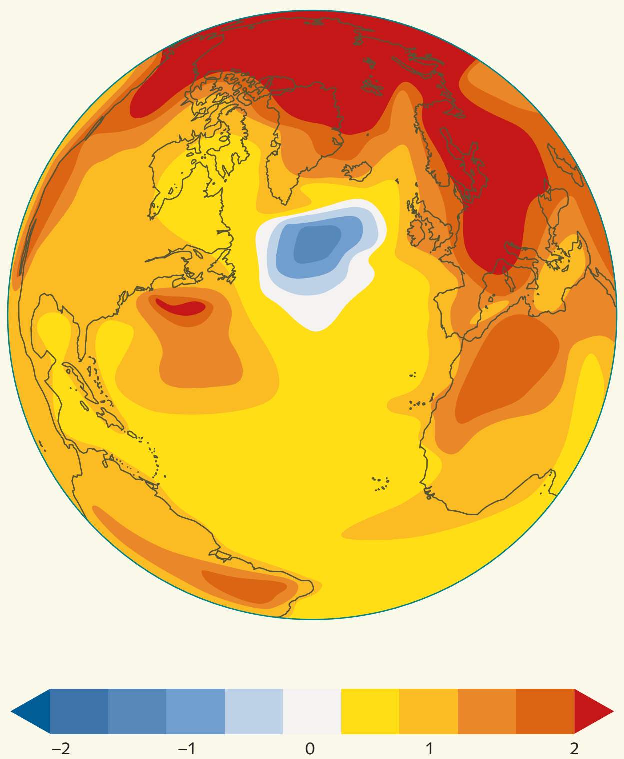
Does more freshwater in the Arctic Ocean weaken the Gulf Stream?

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.

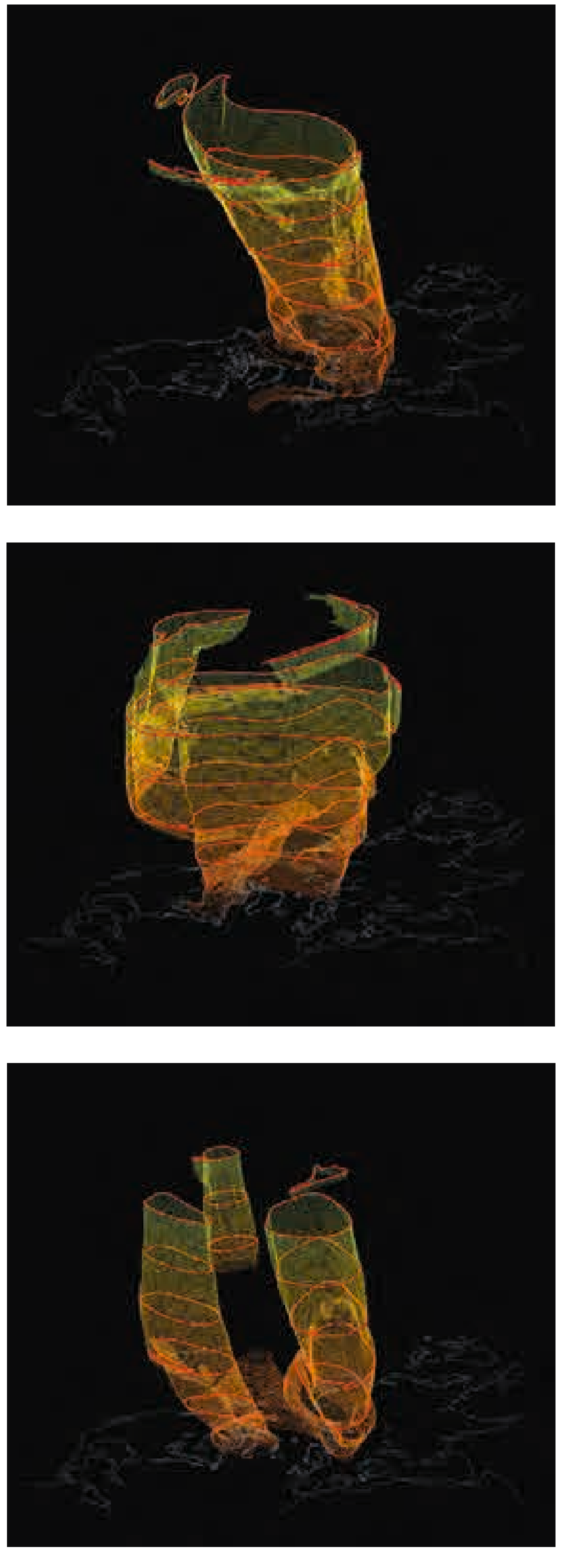
3.9 > Dirty ice: Soot and dust particles darken the surface of the Helheim Glacier in southeast Greenland.

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.

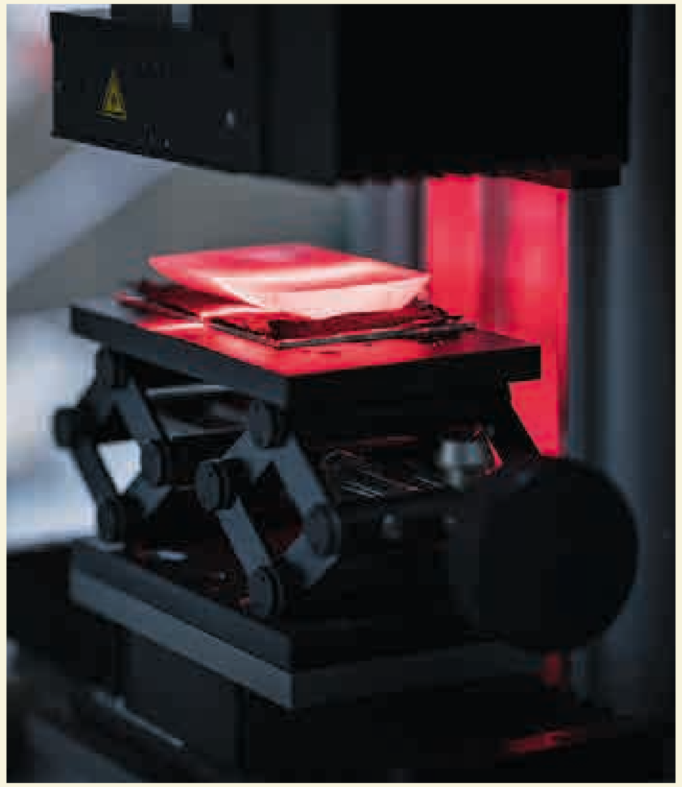
A large part of the knowledge we have about the climate history of the polar regions comes from ice cores. These are cylindrical ice samples with a diameter of ten to 15 centimetres, which researchers drill from glaciers and ice sheets using a vertical hollow drill pipe. The ice cores provide a chronological 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.

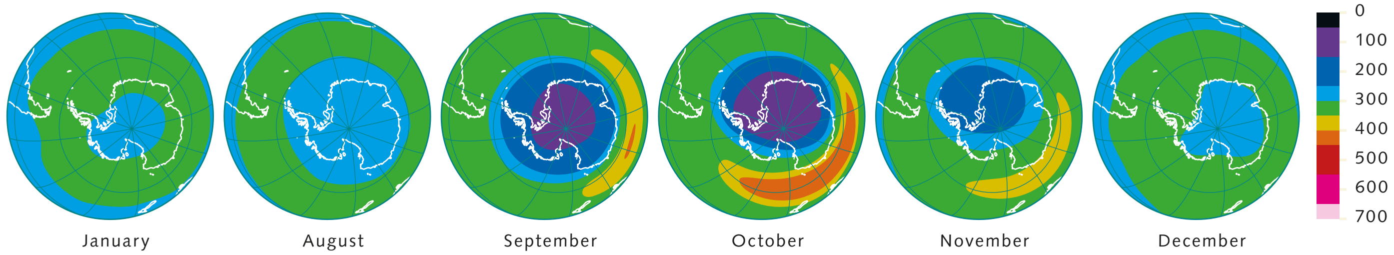
The resulting climate time series from ice cores extends back 800,000 years in the Antarctic while in Greenland it goes to 128,000 years ago. Their high resolution and level of detail have enabled fundamental advances in knowledge. Thanks to the ice cores, we know that the carbon-dioxide concentration 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.

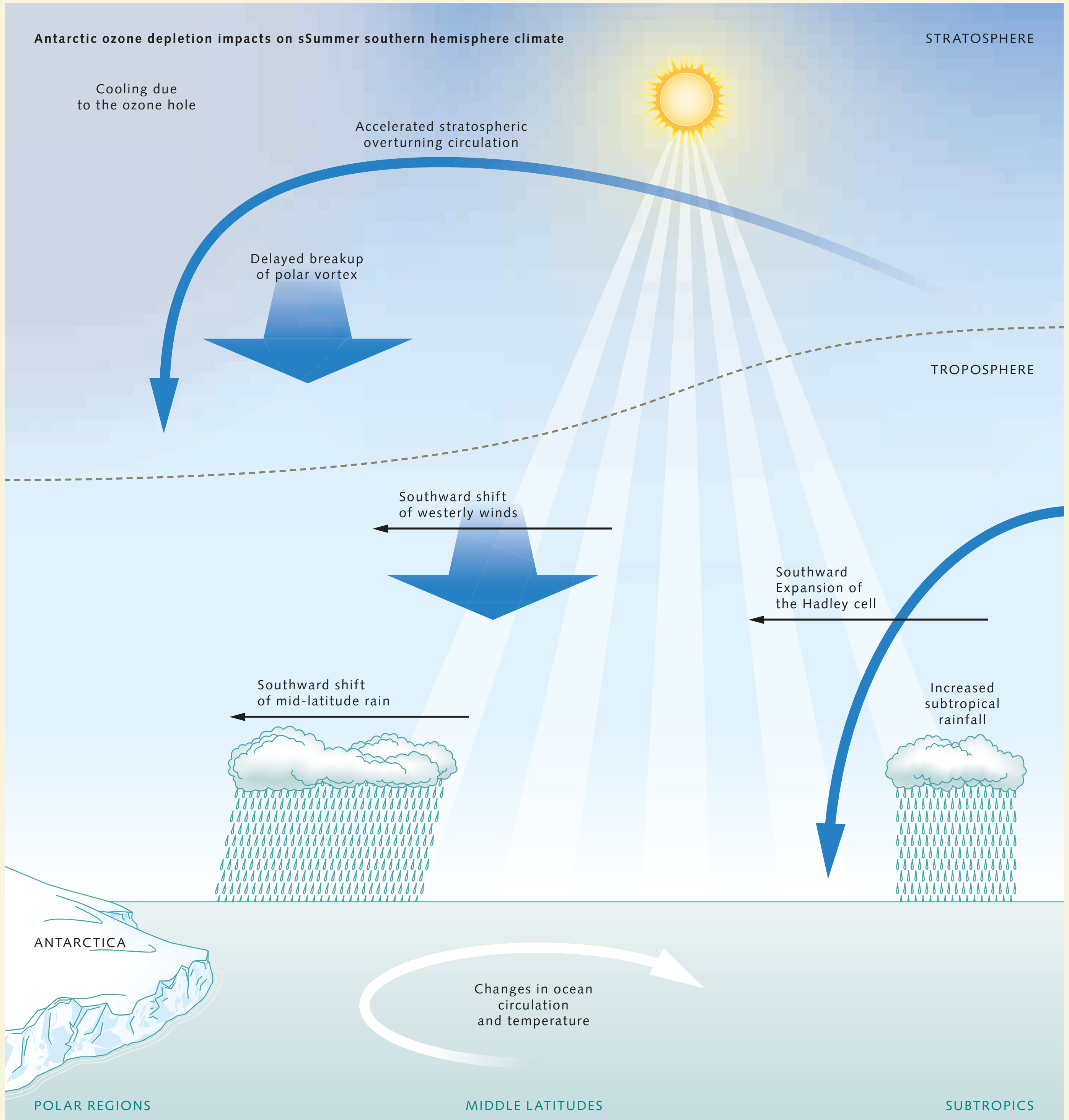
Researchers consider an ozone hole to be present when the ozone concentration in the stratosphere falls below a threshold value of 220 Dobson Units. This unit of measurement, named after the British physicist and meteorologist Gordon Dobson (1889–1976), denotes the total sum of ozone molecules in the 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

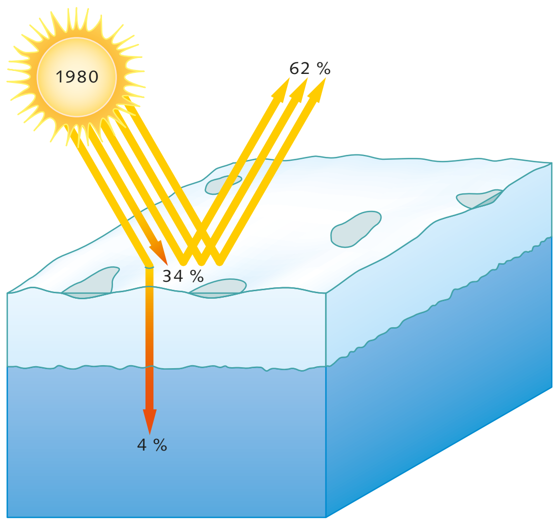
The areas of sea ice in the polar regions react very sensitively to climatic changes. If the geographical range of sea ice increases, it is an indication that the planet is cooling down. But if the area of ice shrinks, it is a sign of global warming. For this reason, climate research also focuses on 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:

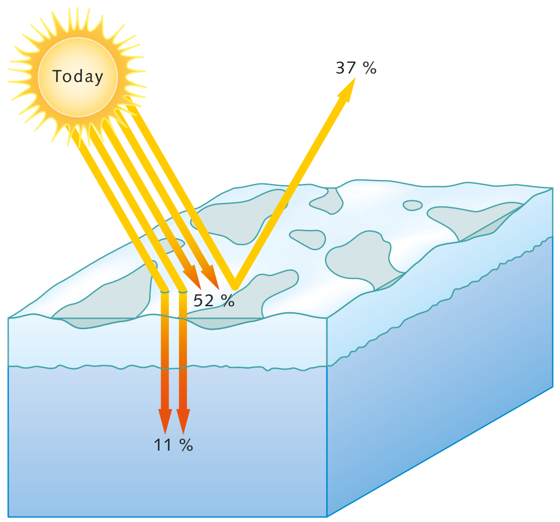
- Sea ice reflects the incoming solar radiation and this cools the Earth's surface.
- During its formation it releases brine, stimulating the circulation of water by increasing the density of the underlying water masses so that they sink.
- As an insulating cover, it limits the exchange of gases and 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





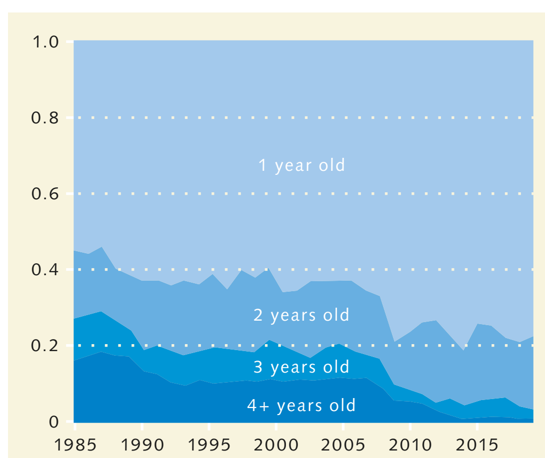
3.17 > The sea ice in the Arctic is thinner today than it was in the 1980s, and larger portions of it are covered by meltwater pools. These two factors lead to increased absorption of solar energy by the ice cover and the ocean below, which further reinforces the decline of sea ice.

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.

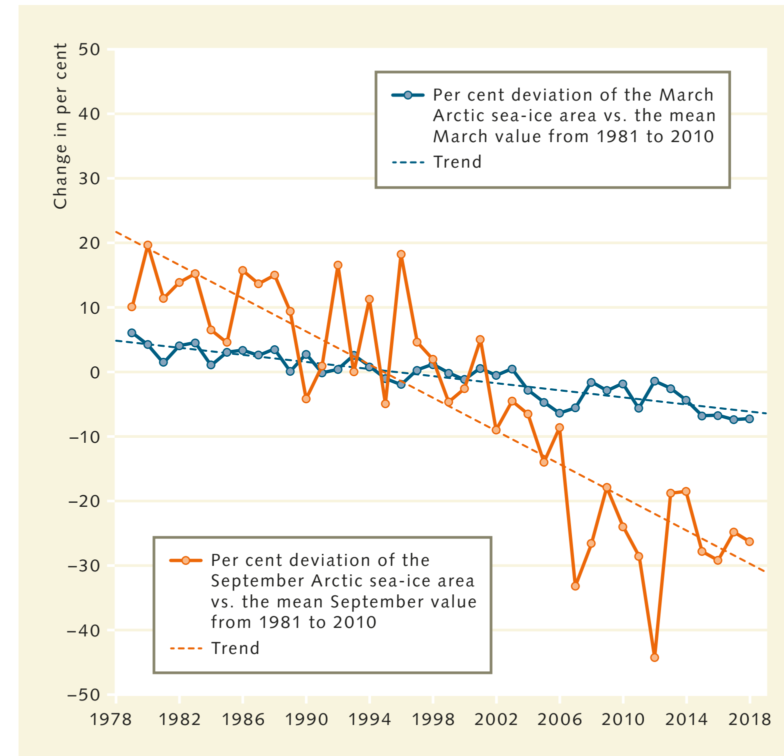
The shrinking sea-ice cover in the Arctic region is one of the most visible changes to the Earth's surface over the past three decades. Scientists even go so far as to say that, due to global warming, the Arctic no longer transforms into an extreme ice world in winter as it once did. This statement is 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, multi-seasonal, 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.



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.

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 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

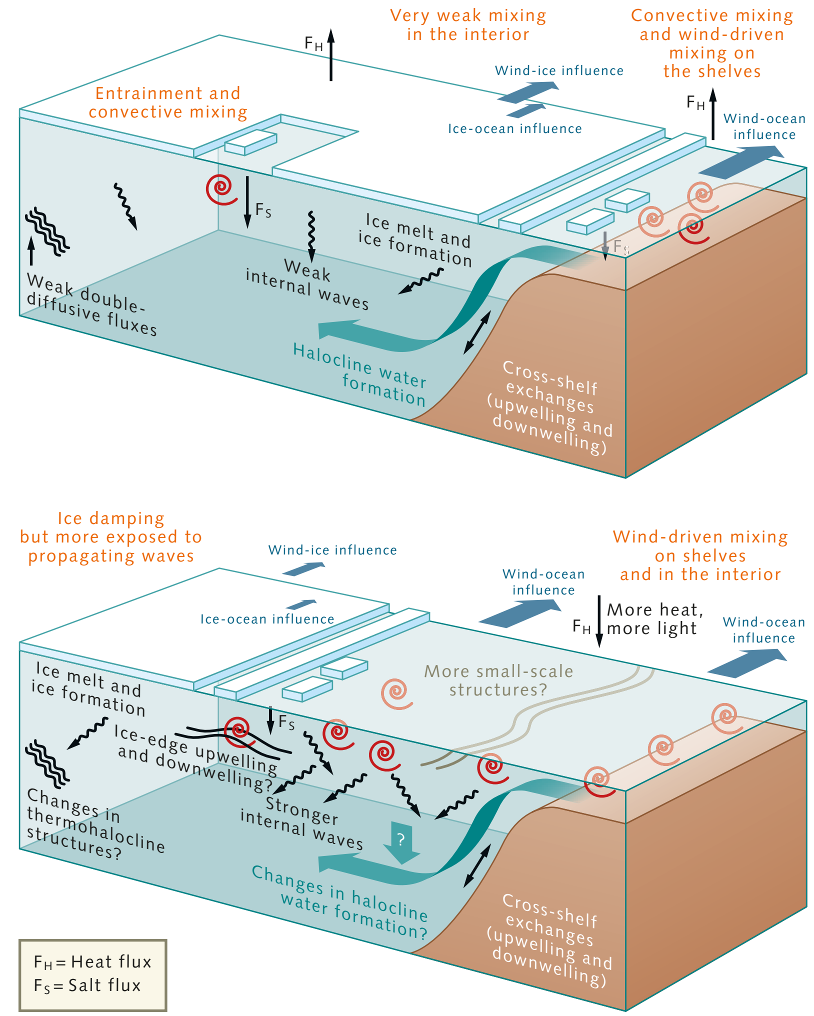
3.22 > In the past, researchers encountered pancake ice only in the Antarctic. But now the winds and waves have enough room and the opportunity to create these characteristic deformations.

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.



3.23 > 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

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

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

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.

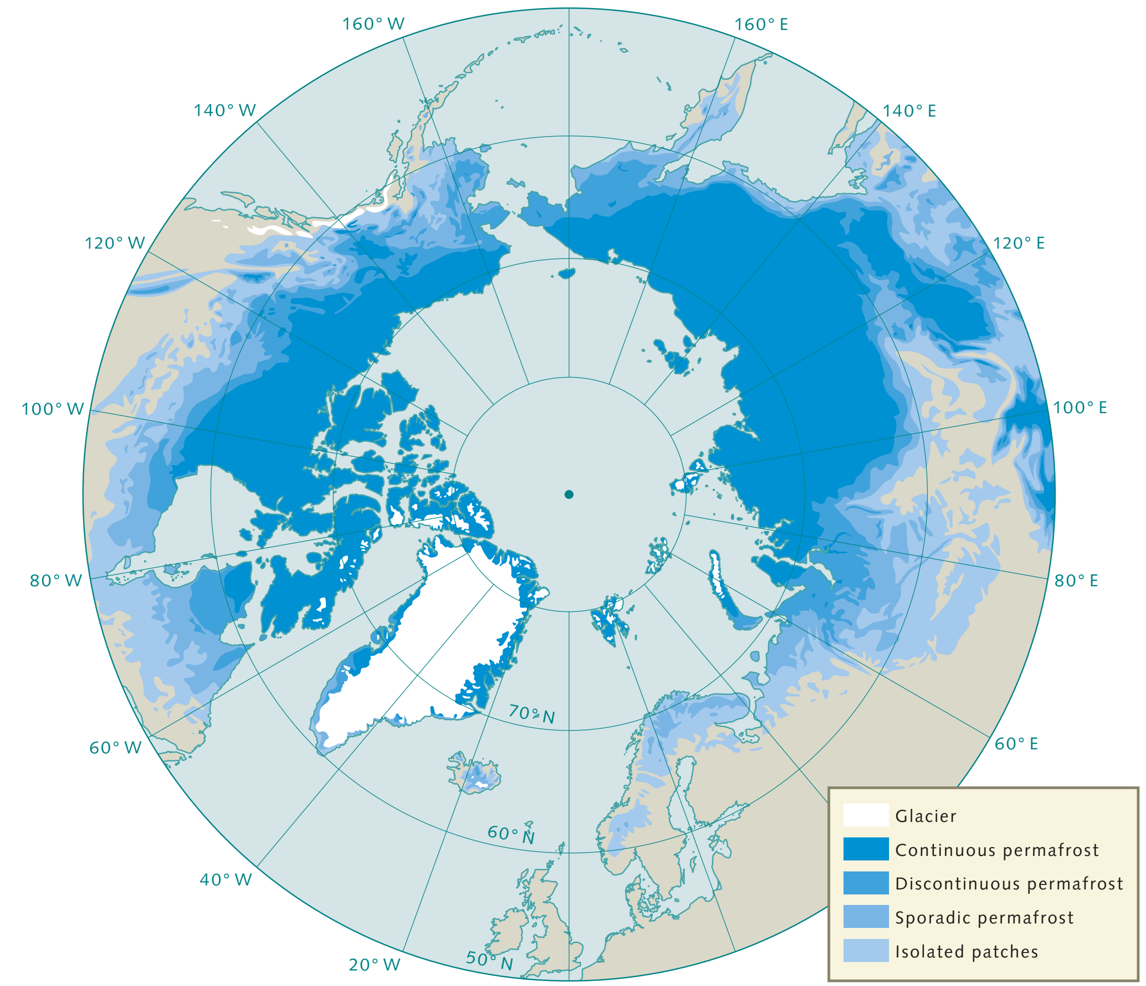
A temporary lake landscape

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.

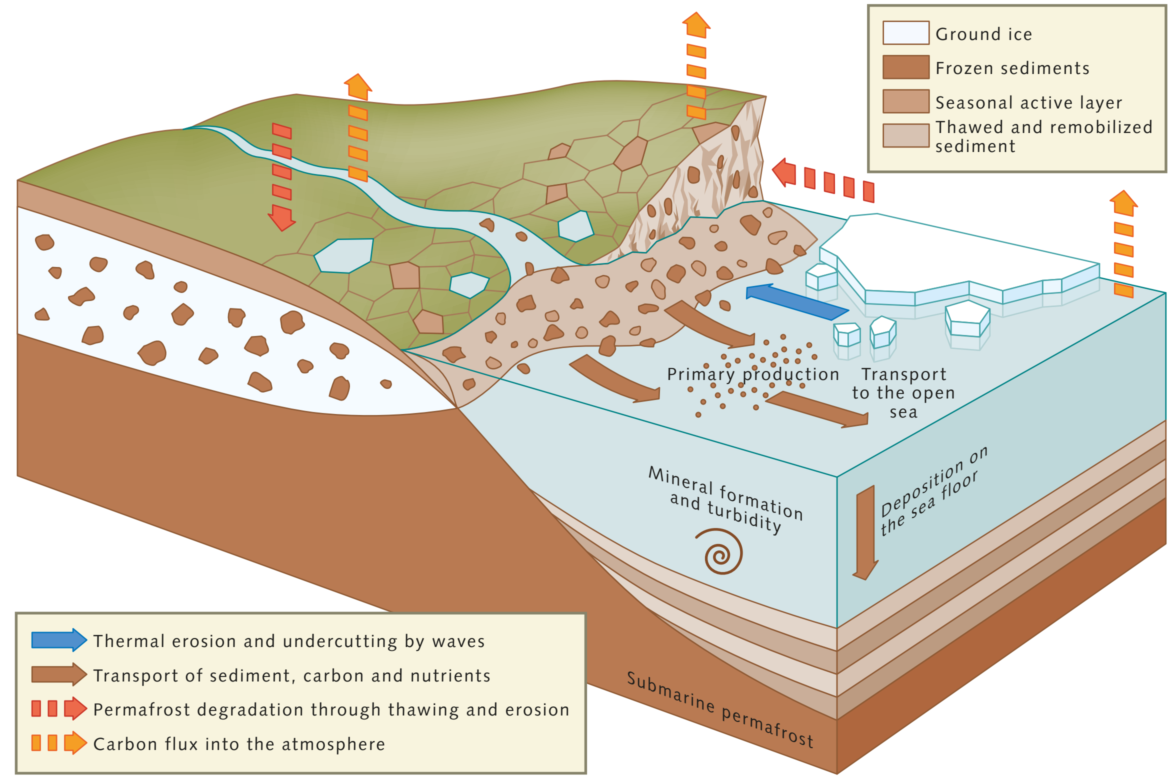
The fire in the tundra was ignited by lightning during the unusually warm and dry summer of 2007, and by the time of the first snowfall in October it had devoured an area of 1039 square kilometres. Investigations following the fire determined that it was the largest wildfire in Alaska's tundra in 5000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

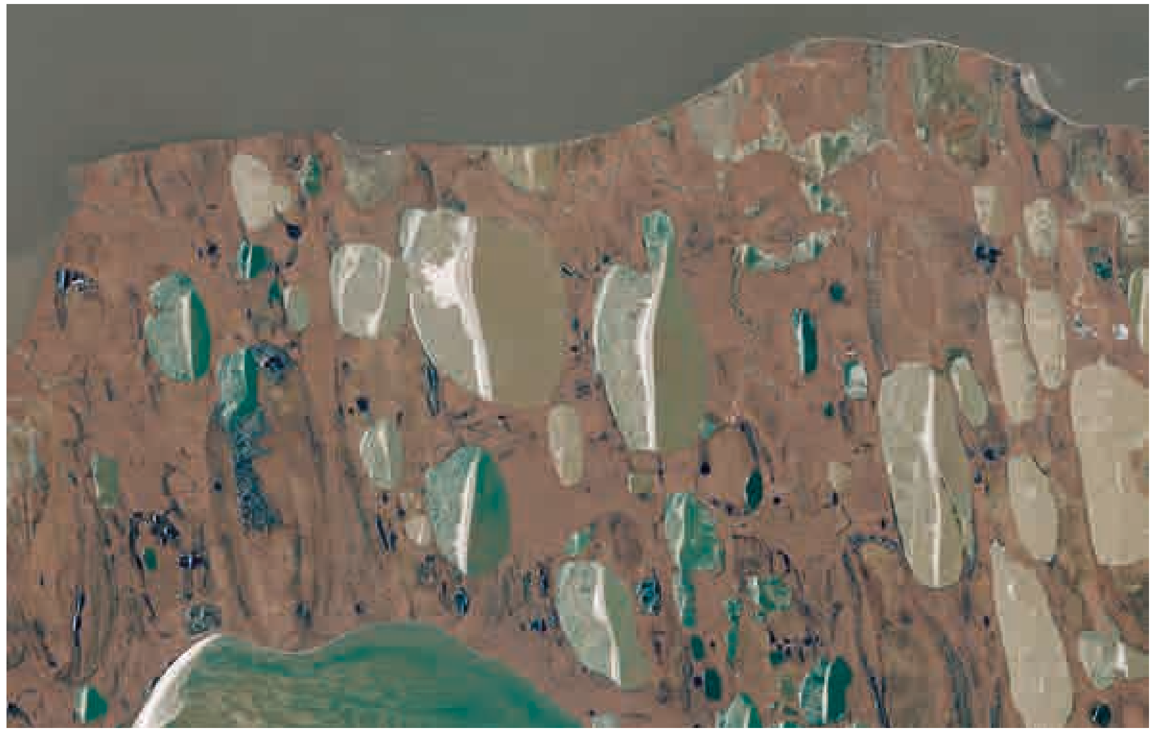
Erosion on the Arctic coastlines averages 50 centimetres each year. But this value is much greater in areas where there is less sea ice, which would otherwise protect the coasts from the destructive power of wind and waves, and in areas where the active layer of the permafrost thaws ever deeper due to 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

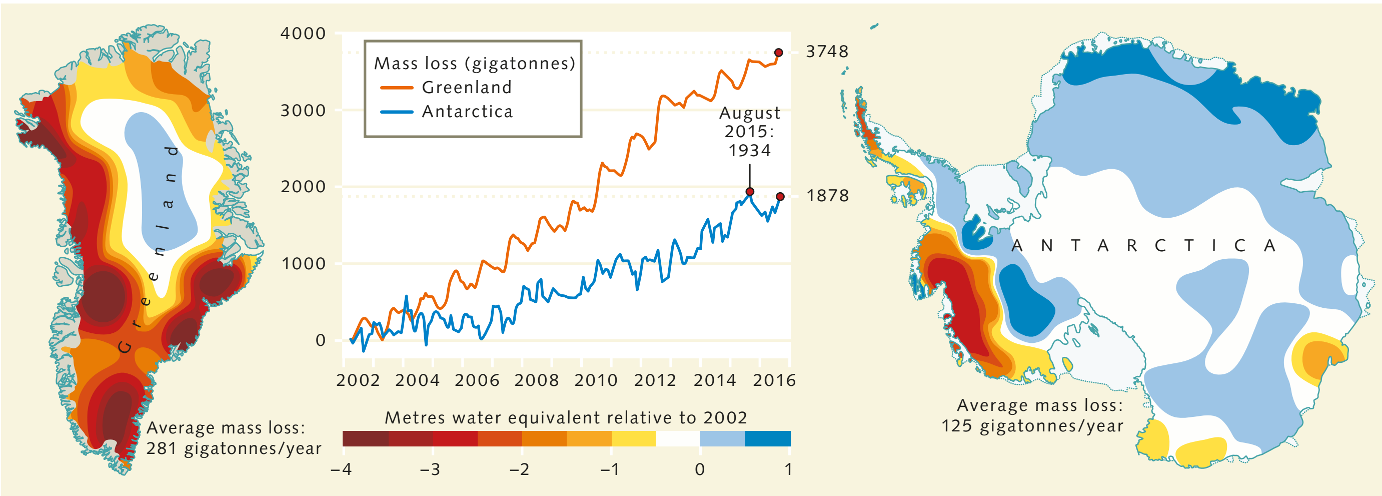
In order to minimize the uncertainty factor in the mass balance calculations for glaciers and ice sheets, the satellite mission GRACE (Gravity Recovery and Climate Experiment) was begun in 2002. GRACE comprises two identical satellites that circle the Earth at an altitude of 490 kilometres, one behind 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 col-

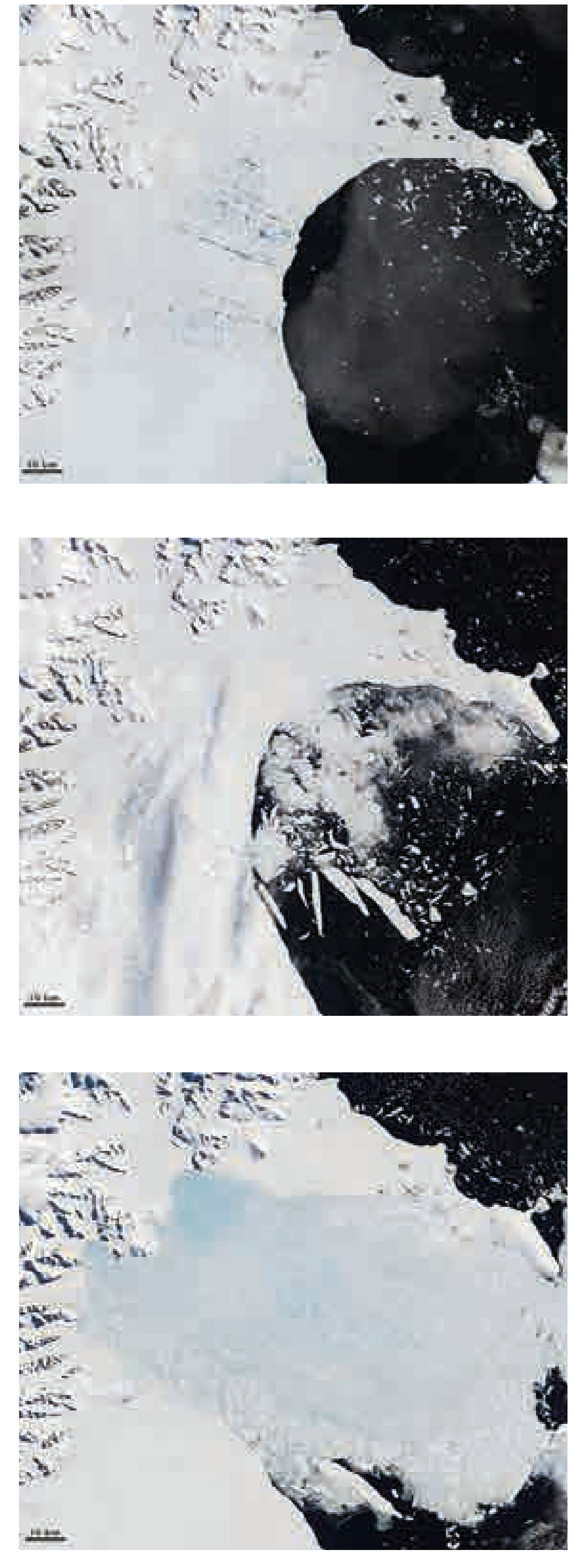
lapsed in recent decades, with three of them losing as much as 70 per cent of their ice area. This combination increased the rate of ice-mass loss on the peninsula to 25 gigatonnes per year. In East Antarctica, by contrast, the ice loss vs. growth remained more or less in balance over the 25-year period. 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-



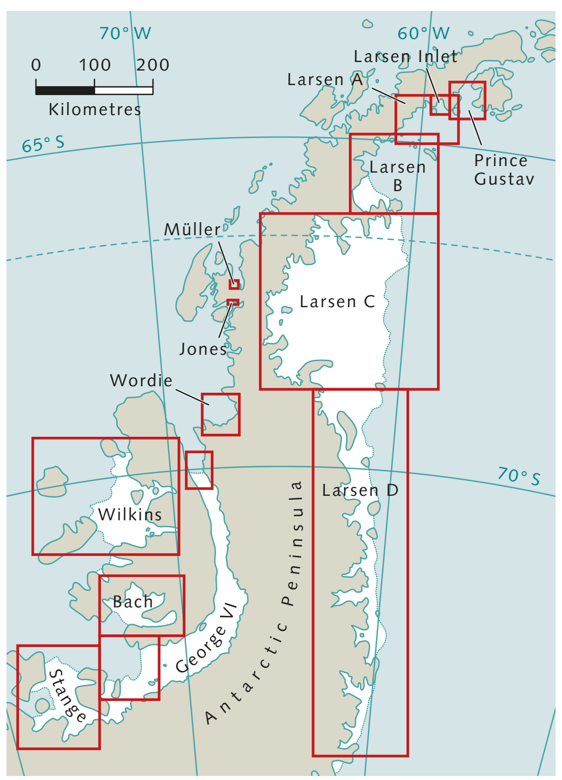
3.37 > The Larsen B Ice Shelf, on the east coast of the Antarctic Peninsula, collapsed during the southern hemisphere summer of 2002 within a period of less than six weeks. The top image (31 January 2002) shows the ice still intact and the many meltwater lakes that had already formed on its surface. 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).

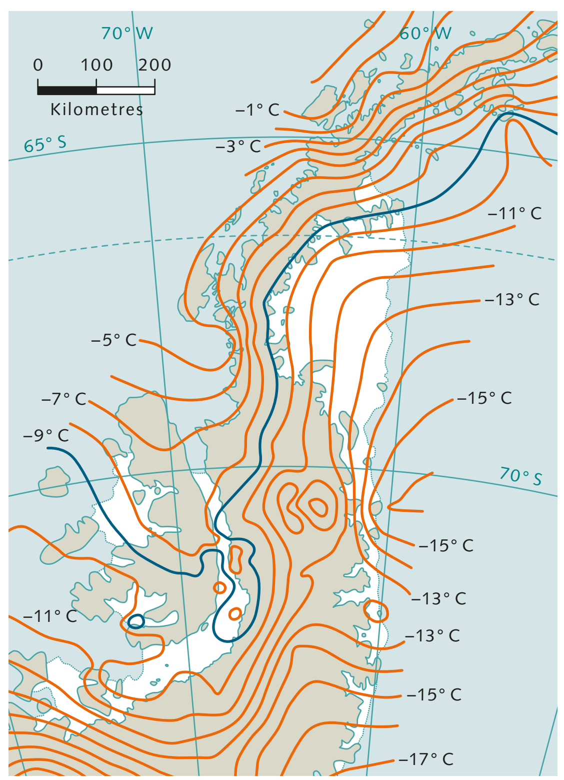
Larsen Ice Shelf
The Larsen Ice Shelf, which is divided into four segments: A, B, C and D, is named after the Norwegian whaling captain and Antarctic explorer Carl Anton Larsen (1860–1942). In December 1893 he sailed along the ice shelf in the western Weddell Sea with his vessel *Jason*.

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.

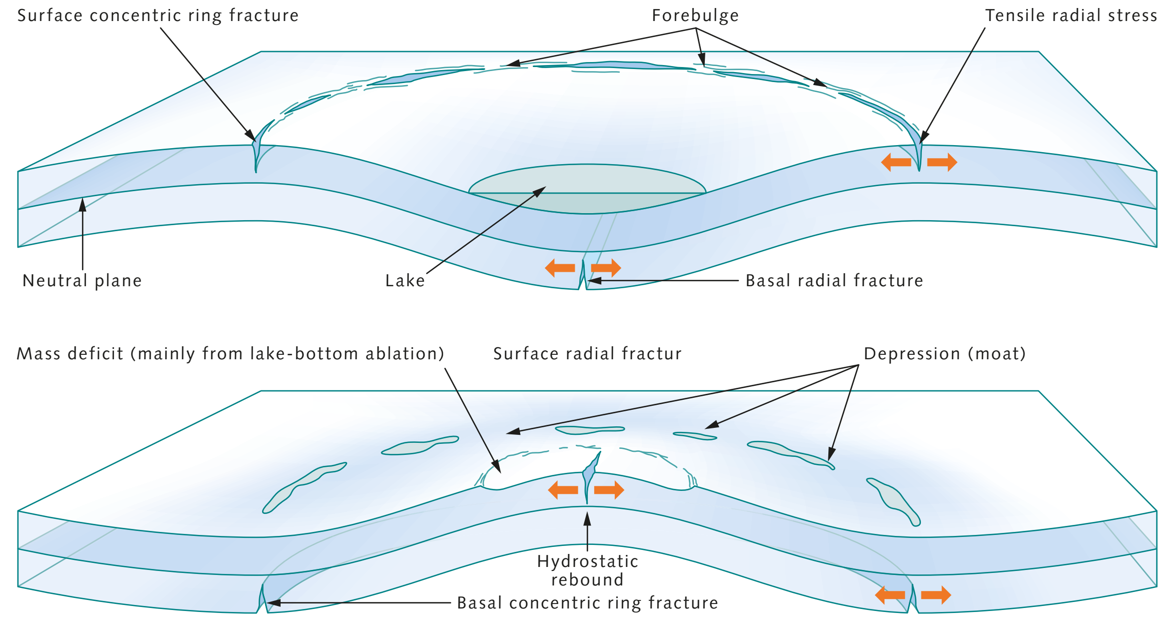
There were originally twelve ice shelves along the length of the Antarctic Peninsula that fed off the glaciers that form in the mountainous regions of the peninsula. The only source of their ice masses were the snow and rain that falls on the peninsula. These glaciers, and those that remain today, were 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 Shackelton'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.

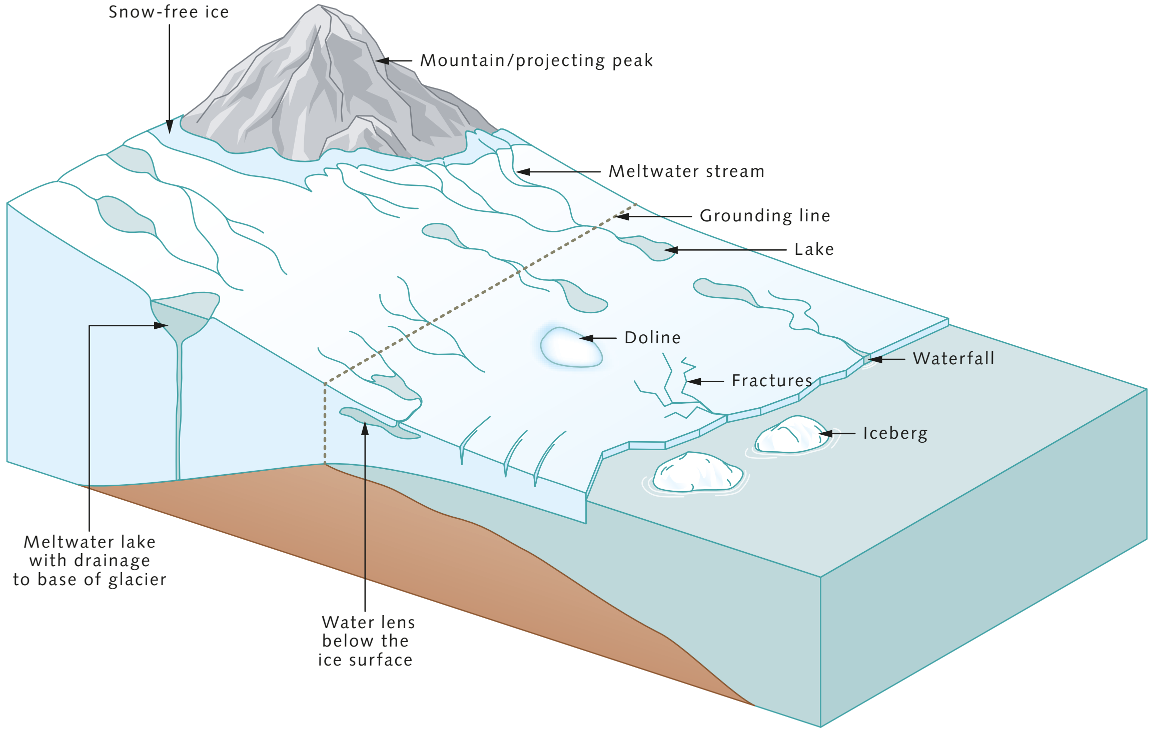
New satellite observations, as well as aerial photographs and mass-balance models, suggest that the extent of ice loss due to melting and its significance for the mass balance in Antarctica are greater than previously believed. In 2017, scientists counted nearly 700 different networks of meltwater lakes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

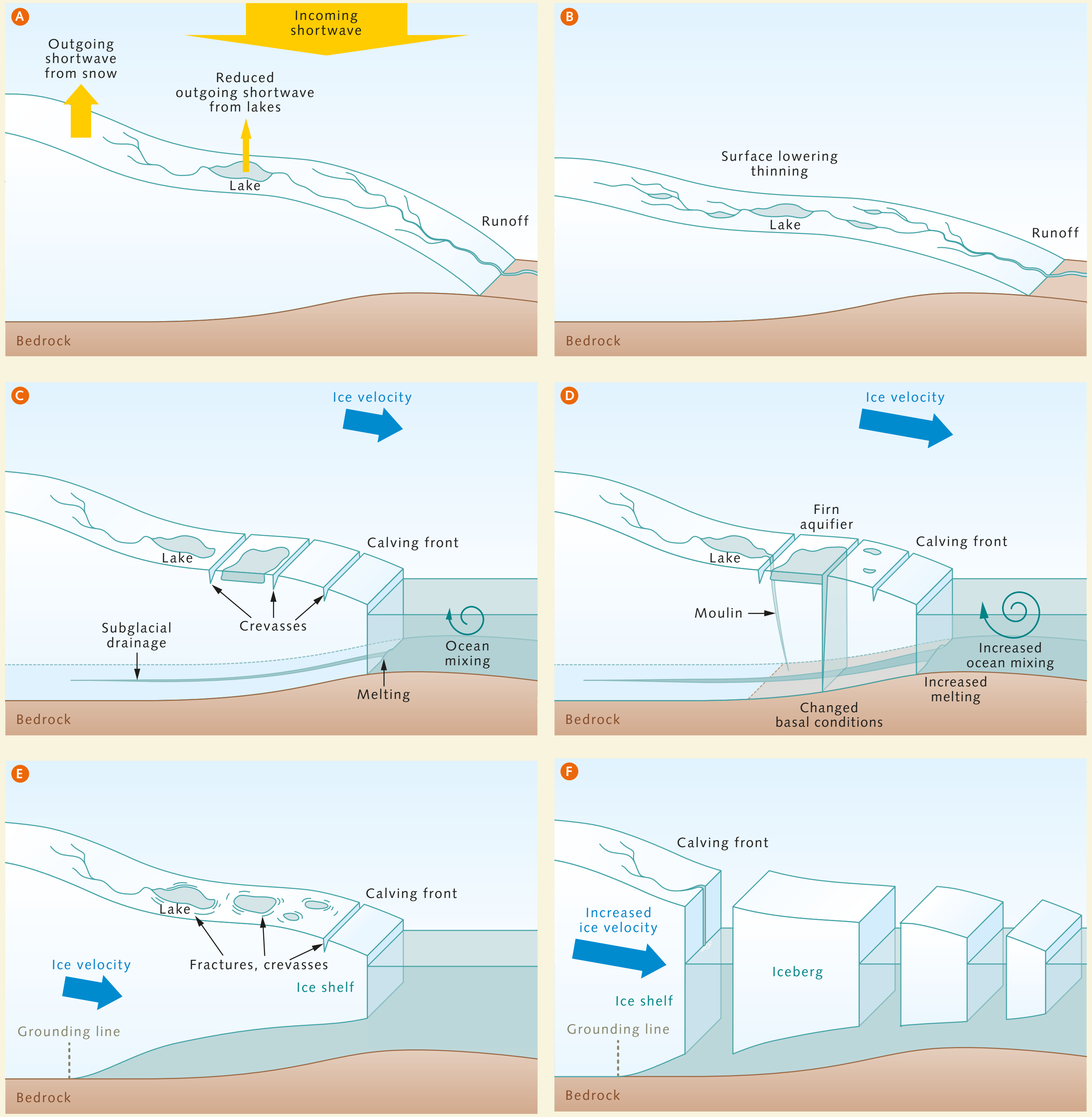
Heat incursion into the Amundsen Sea

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.

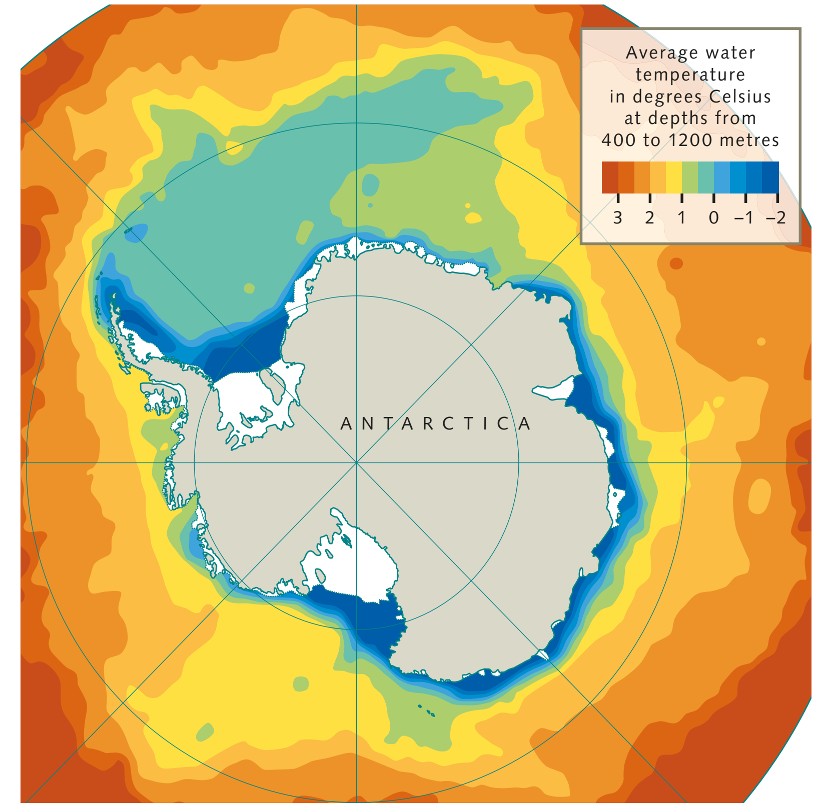
A passage through the troughs

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.

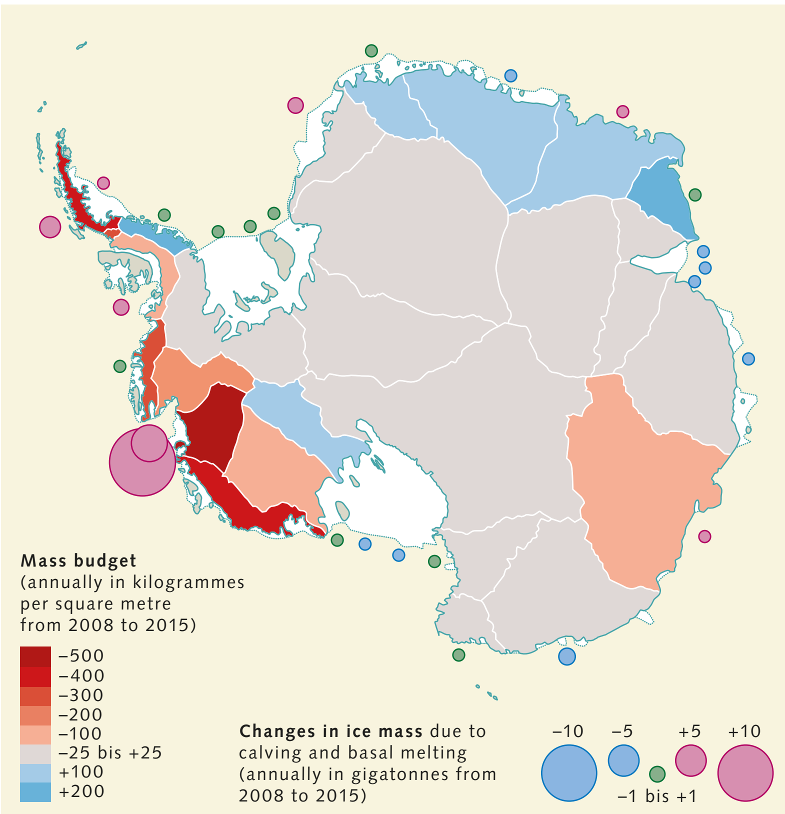
Today, the amount of inflowing deep water is influenced, among other things, by the winds over the Amundsen Sea. If the westerly winds are dominant, a great deal of warm water flows in. But if the easterly coastal winds prevail, the inflowing current weakens. And the El Niño phenomenon in the southern 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.



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.

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



3.45 > 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.

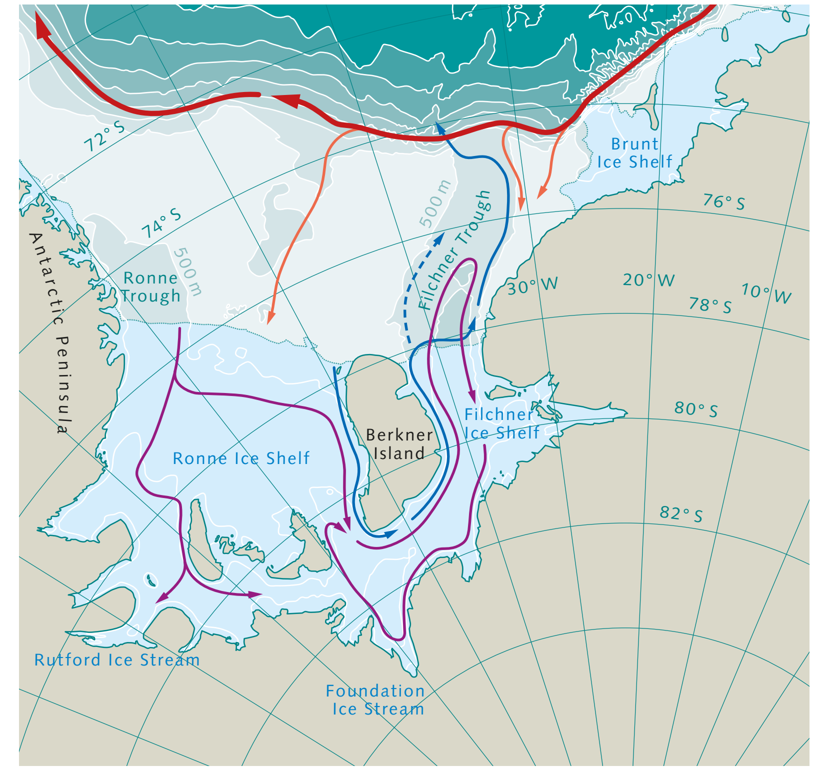
Model calculations by German polar researchers, however, indicate that this cold-water barrier protecting the Filchner-Ronne Ice Shelf could suffer a permanent collapse in the coming decades, triggered by higher air temperatures over the Weddell Sea. Researchers today are already witnessing the first 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.



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.

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.

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.

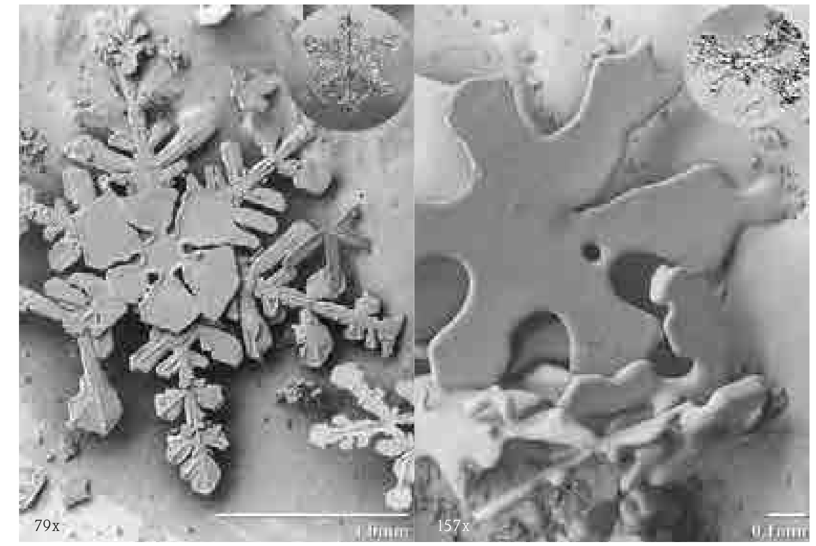
Greenland – warming hotspot

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.

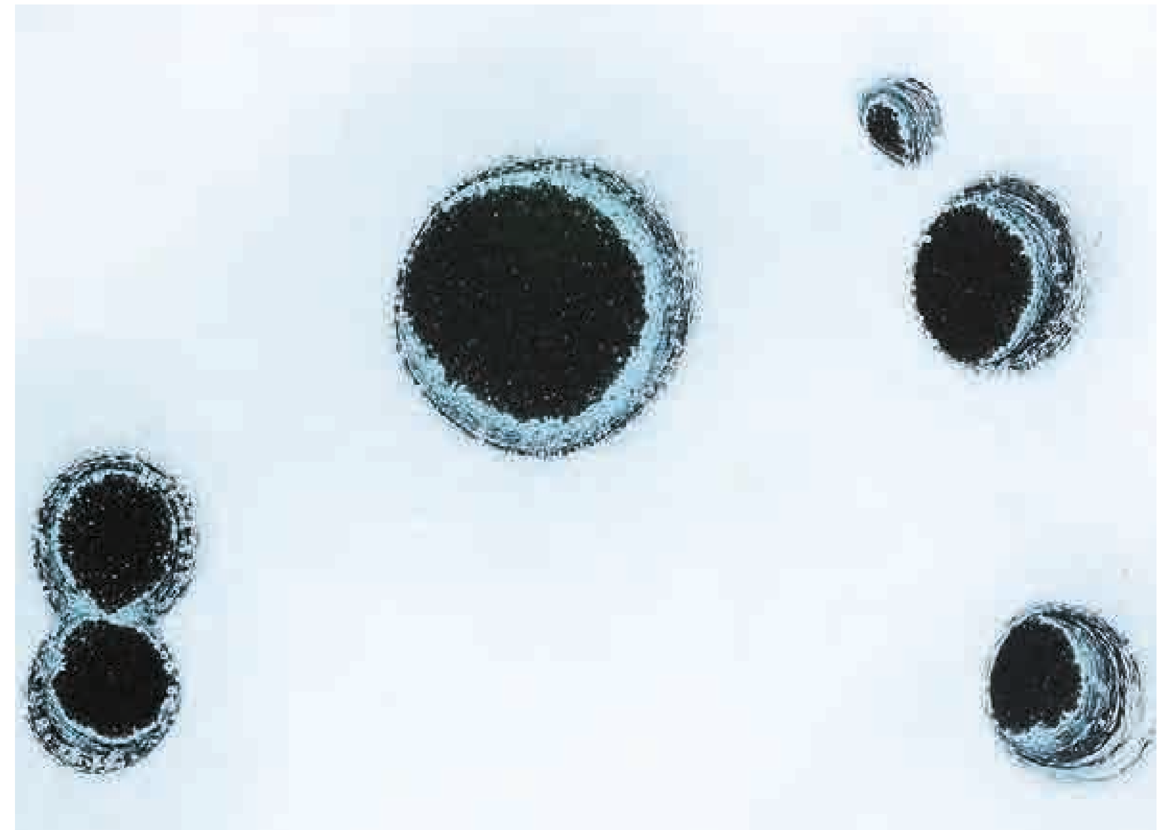
The amount of surface melting is also influenced in a complex way by clouds. Measurements on the highest plateau of the Greenland Ice Sheet, for example, have shown that even at these elevations the snow layer sometimes melts in summer, when clouds comprising a particular mix of water drops and ice crystals 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.

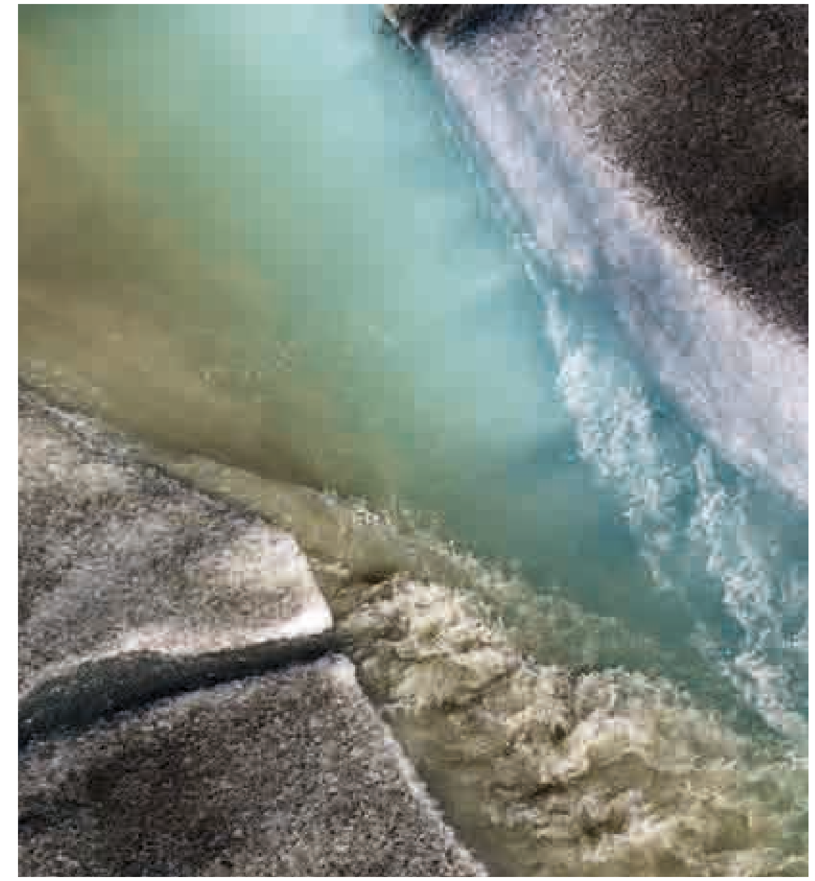
and stability. The ice rubbing along the steep rock walls of the fjords is subjected to an effect similar to that generated by the brake shoes on a car, which tends to slow the glaciers down. But the shorter the distance of contact between the sides of the glacier tongue and the rocks, the less braking 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.

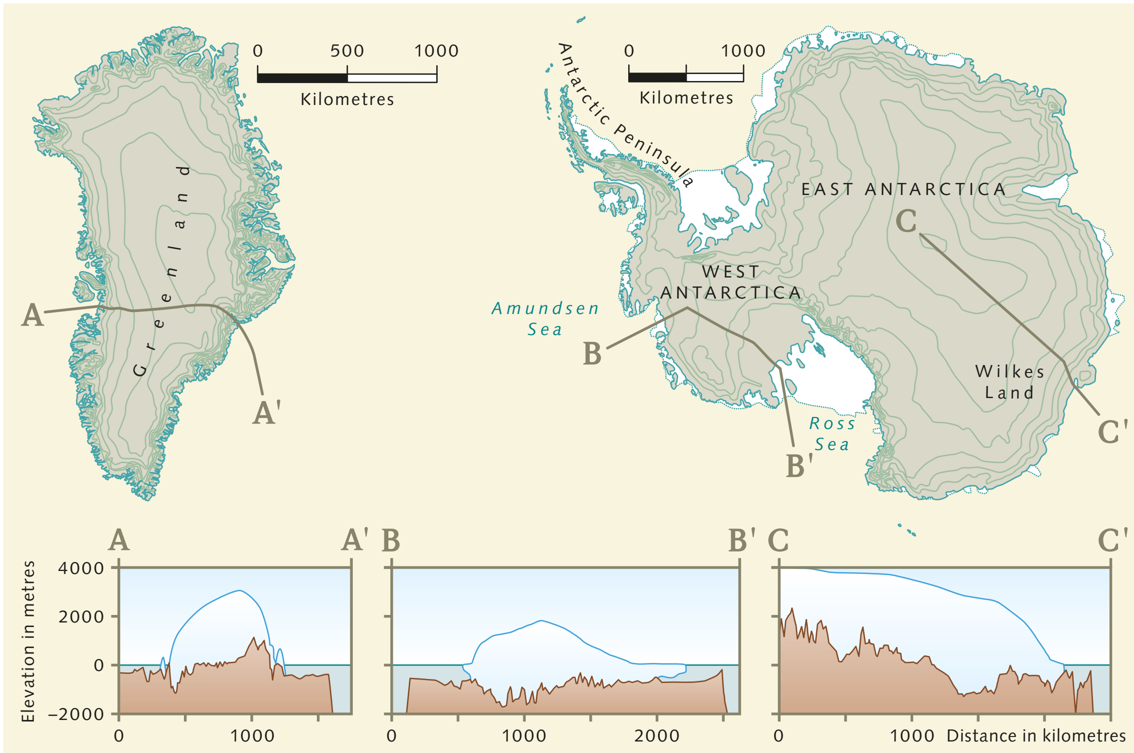
Although the flow velocities of most of Greenland's glaciers have increased, the number of iceberg break-offs, and thus the rates of retreat of the ice tongues are highly variable. While some glaciers appear to be rather stable, the ice tongues of others are rapidly becoming shorter, as exhibited, for 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.



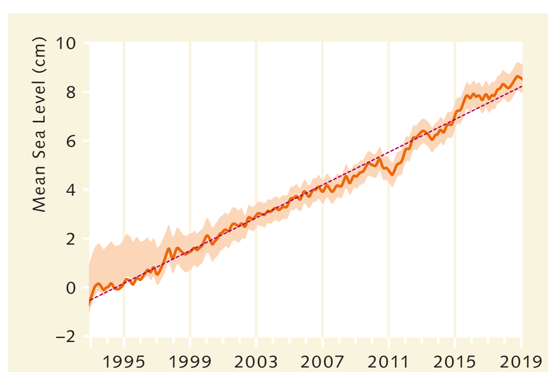
3.53 > While large portions of the two Antarctic Ice Sheets rest on land surfaces that are below sea level and are thus accessible to warm water masses, in Greenland this configuration is only known in areas where the ice bodies occupy deep glacial troughs. The rest of Greenland's land surface is still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

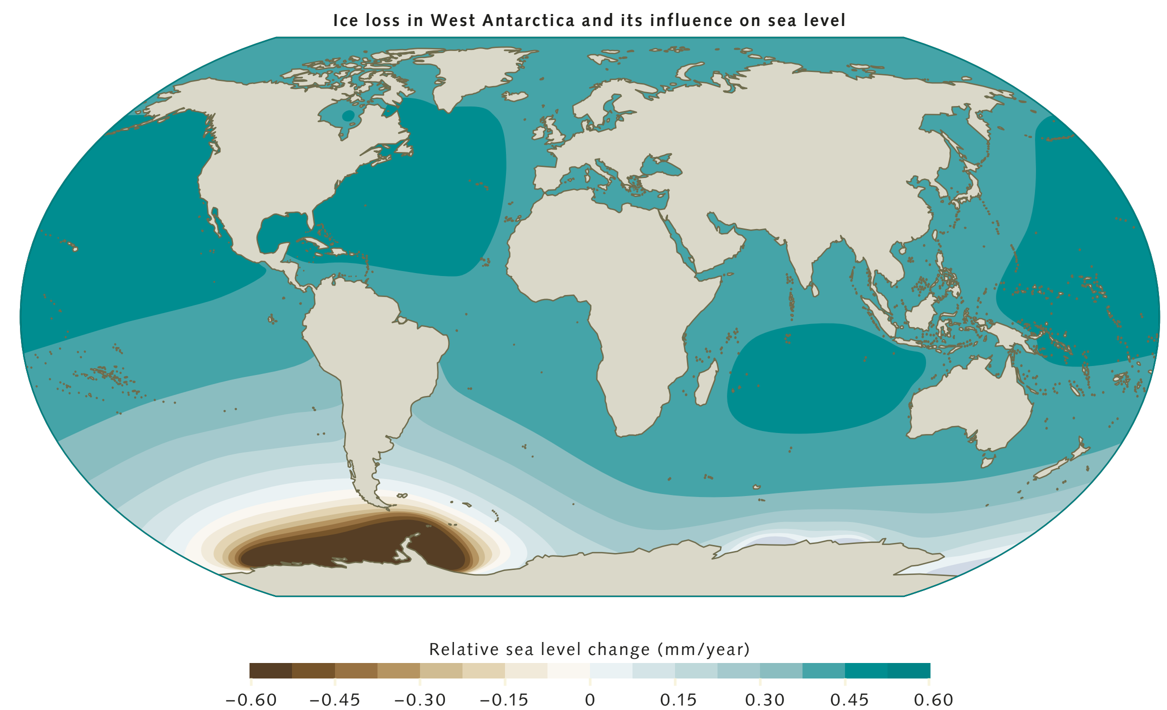
Accelerating sea-level rise

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.



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.

4 Polar flora and fauna

> Short summers, extremely cold winters and vast amounts of ice and snow which reduce the food supply – the Arctic and Antarctic are among the regions most hostile to life on Earth. However, using an impressive range of adaptation strategies, plants and animals have managed to conquer even these areas and have formed globally unique biocoenoses. Yet in times of climate change their future has become highly uncertain.

Living in the cold

> Species diversity in the northern and southern polar regions is primarily determined by geographic conditions. While in the Antarctic almost all life is dependent on the ocean, the Arctic also hosts impressive diversity in its terrestrial areas. Life in both regions flourishes first and foremost during the short summers and subsequently defies the ice and cold by means of remarkable survival strategies.

Three commonalities, many differences

The polar regions' special geographic and climatic conditions present the fauna and flora of the Arctic and Antarctic with particular challenges. For millions of years now, organisms in both regions had to:

- overcome cold to extremely cold ambient temperatures,
- deal with the presence of snow and ice in its various forms, and
- endure extreme seasonal fluctuations of sunlight and temperatures.

The alternating conditions of permanent solar radiation during the polar day and permanent darkness during the polar night mean that plant biomass, and thus food for all higher trophic levels, can only be produced during the summer. During the dark and cold part of the year, those animals which do not migrate to warmer regions must therefore live on their food and fat reserves, consume carrion, or graze on animal and plant residues that have sunk to the sea floor.

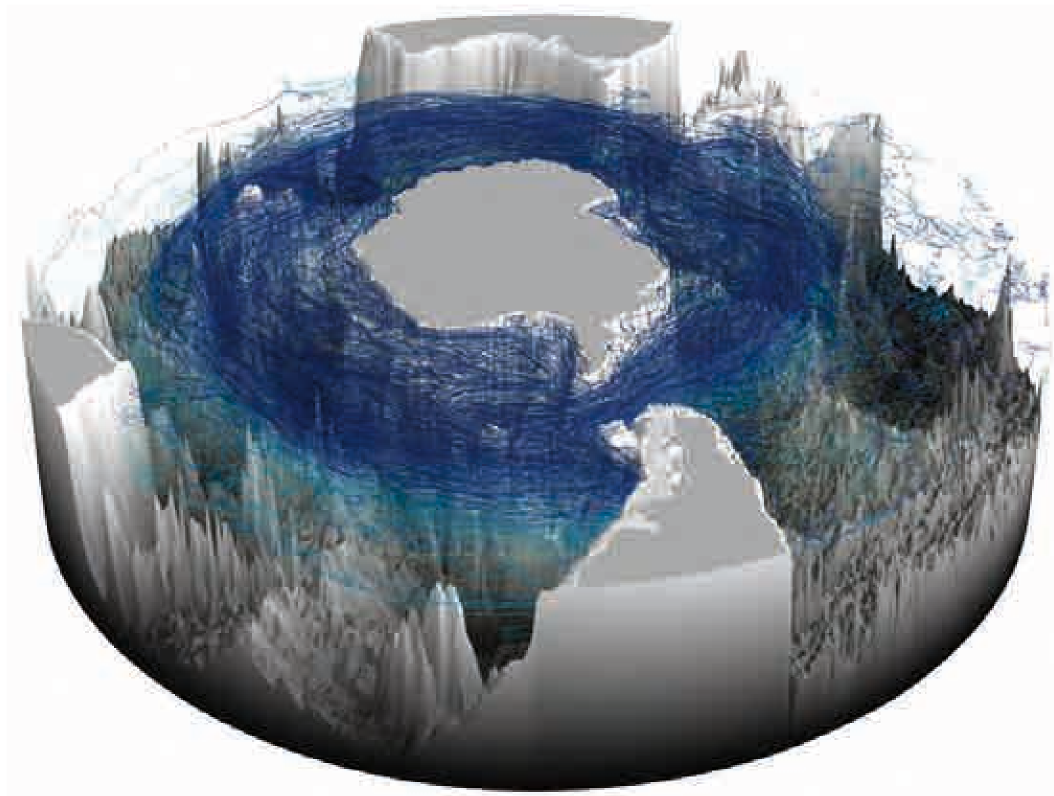
Nonetheless, both the Arctic and Antarctic environments have given rise to a great diversity of life. In the north polar region more than 21,500 species of fauna and flora have now been identified, all of which have adapted to the extreme conditions – from bacteria and viruses living on glaciers and fish that spend the first years of their lives hidden under the marine ice, to the well-known species such as the Arctic fox or the polar bear. There are approximately 14,000 Arctic terrestrial species; a further 7600 species live in the Arctic Ocean.

In contrast, the terrestrial life of Antarctica is relatively species-poor. A mere 1600 animal and plant species occur in the few ice-free terrestrial areas of the Antarctic. The ocean, however, is teeming with life – some 10,630 species have been identified, with the majority displaying special adaptation mechanisms that can be found nowhere else on Earth.

A matter of geographic location

A comparison of the ecosystems of the two polar regions highlights the significant differences between them. While there are large-scale, glacier-free areas of tundra and extensive river systems in the Arctic, both of which produce sufficient biomass during the summer to feed even large herbivore species such as caribou and musk oxen, 98 per cent of the Antarctic landmass is still covered in ice. This means that lichens, mosses and higher plants can hardly find substrates on which to grow. Therefore, the main food source for all the animals native to the Antarctic is the ocean which completely surrounds the continent.

The resultant isolation of the Antarctic from the rest of the world has had a similarly lasting impact on the development of life in the south polar region as its glacial history. For more than 34 million years now, oceanic basins more than 3000 metres in depth have separated Antarctica from the surrounding land masses of South America, Africa and Australia. Even at its narrowest point, at the Drake Passage, the Southern Ocean is still 810 kilometres wide. Terrestrial species of fauna intent on migrating to Antarctica from temperate latitudes would have had to be capable of long-distance flights or swims even in the past. Once they had overcome that obstacle, the Antarctic immediately presented them with the next challenge – several times over the past millions of years the southern continent became completely covered in ice, sometimes even beyond its coastline. The Antarctic terrestrial species were left with the choice to either migrate or to move out onto the marine ice. Otherwise they faced extinction.



4.1 > A three-dimensional model of the Southern Ocean. With its deep basins and circulating water masses, it continues to form a barrier that many animal and plant species from more northern latitudes can scarcely overcome. Similarly, it has prevented species native to the Antarctic shelf sea areas from migrating northwards.

In comparison, settling in the Arctic was much easier as it is directly connected to large continental land masses stretching far south and into warmer climatic zones. Eurasian and North American species of fauna and flora adapted to the cold were therefore able to colonize the north polar region by land. When during the last glaciation large ice shields formed in the Arctic, this did not generally spell the end of terrestrial life in the way it did in Antarctica. For one thing, the Arctic species had the opportunity to shift their ranges toward the south and thus to flee from the ice. Moreover, during this glaciation the Arctic was never entirely covered by glaciers and ice shields. Regions such as Beringia and eastern Siberia remained ice-free and served as a refuge for many organisms. As a result, the north-eastern tundra regions of Russia are among the most species-rich terrestrial areas of the Arctic to this day.

Given that the Arctic is not separated from more southern climes by oceans or high mountain ranges it is not surprising that the north polar region hosts many terrestrial predators such as polar bears, wolves and Arctic foxes while there is not a single four-legged predator species in mainland Antarctica. Instead, millions of penguins breed in the Antarctic – birds that cannot fly and that know no enemies outside of oceanic waters. If penguins were resettled in the Arctic, they would easily be picked off by polar bears and other predators, given that these large birds have no intuitive sense of danger when on land. The only bird species resembling penguins which ever lived in the Arctic was the flightless great auk *(Pinguinus impennis)*. It lived on remote rocky islands in the North Atlantic were there were no polar bears, wolves or foxes. However, in the early 19th century European seafarers discovered the birds' colonies. They hunted the defenceless auks to extinction in a mere four decades. The last great auks were killed in June 1844 on the Icelandic island of Eldey.

4.2 > Four endemic species of true seals are at home on and underneath the jagged Antarctic pack ice. These include the crabeater seal, Ross seal, Weddell seal and leopard seal.

A "biodiversity pump"

The geographic conditions in the Arctic and Antarctic have also had a decisive impact on the species diversity of the polar seas. The ring-shaped Southern Ocean made it possible for many of its inhabitants to establish ranges encircling the entire continent. At the same time, the Circumpolar Current, which reaches great depths, and the rapidly decreasing water temperatures at the top 200 metres of its water column impede the migration of species from more northern climes. Moreover, water temperatures have decreased since the Drake Passage opened 34 million years ago – at first there was only episodic cooling and interim warming phases but in the past 15 million years temperatures have continuously declined. The Southern Ocean is on average ten to twelve degrees Celsius colder today than it was 40 million years ago.

Sea ice conditions in the Antarctic changed in step with the cooling of the Southern Ocean, with far-reaching consequences for life in and underneath the sea ice, in the water column, and on the sea floor. The more ice formed in the Antarctic in the course of a cold period and the further glacial and shelf ice masses expanded out into the ocean, the less space there was for residents of the shelf, such as sea-floor dwelling sponges or starfish. Many shallow-water areas became completely uninhabitable and formerly conjoined marine regions were separated by the glacial advance. Scientists believe that many of the marine organisms inhabiting the continental shelf seas at that time were forced to migrate down the continental slope or into the deep sea. At the same time, however, the current assumption is that the isolation of habitats of the continental shelf gave rise to new species. Since the Antarctic ice masses have repeatedly expanded and contracted over the past 2.1 million years, biologists speak of a "biodiversity pump". The premise here is that the repeated isolation of biocoenoses (cold period, growth of ice mass) and the subsequent opportunity for expansion (warm periods, retreating ice) provides perfect conditions for the evolution of a unique and highly differentiated species diversity which, moreover, includes a high proportion of endemic species, i.e. species of fauna and flora that can only be found in the Antarctic. Approximately 50 per cent of Antarctic sea squirts, anemones, bryozoans, mussels and sea spiders are endemic species; roughly 75 per cent of sea snail species are endemics and for Gammaridea, a suborder of amphipods, as well as for octopuses the proportion of endemic species is as high as 80 per cent. In this way the Southern Ocean has given rise to a much greater and more colourful level of biodiversity than one would expect at first sight. Biologists have identified more than 8000 different species of invertebrates in the Antarctic, and some regions have not even been properly studied as yet.

The fish fauna of the Antarctic continental shelf seas is dominated by a group of Antarctic fish termed Notothenioidei. They constitute more than 70 per cent of species diversity and more than 90 per cent of fish biomass in the continental shelf seas. However, there are also faunal groups for which to date there are only occasional sightings in the Antarctic continental shelf seas, the red king crab for example, or which as yet do not occur in the Antarctic. The latter include lobster and hermit crabs, which also explains why the benthic fauna of the continental shelf has not developed defence mechanisms against clawed predators.

Southward migration

Geologically speaking the Arctic Ocean is younger than the Southern Ocean which means that species of high northern latitudes had less time to adapt to polar conditions than the southern fauna. But they, too, had to survive periods of large-scale ice formation, for example some 140,000 years ago when major ice shields covered North America and northern Europe and pushed their up to 1000 metres thick shelf ice onto the entire Arctic Ocean, which presumably became completely frozen over.

At that time, the biocoenoses of the Arctic Ocean either withdrew to greater depths or they migrated to more southern latitudes along the Atlantic and Pacific coastlines. When the ice masses slowly disappeared it took some time for the marine organisms to recolonize the Arctic ecosystems. Biologists therefore consider the diverse biocoenoses of the Arctic marginal seas to be not much older than 125,000 years. Moreover, in the Arctic Ocean scientists distinguish between the Atlantic and the Pacific sector respectively. Their inhabitants migrated from the respective neighbouring ocean and separately adapted to the polar conditions. It is for this reason that to this day different species play the exact same role in the two sectors' ecosystems.

In the Arctic, furthermore, it has been and still is much easier than in the Antarctic for inhabitants of the continental shelf seas to migrate from one continent to the next, given that the northern coastal areas of Europe, Asia and North America share contiguous offshore shelf areas. Antarctica, in contrast, lacks such a shallow water connection to neighbouring continents. In the Antarctic, therefore, the pressure to adapt has always been much higher than in the Arctic. During cold periods, marine organisms of the Southern Ocean had significantly fewer refuges at their disposal than species of the far north. The organisms of the Southern Ocean had only two options – they either adapted or they became extinct. It is for this reason that Antarctic marine life developed significantly more sophisticated adaptation mechanisms than the inhabitants of the Arctic Ocean.

4.3 > Antarctic white-blooded fish such as this juvenile blackfin icefish inhabit the world's coldest marine regions and have no haemoglobin in their blood.

4.4 > In order to escape the Arctic winter cold, the Arctic tern *(Sterna paradisaea)* leaves its Arctic breeding areas in August and flies to the edge of the Antarctic pack ice zone. In the course of this migration the birds cover a distance of some 35,000 kilometres – the greatest distance covered by any migratory bird species.

Survival tactics of terrestrial animals in the polar regions

Conditions in the Arctic and Antarctic are characterized by extreme fluctuations over the seasons. In summer there is sunlight, warmth, ice-free terrestrial and water surfaces and an overabundance of food resources; in winter, however, conditions are the exact opposite. In the Arctic, for example, winter surface temperatures drop to around minus 40 degrees Celsius for weeks, and minimum temperatures of minus 50 to minus 60 degrees Celsius are not uncommon. There are also major temperature differences between north and south as well as between coastal regions and more inland areas respectively. Such contrasts can only be survived by species that adopt one or more of the following survival tactics:

- fleeing the cold by migrating to warmer areas (migration),
- surviving the winter in a protected location (dormancy or hibernation),
- optimizing body heat regulation, and
- provisioning by means of accumulating large body fat reserves.

Fleeing from hunger and cold

The flight from low temperatures and food scarcity is a tactic used primarily by the many seabirds occurring in the polar regions. The Arctic hosts a total of 200 bird species, the majority of which are geese, ducks, shorebirds and seabirds. Compared to temperate regions there are few songbirds. Most of the Arctic bird species spend only a few summer months in the far north. As winter approaches, 93 per cent of the species migrate to warmer regions. Their migration routes lead to regions all around the world. While many of the geese, passerines, owls, birds of prey, auks and gulls overwinter in adjacent temperate latitudes, some of the shorebirds, phalaropes, and the Sabine's gull *(Xema sabini)* migrate as far as to the tropics and Australia. The bar-tailed godwit *(Limosa lapponica)*, for example, flies 12,000 kilometres from its breeding area in Alaska over the Pacific to New Zealand. Long-distance migrants such as the Arctic tern and skuas even target Antarctica where they overwinter on the edge of the Antarctic pack ice zone. This means that on their way from the Arctic breeding areas to the Antarctic overwintering areas and back the birds cover a distance of up to 80,000 kilometres per year. But this effort is worth it as both polar regions provide the birds with an abundance of food during the summer. And as the Arctic terns rely primarily on their eyesight for hunting they benefit significantly from the fact that in their chosen habitats the sun does not set for a total of eight months, enabling them to theoretically hunt for prey around-the-clock.

However, there are also bird species in the Arctic that do not migrate to warmer areas. Among the terrestrial birds, these include the common raven *(Corvus corax)*, rock ptarmigan *(Lagopus muta)*, snowy owl *(Bubo scandiaca)* and Arctic redpoll *(Acanthis hornemanni)*. Among the

4.5 > A herd of caribou moves through the Arctic National Wildlife Refuge in October in search of food. At this time the region has already seen snowfall which means that the animals need to scrape away the snow from potential grazing areas.

seabirds that spend winter in the far north are the black guillemot *(Cepphus grylle)*, thick-billed murre *(Uria lomvia)*, ivory gull *(Pagophila eburnea)*, Ross's gull *(Rhodostethia rosea)* and common eider *(Somateria mollissima)*.

Mammals also undertake seasonal migrations – baleen whales for example or reindeer *(Rangifer tarandus)*, known as caribou in North America. In eastern Alaska as well as in the Canadian Yukon Territory, for example, every spring a herd of between 100,000 and 200,000 of the so-called Porcupine caribou undertakes a 1300 kilometre northward migration to the coastal plains of the Arctic National Wildlife Refuge where the females give birth to their calves. The kindergarten on the coast of the Arctic Ocean offers many benefits to the wild herd. The landscape is flat and without forest cover, allowing the caribou to spot potential predators such as bears or wolves from afar. The fresh ocean breeze keeps the annoying mosquitoes in check, and there is a plentiful supply of food and water. At the end of the summer the caribou start on the return journey to their winter territories in the more southern Ogilvie Mountains. Other herds migrate even further south and overwinter in the subarctic boreal forests. But a few herds spend the winter in the tundra.

Homoeothermic or poikilothermic

Birds and mammals have a unique characteristic in the animal world: They are the only organisms able to maintain a constant internal body temperature regardless of external temperatures, which is why they are called homoeothermic or endothermic organisms. The internal body is taken to include those areas of the torso and head containing all the vital internal organs (intestines, central nervous system, and brain) that also generate heat when the organism is at rest. The body core temperature is generally more or less constant while the temperature of the body shell, including the skin and extremities, fluctuates more strongly.

The body core temperature of humans is 37 degrees Celsius. Hedgehogs have a core temperature of 35 degrees Celsius and swallows of 44 degrees Celsius. The body core temperature of carnivores, horses and humans fluctuates by one to two degrees Celsius throughout the day dependent on activity. An increase of more than six degrees Celsius is life-threatening to most homoeothermic organisms and generally results in death by hyperthermia. In contrast, death by hypothermia occurs when an organism's body temperature decreases and its body core temperature falls below a species-specific level. Humans for example are in a critical condition if the temperature of their blood falls below 27 degrees Celsius.

Fish, amphibians or reptiles are not greatly impacted by a slight drop in body temperature. They are among the poikilothermic organisms or ectotherms. These terms are used for all organisms whose body temperature is fully dependent on the temperature of their environment and is generally not influenced by the animals' metabolism. Poikilothermic animals have developed characteristic behaviours which allow them to regulate their own body temperature. Salamanders for example bask in the morning sunshine in order to reach "operational temperature" while many flying insects warm up by means of rapid contractions of their wing muscles.

Thermoregulation

Just like all other homoeothermic animals in the polar regions, these caribou face the challenge of maintaining their body core temperature at a level of between 37 and 41 degrees Celsius despite the air around them being up to 100 degrees Celsius colder. The only way to achieve this is to prevent the loss of body heat to the environment. This is a difficult task as body heat can be lost in three different ways:

- by heat conduction,
- by heat radiation and
- by evaporation.

The animals must control all three processes to conserve body heat. Homoeothermic species have developed a range of remarkable behaviours in order to minimize heat loss. Among others, these include:

- curling up into a ball (reducing the body surface to volume ratio),
- huddling together in a group for mutual warmth,
- withdrawing to a protected location,
- accumulating a warming layer of fat or a double layer winter coat or plumage, and
- cooling down their breath and extremities.

4.6 > Polar bears are very good swimmers and, as this large male demonstrates, they are also good divers. However, the animals get cold very quickly in the water. On long-distance swims mature bears with a thick layer of body fat for insulation have better chances of survival than juvenile bears.

To curl up means to make yourself as small as possible. Many species, from polar bears to Arctic redpoll, curl up into a ball in winter or draw in their head and limbs so as to minimize their body surface. The more spherical the body, the smaller is its surface to volume ratio and the less heat is lost by the animal by way of conduction or radiation. Polar bears often cross their paws over their muzzle as they lose most body heat from their nose and face which is covered in only sparse hair.

Animals living in groups, herds or colonies often stand closely together in order to warm each other and thus to minimize their own heat loss. The most well-known example is the circular "huddles" of emperor penguins in Antarctica. In winter when ambient air temperatures can be as low as minus 50 degrees Celsius and the males must stay on the ice to incubate the eggs, the birds huddle together by the thousands and so closely together that up to ten penguins may be squeezed up on a square metre of ground – back to belly, side-by-side and with the head placed onto the shoulder of the penguin in front. In the middle of this giant incubator the air warms to up to 24 degrees Celsius. This is however too warm for the birds at the centre who gradually seek to escape the heat. The birds on the margins meanwhile are cold and slowly push towards the centre. This is why the penguins continuously change their position and why the huddle is constantly moving with each bird at some point enjoying the warmth. In this manner these large birds are able to reduce their heat loss by half even during the harshest of winter storms. Arctic musk oxen display similar behaviour. On cold days the members of the herd form a tight circle, allowing the animals to warm each other and collectively remain relatively unimpacted by icy winds.

A third strategy employed to reduce heat loss is to withdraw to a protected area. This could be a cave or else the animals may curl up and let themselves get snowed in. Polar bears, wolves, foxes, hares and ptarmigans are known to at least temporarily seek shelter in snow dens during the winter. Smaller Arctic species such as lemmings or stoats must even spend most of the winter underneath the insulating snow cover due to their small size and the associated heat loss. Dependent on the thickness of the snow cover, temperatures may be as high as zero degrees Celsius, allowing these small mammals to survive.

Birds and mammals overwintering in the polar regions also protect themselves from the freezing cold by means of a dense winter coat or plumage. In mammals and birds which need to enter the water in search of food, or in whales which spend their entire lives in the ocean, a thick layer of fat (blubber) generally takes on this insulating function. Just how well feathers or fur can conserve body heat depends on two factors, one being the individual thermal conductivity of each individual hair or feather, the other being the degree to which the coat or plumage is able to trap an insulating layer of air near to the body, as the thermal conductivity of air is only half that of hairs or feathers. Presumably this is the reason why the guard hairs of caribou are hollow and internally sectioned into thousands of tiny air cells, each separated from the next by a thin wall. In this manner, the animals' guard hair does not only protect them from external influences such as snow or rain, it also forms a second and very effective layer of insulation in addition to the underfur.

The fur's insulating characteristics differ significantly between species, with the ability to retain heat generally increasing with the thickness of the layer of fur. The insulating effect of the fur or plumage can be further increased by fluffing up the plumage or erecting the hairs, thus trapping a greater amount of insulating air near to the body. Small furry mammals such as lemmings or stoats are clearly at a disadvantage when it comes to keeping themselves warm by means of their body hair. They need a short-haired coat that still allows them to move.

But the large mammals with rather thick coats must also pay attention to a number of factors so as to avoid dying of hypothermia. The polar bears' long guard hair for example provides superb insulation as long as the coat is dry. However, when the bear jumps into the sea, for example in order to swim from one ice floe to the next, water reaches the skin, and water conducts heat away from the body 25 times faster than air. At moments like that fully grown bears trust the insulation provided by their thick blubber which reaches a thickness of up to 11.4 centimetres. For bear cubs, however, a swim like that can be very dangerous as they lose heat very rapidly. They are similarly at risk when it rains as both rain and sleet considerably impair the functional characteristics of fur or plumage.

Icy winds can also result in significant heat loss. When wind passes through fur or plumage it swirls the layer of air close to the body, thus reducing its insulating function. Snowy owls, for example, that are exposed to 27 kilometre per hour winds at an ambient temperature of minus 30 degrees Celsius lose heat so quickly that in order to not freeze to death they need to generate twice as much heat as would be required if the air was still. In contrast, the guard hair and underfur of reindeer and musk oxen provides such complete insulation that the animals loose little or no heat even during winter storms.

Whales, polar bears and seals protect themselves from the cold by means of thick blubber. While the insulating capacity of this layer of fat is not as great as that of fur, it is also functional in the water where fur generally fails as a means of protection. This layer of fat can be impressively thick. In bowhead whales *(Balaena mysticetus)* it can reach a thickness of up to 30 centimetres. And just like the coats of reindeer and musk oxen, blubber also changes with the seasons, at least in seals. Their blubber is at its thinnest in summer when the animals' moult forces them to stay on land and fast. In the run-up to winter they fatten up again and blubber thickness increases.

Penguins such as Adélie and emperor penguins protect themselves from the icy cold by means of a plumage that offers superb insulation. However, when they are diving in the sea the feathers are compressed and the trapped air is expelled which means that the plumage loses its insulating properties. The birds' blubber then protects them to some extent from heat loss.

The queen of the tundra

The Arctic bumblebee species *Bombus polaris* is one of the first insects to be seen flying in the tundra in springtime. *Bombus polaris* differs from most other insects in that it is not greatly impacted by cold spring air. Even though as an insect it is an ectothermic organism, this bumblebee has found ways to stay warm. On sunny days the queen and her workers sit exposed to the sun for a while in order to warm up their bodies. The quickest way to do that is to bask inside an Arctic poppy flower *(Papaver radicatum)*. The petals of its conical flower act like mini-mirrors, reflecting sunlight into the centre of the flower.

When cloud cover impedes sunlight the bumblebees turn on their internal heating system – they begin to shiver their large flight muscles which allows them to bring their body temperature up to the minimum flight temperature of 30 degrees Celsius even if the ambient temperature is significantly lower. The Arctic bumblebee's thick coat of hair helps them to trap and conserve this heat.

Their ability to utilize thermoregulation allows the Arctic bumblebees to start foraging for food as early as May, at a time of spring when the cold still forces most other insects in the Arctic into a state of torpor. And this bumblebee is in a hurry – the queen's first task as the only member of its colony to survive the winter is to gather pollen and nectar in order to gain strength. Next she will build a nest in a subterranean burrow and produce an initial brood consisting only of workers as the foundation of a new colony. In late summer the queen lays eggs for a second time. This brood produces drones (males) and hundreds of queens. However, on average only one queen per colony survives the coming winter. The old queen dies along with the other members of its colony.

Bombus polaris occurs in the northern tundra regions of Alaska, Canada, Scandinavia and Russia and is considered a key pollinator in these regions. There is only one other bumblebee species, *Bombus hyperboreus*, that survives this far north of the polar circle. In cuckoo-like fashion its queens like to enter and take over Arctic bumblebee nests. They deposit their eggs and let *Bombus polaris* workers take care of the brood.

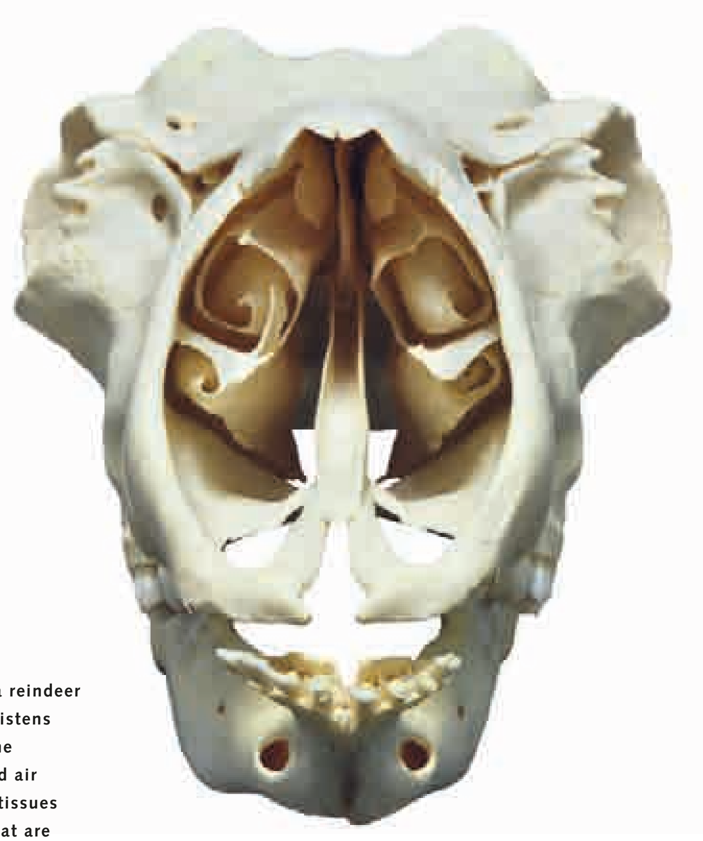
4.7 > The Arctic bumblebee species *Bombus polaris* flies even in cold weather. The inspect generates the body temperature needed for this by basking in the sun or by shivering its flight muscles.

Physiological protective mechanisms against heat loss

Animals can also prevent the loss of body heat by conduction if they cool down external body parts or their limbs while maintaining a constant body core temperature. This type of behaviour is displayed by, for example, reindeer, emperor penguins and gulls. Under certain circumstances they are able to lower the temperature of their feet to close to freezing while their body core temperature remains at a normal level.

The often badly insulated extremities can be cooled down to this extent as the blood vessels in legs, wings or flippers are located so closely together that heat can be exchanged between arteries and veins. Warm arterial blood originating in the centre of the body passes on its heat to venous blood which had previously cooled down in feet or fins and is being transported back towards the body core.

In this way, only blood already cooled down reaches the extremities, thus greatly reducing heat loss from feet, flippers or wings.



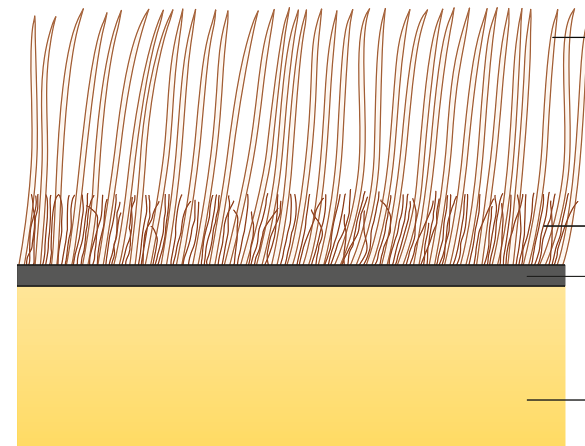
4.8 > When a reindeer inhales it moistens and warms the incoming cold air by means of tissues in its nose that are richly supplied with blood vessels. These tissues are supported by curled, thin bone structures, clearly visible in this photo of a reindeer skull.

Reindeer have such long legs that the close proximity of veins and arteries alone is sufficient for heat exchange. In the seals' short flippers, however, the heat exchange is amplified by the veins branching into blood vessels surrounding the centrally located artery which conducts heat to the veins. Moreover, the animals can regulate their blood flow and thus also the heat supply to their extremities – they may want to reduce heat loss in a cold environment, or they may want to quickly cool down, for example following major exertion or when they are at risk of overheating.

Surprisingly, the animals do not lose sensation in their wings, flippers or paws even when these have become very cold. Impulse transmission in nerves and muscles of the ball of the foot of Arctic wolves and foxes continues to function even when the animals stand on cold surfaces with temperatures down to minus 50 degrees Celsius and their paws have cooled down to freezing point. Studies have shown that the muscles and nerves in poorly insulated extremities still function when the tissue has reached a minimum temperature of minus six degrees Celsius – an adaptive mechanism that appears to be widespread among mammals and birds in high and medium latitudes.

A similarly sophisticated system helps animals to not unnecessarily lose heat and water vapour to the environment when breathing. When a human exhales at an ambient temperature of minus 30 degrees Celsius, one can see the roughly 32 degree Celsius warm and moist breath as it exits the nose in the form of a light cloud of vapour. Reindeer, in contrast, do not produce such a cloud. The air they exhale is dry and cooled down to 21 degrees Celsius, thus reducing water and heat loss to a minimum. Once again, the secret of these energy savings is effective heat exchange which in this case happens in the nose. In contrast to the human nose, the nasal cavity of reindeer contains numerous convoluted muscous and other membranes that are richly supplied with blood. This nasal structure is highly beneficial in two ways: Firstly it increases the surface area of muscous membranes along which inhaled or exhaled air passes. This gives the reindeer sufficient opportunity to expel or retain heat and water in its breath. Secondly, the complex nasal anatomy divides the breath into numerous thin layers of air, thus further optimizing heat exchange.

When a reindeer inhales, the icy cold polar air passes over the well-perfused nasal membranes. In less than a second it is moistened and its temperature is raised to the animal's body temperature. The air reaching the lungs has a temperature of 38 degrees Celsius and is sufficiently moist to ensure optimum oxygen uptake. As a result of the heat transfer to the inhaled air, the membranes briefly cool down. When the animal exhales, its warm breath once again passes the now cooled nasal membranes and transfers back some of the heat. This cools down the breath to 21 degree Celsius and most of the water vapour it contains condenses. This mechanism ensures that reindeer exhale only cool and dry air, thus saving a great deal of body heat and moisture. The latter is critical in particular when all ponds, rivers and lakes are frozen during the winter and the animals are forced to consume snow in order to obtain water.



4.9 > A thick layer of blubber and warming underfur protects polar bears from losing body heat to their environment. Moreover, the transparent guard hairs allow for solar radiation to reach the skin which means that the bears can warm up in good sunny weather.

Despite their thick winter coat and their sophisticated heat-conserving mechanisms it is possible for the animals to lose heat and for their body temperature to drop to dangerous levels. When this happens, most of the animals increase their metabolism and begin to shiver, generating heat by means of muscle contractions. Wind and moisture generally accelerate heat loss while sunshine can help the animals to maintain their body temperature. Harp seals, for example, bask in the sun when they are cold, a strategy also employed by polar bears. Their long transparent guard hair is particularly suited to letting solar radiation pass through, allowing for its optimum absorption by the bears' black skin.

The polar bears' guard hair also has another special characteristic. It absorbs the longwave heat radiated by the bears themselves. Simply put, it re-absorbs much of the heat radiated by the bears despite their thick underfur. This means that the animals lose very little heat from their body surface. However, this can also be disadvantageous, for example when the bears move swiftly. It can quickly put them at risk of overheating. This is the reason why most of the time polar bears move at a rather leisurely pace. And if they ever get too hot after all, these largest of all terrestrial Arctic predators cool down by jumping into the water.

That option is not generally available to reindeer, even though they often overheat especially in winter under conditions of great exertion. At such moments, reindeer cool down the most critical parts of their brain by directing cold blood from their nasal membranes through a facial vein towards their brain. Just before reaching the brain, a heat exchange takes place with the blood flowing through the carotid artery. This mechanism ensures that only blood at normal temperature circulates in the brain while the surplus heat is distributed to the rest of the body until such time as the strain has subsided and the heat can once again be exchanged by the nasal membranes.

Thermoregulation in young animals

In the polar regions, animal offspring is born at very different times and under a variety of conditions. Nonetheless, all young animals have one thing in common – their ratio of body surface to body mass is significantly worse than that of their parents, which means that young animals suffer relatively greater heat loss. Most of them are born without fur or plumage, or if they are, then its insulating powers are not nearly as good as their parents' coat. This is a particularly perilous situation if the young birds or mammals are wet at birth.

Polar birds and mammals have developed special behaviours to ensure that their offspring have a chance at survival. Altricial species the young of which require a lot of parental support at the start, such as polar bears or lemmings, generally give birth at a protected location, such as

4.10 > As can clearly be seen in this infrared image, polar bears primarily lose body heat from their noses which are only sparsely covered in fur.

a snow cave, den or nest. While a polar bear female is forced to fast for the first three months after giving birth because she never lets her cubs out of her sight, lemming females must leave their young at times in search of food while their pups stay behind in the burrow on their own. During this period the baby lemmings' body temperature drops to well below 20 degrees Celsius but this does not kill them. During the first days of their lives they are surprisingly immune to cold. The older the pups are, the better they get at regulating their own body temperature. The strategies they employ include muscular heat generation (shivering), a thicker fur, or the burning of fatty acids from their brown fat, a process often described in the special literature as nonshivering or biochemical thermogenesis.

Brown fatty tissue can be found in almost all newborn mammals. Its cells are significantly smaller than those of the white, insulating fatty tissue. It contains many small lipid droplets and a particularly large number of mitochondria, the cells' power plants. The breakdown of lipids in mitochondria generates heat which enables a variety of polar mammal species to survive.

In contrast, newly hatched birds are dependent on being kept warm by their parents. Antarctic procellariids (a group of seabirds including petrels and shearwaters), for example, hatch at an average temperature of minus 25 degrees Celsius on bare rock. Once the chicks are hatched, their parents must keep them warm for at least eleven days. The chicks of emperor penguins hide in their parents' brood pouch for up to 50 days – initially that of the male, and subsequently in the female's brood pouch when she returns from the ocean and for the first time feeds the chick food sourced at sea.

Reindeer calves and ptarmigan chicks must stand on their own feet from day one. They are precocial species. Unlike penguin chicks they are born with their own protection against the cold. Ptarmigan chicks hatch with warming plumage, are strong enough to walk long distances even on their first day, and are able to maintain their body temperature by means of breast muscle shivering. Nonetheless, the little ptarmigans seek their mother's warmth when their body temperature drops to below 35 degrees Celsius. Young reindeer and musk oxen get cold in particular when there is wind, rain or sleet. At such times their coat loses its warming traits much faster than that of their parents. The offspring primarily resorts to the burning of lipids from their brown fatty tissue in order to stay warm. Most seal pups in the polar regions must also avoid the water. They are born with a woolly and normally white covering of lanugo which only keeps them warm as long as it stays dry.

Body heat generation requires energy which the offspring of mammals obtain from their mothers' milk. The milk of species that are at home in the polar regions is particularly high in fats. In whales, seals and other marine mammals the milk's fat content is between 40 and 50 per cent, while the milk of terrestrial species contains between ten and 20 per cent fat. (For comparison: normal cows' milk has a fat content of roughly four per cent.) The young of different species are suckled for different lengths of time. While hooded seals nurse their pups for only two to four days, walrus calves suckle for more than a year.

When food becomes scarce

Animals in the polar regions must not only deal with extreme air and water temperatures. They are also faced with the challenge that they can only find sufficient amounts of food at certain times of the year. Different species solve this problem in very different ways. Musk oxen, for example, can lower their metabolism by 30 per cent. Similar observations have been made in Arctic foxes, Arctic hares and ptarmigans. The animals also limit their movement radius in order to save energy. Reindeer on Spitsbergen spend up to 80 per cent of the day in a standing or lying position during the winter as any amount of exertion and any additional step in the snowy terrain has a price. If the animals begin to trot their energy consumption quadruples even if the herd moves at only a moderate pace of seven kilometres per hour.

For this reason, most of the animals build up major fat reserves in times of plenty as something of an "insurance policy". As early as in August, ptarmigans on Spitsbergen begin to eat anything and everything they can find. By November the birds will have gained so much weight that their layer of fat comprises 30 per cent of their bodyweight. They do however need this amount of reserves as the birds need to draw on these whenever winter weather makes it impossible for them to search for food, for example when there are heavy storms. By February the birds have generally exhausted their fat reserves. In reindeer and musk oxen the quantity of fat reserves also determines whether a female is fertile and able to produce offspring.

The Arctic ground squirrel *(Urocitellus parryii)* is among the few polar species that sleep through the winter. Despite the fact that the squirrels' body temperature drops down to as low as minus three degrees Celsius, their blood does not freeze and their organs and tissues are not damaged by ice crystals. To avoid death by hypothermia the animals wake up every three weeks from their state of torpor and begin to shiver for one or two days which raises their body temperature back up to 34 to 36 degrees Celsius. In the course of this process the squirrels burn a lot of fat which they had accumulated during the short summer. They then fall back into hibernation.

In polar bears, only pregnant females spend the winter in a snow den where they also give birth to their cubs. Juvenile bears and adult males are more or less active throughout the winter; after all they need to accumulate a great deal of body fat as long as the sea ice allows them access to the seal territories.

4.11 > An Arctic ground squirrel is curled up in its den on a bed of moss and sleeps through the winter which can last for seven to nine months. The animals are active only during the short Arctic summer.

Since seals moult once a year they too face a regular period of fasting. During this time the animals stop searching for food and reduce their metabolism by half. They generate body heat and kinetic energy solely by drawing on their fat reserves. In contrast, Arctic foxes and stoats do not solely rely on their accumulated body fat. They also hoard food, a task that keeps them busy from September to November. Some animals hide their kills in many different places while others store them all in one place. The biggest known hoard of an Arctic fox contained 136 seabirds which the predator had apparently taken at a breeding colony. For stoats there are reports of individual animals accumulating as many as 150 killed lemmings in winter stores.

Adaptations to light conditions

One of the polar regions' unique characteristics is the change between long periods of daylight in summer (polar day) and long periods of darkness during the winter (polar night). In the interim periods, light conditions change so fast that in places such as Spitsbergen or in northern Greenland day-length increases or decreases by 30 minutes per day. These changes require constant behavioural adaptations on the part of the animals, as the available light not only determines the animals' daily rhythm but also their annual calendar and thus the timing of important events such as mating, hibernation or moulting. This is true not only for organisms residing in the southern and northern polar regions but also for the animals in the rest of the world.

The animals' internal clock is regulated by means of biochemical processes which commence when information on light conditions is received by special light-sensitive neurons in the eyes' retina. The signals are transmitted along neural pathways, first to the suprachiasmatic nucleus and subsequently to the pineal gland. The former is a nucleus within the brain; it is situated in the hypothalamus and is, just like an internal clock, responsible for controlling the circadian rhythms of mammals. The pineal gland is located at the back of the midbrain. Only during periods of darkness does it produce the hormone melatonin which is then released into the blood and the cerebrospinal fluid. This means that with decreasing night length, the amount of melatonin in the body also decreases and in turn so does its process-inhibiting impact.

Simply put, melatonin synchronizes all the processes taking place in an animal's body and adapts its internal clock to the current time of day and season. However, polar species display a special characteristic in this respect. While most animals outside of the Arctic and Antarctic are active during the day and rest at night, Arctic and Antarctic species adapt their behaviour to the current light phase.

Arctic ptarmigans are a good example. During spring and autumn when the sun rises and sets they search for food in the morning and evening, just like many other bird species. However, during the phases of constant darkness and constant brightness respectively the birds are basically searching for food around the clock except for some breaks. This same pattern of behaviour has been observed in reindeer on Spitsbergen and in Adélie penguins. Similarly, it is known that male emperor penguins do not have strikingly high levels of melatonin even during the polar night. The animals thus do not display typical diurnal rhythms during the polar day and polar night.

It is easier for reindeer than for other animals to search for food even during long periods of darkness as they are able to detect light in the ultraviolet spectrum. This ability provides them with a crucial advantage. Since snow and ice largely reflect incoming ultraviolet light, the animals see the landscape as a light-coloured surface. In contrast, anything that absorbs UV light appears black to them. This includes lichens, the reindeer's main food source during the winter. But white fur (polar bears) and the fur of wolves also only reflect a small portion of UV light. The reindeer can therefore detect potential attackers at an early stage which greatly increases their chances of survival.

Scientists also assume that the UV light allows the animals to detect the texture of a snow surface, since the proportion of reflected UV light changes with the snow cover's physical characteristics. Presumably the herds are able to see at first glance whether it is worth searching for food in a particular place, or whether they would be better off taking a little detour because the snow in a particular location is too harsh or too soft to cross.

Changing colour at the start of winter

The changing light conditions also signal the start of the typical moult which gives Arctic foxes, Arctic hares, stoats and other animals their mostly grey or brown summer coat and their white winter coat. In the temperate and polar latitudes of the northern hemisphere there are 21 species of mammals and birds at present that change colour with the seasons. This means that the animals have to grow an entirely new coat or plumage twice a year. While the evolution of seasonal colour changes is not yet fully understood, presumably the species developed this ability independently of each other. Interestingly, however, different species in a region change their colour almost at the same time and hold onto their winter plumage or winter coat for a similar period, in alignment with the general local timing of the first snowfalls and the length of time the snow cover tends to persist. Species living in areas with highly variable or patchy snow cover have also adapted their coat colour to these conditions. Their winter coat or plumage contains a number of pigmented hairs or feathers and generally appears speckled whitish-brown or whitish-grey.

Scientific research has been conducted into the purpose of the colour change. The results indicate that it primarily serves camouflage and thermoregulation. A white coat or plumage in winter is highly advantageous for both predators and prey. If the landscape is covered in snow, both groups are harder to be spotted by their respective adversaries. The former has greater prospects of catching food while the latter has a greater chance of survival. For this reason, scientists consider a species' ability to camouflage themselves as being one of the primary drivers in the evolution of mammalian coat colour.

However, an animal can only optically become one with its environment if the moult and the onset of snowfall or snowmelt take place more or less at the same time. If the onset of winter is delayed or if the snowmelt starts much too early in the year, the animals have the wrong coat colour and their evolutionary advantages turn into disadvantages. It is for this reason that species which change their coat colour face a greater threat to their existence from climate change than animals that maintain their coat colour.

Scientists consider birds to be an exception to this rule as often their self-awareness is so strong that they notice the discrepancies between the colour of their environment and their plumage respectively and adapt their behaviour accordingly. Rock ptarmigan and white-tailed ptarmigan,

4.12 > Rock ptarmigan, Arctic hare, stoat and Arctic fox are among the world's 21 animal species that change the colour of their coat or plumage with the seasons. This makes it harder for both predators and prey to be spotted and increases their chances of survival. Often the winter coat or winter plumage also has better insulating properties compared to the summer coat or plumage.

for example, only rest in locations where the dominating ground colour matches that of their plumage. And researchers in Canada observed ptarmigans that deliberately dirtied their plumage when the snowmelt began too early and the birds in their clean white winter plumage were at risk of being detected too easily.

Another effect of the change from summer to winter coat is that the animals improve their furs' insulating properties. Colourless or unpigmented hair tends to be somewhat broader than pigmented hair or it contains a greater number of air-filled chambers, thus improving its insulating qualities. Additionally, the white winter coat is often longer and denser than the summer coat. This is true for the Arctic fox, the northern collared lemming *(Dicrostonyx groenlandicus)* and the Djungarian hamster *(Phodopus sungorus)*.

Just like many other processes, the moult is triggered by changes in melatonin concentrations. When melatonin increases in the autumn, signals are transmitted to the pituitary gland which produces the growth hormone prolactin, among others. This hormone in turn regulates hair growth and other functions. When the prolactin concentration rises in the spring, collared lemmings and Arctic hares lose their winter coat and commence their search for partners. However, if the production of this hormone is suppressed, Arctic foxes, lemmings and other animals produce their light-coloured winter coat. In experimental studies, mammals whose prolactin production was suppressed kept their winter coat throughout the entire year, independent of day-length.

Vascular plants
The term vascular plants is applied to all ferns and seed-producing plants, as these have internal vascular tissues which distribute resources through the plant.

But melatonin also inhibits the production of the pigment melanin which gives skin, feathers and eyes their colour. In animals with seasonal coat colours, a high melatonin concentration thus directly results in the growth of a white winter coat. There is less of an understanding as to how day-length and hormones regulate the moult and change of plumage in birds. In part this is due to the fact that birds have at least three "internal clocks". Information regarding changing day-length is processed not only in the pineal gland, but also in the hypothalamus and in the eyes themselves. Moult and reproduction are coordinated such that the change in plumage does not commence before the breeding period has finished.

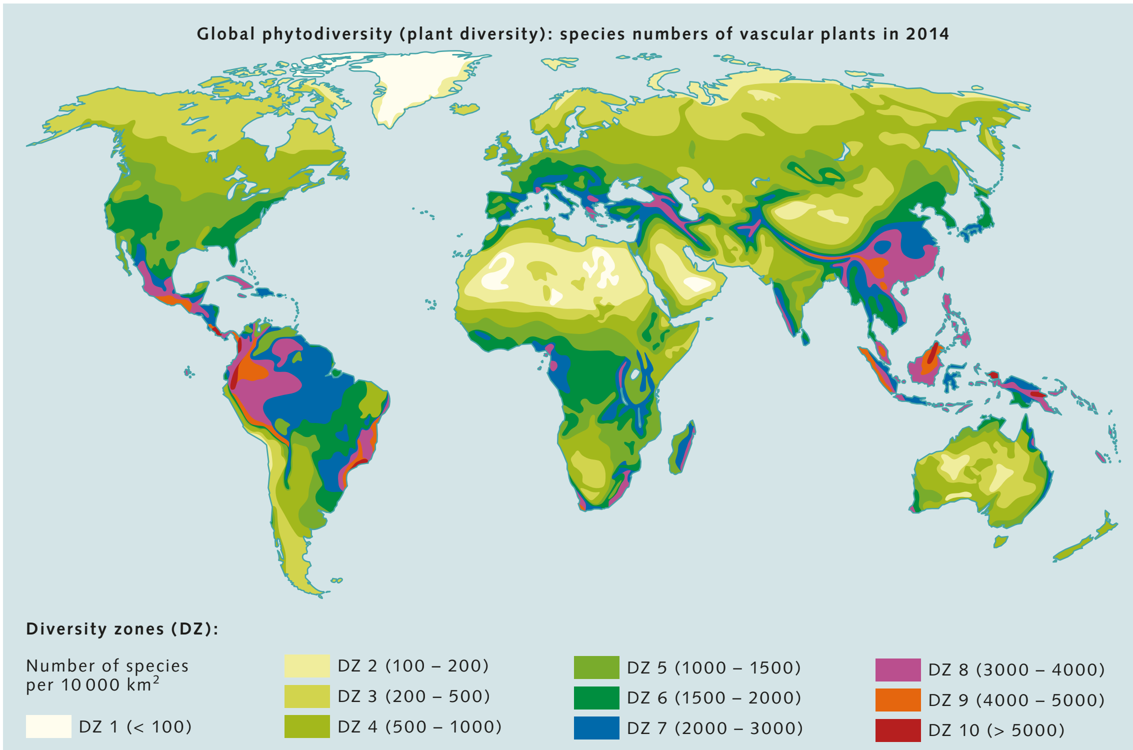
In contrast to day-length, environmental factors such as temperature and snowfall only have a limited impact on the change in coat or plumage. Studies have shown that low autumn temperatures accelerate the growth of winter coats or plumage in mammals and birds respectively. Moreover, ptarmigans were shown in experiments to produce a darker winter plumage if they were kept at higher temperatures. In contrast, a cold spring with plenty of snow slowed down the change from winter to summer colour. The moult, however, is solely triggered by day-length.

The flora of the polar regions

Despite their extreme climate, the north and south polar regions host a remarkably rich flora in places. For example, in the Arctic researchers have counted almost 100 different species of vascular plants, mosses and lichens in an area of 25 square metres, making the site examined roughly as species-rich as the most species-rich grasslands of the temperate and subtropical latitudes. Compared to tropical rainforests, however, the polar regions are indeed species-poor. This is primarily due to the low temperatures, the short growing season, the lack of nutrients, the difficulty of rooting in permafrost soils, and extreme weather events in the Arctic such as the typical spring floods. Moreover, growing conditions for plants in the polar regions are often greatly divergent between locations. On the Siberian Taymyr Peninsula, for example, a mere 500 kilometres separate the sub-Arctic with its relatively lush growth from the polar desert of the High Arctic in which only few plant species survive.

The vegetated lowlands of the Low Arctic are also termed tundra. This term is derived from the word *tūndar* which, in the language of the Saami, the original inhabitants of northern Scandinavia, means "a plain devoid of trees". While in addition to grasses and vascular plants willow, birch and alder, all of which have tree relatives further south, do indeed grow in the tundra, they do not grow up high in the classic tree shape but form creeping scrub or mats just above the ground, not least in order to escape the icy winds. In the northernmost areas of

4.13 > Blueberries in the Arctic ripen only towards the end of summer. The Inuit say it is incredibly laborious to gather them as the plants grow so closely to the ground that one has to crawl through the tundra on all fours in order to pick them.



4.14 > Vascular plant species diversity is highest in the tropics and declines with increasing latitude. In the Arctic, the regions relatively species-rich are primarily those that were not glaciated during the past ice ages.

Siberia, on the eastern and western coasts of Greenland, in the Canadian Arctic Archipelago and in the north of Alaska the areas of tundra grade into the High Arctic with its thin vegetation cover dominated by lichens, mosses and dwarf vascular plants. To its south, the tundra is in many areas bordered by the subarctic krummholz zone consisting of climatically stunted and distorted trees.

Vascular plant species diversity in the polar regions declines with increasing proximity to the poles. In the Arctic, the current vegetation of which has only developed over the past three million years, an estimated 900 species of mosses and 2218 species of vascular plants have been identified. Almost all of the vascular plants are flowering plants (angiosperms). Gymnosperms, in contrast, are rare in the Arctic and where they occur their species diversity tends to be low.

The majority of Arctic plants are considered to have a circumpolar distribution. Nonetheless there are major differences between different regions in terms of their species diversity and composition. While a mere 102 species occur in the northernmost part, the High Arctic, the southern tundra regions host more than 20 times that number of species. Approximately five per cent of Arctic vascular plants are endemic species, which means that they occur nowhere else but in the Arctic. Those species are mainly forbes and grasses.

The diversity of the Arctic flora is also supported by herbivores. When researchers excluded grazing animals such as geese, lemmings, musk oxen and reindeer from certain areas as part of a study, large amounts of plant litter accumulated, insulated the soil and led to the soil not thawing to a sufficient depth in the summer. Vascular plants could no longer develop a sufficient root network and disappeared. Mosses now grew in their place. Moreover, the herbivores' faeces provide badly needed nutrients, as nitrogen and phosphates are scarce in Arctic soils.

Compared to the Arctic, the Antarctic flora is truly species-poor. In its continental zone, defined by biologists to include the few ice-free areas of continental Antarctica

Angiosperms and gymnosperms
Angiosperms are flowering plants and are characterized by the enclosed ovary, which contains and protects the developing seeds. In contrast, gymnosperms are characterized by the unenclosed condition of their seeds. Gymnosperm seeds develop lying unattached on the surface of individual carpels. European larch and Scots pine are well-known gymnosperms.

4.15 > Biologists differentiate three vegetation zones in the terrestrial north polar region. The High Arctic is the northernmost zone. It borders on the tundra of the Arctic lowlands, and the tundra in turn borders on the northern margins of the boreal zone.

and the eastern side of the Antarctic Peninsula, only a small number of 40 to 50 different species of lichens and mosses thrive. These generally grow in rock crevices or depressions between stones and mainly on dark rocky ground which absorbs most of the incoming solar energy and radiates heat. Most of these lichens are truly extreme survivalists. Even at a temperature of minus ten degrees Celsius they can still photosynthesise and survive even under conditions of strong and persistent desiccation and extreme cold. Some of the species occur even in the ice-free Antarctic dry valleys of Victoria Land.

The western side of the Antarctic Peninsula and the nearby islands offer a warmer and moister climate and thus more favourable conditions for plants. In this zone, termed the maritime Antarctic, two vascular plant species can be found – Antarctic hair grass *(Deschampsia antarctica)* and Antarctic pearlwort *(Colobanthus quitensis)*. The bulk of the Antarctic vegetation, however, is composed of cryptogams. Some 100 species of mosses have been recorded as well as 750 species of lichens and an estimated 700 species of terrestrial and oceanic algae. The number of fungus species has not been determined.

Fighting the cold

With increasing proximity to the poles, conditions for plants deteriorate, or to put it differently, physical and chemical factors which limit plant dispersal have increasingly greater impact. These factors include, for example, the length of the growing season, the duration and intensity of frost periods, and the degree to which the plants are exposed to wind. However, the plants' chances of survival are also linked to available resources. Whether they are in the tropics or in the polar regions, plants can only exist if their carbon budget is positive, which means they must be able to sufficiently photosynthesise in order to grow and store energy reserves in the form of glucose or starch. To this end the plants require sufficient amounts of heat, water, light, carbon dioxide and nutrients as well as oxygen. The latter is required in particular by plants growing in wetlands or swamps.

The polar regions rarely offer ideal conditions for plant growth. The Arctic flora has therefore developed a range of adaptation mechanisms that allow them to tolerate conditions of nutrient deficiency, cold and darkness and to survive with little or no harm extreme events such as prolonged snowfall or spring floods. These adaptations include the following:

- slow, resource-conserving growth,
- a more brown than green coloration,
- a squat stature,
- heat-optimizing characteristics such as fine hairs or special flower shapes,
- mechanisms to protect cells from frost damage,
- a large number of important enzymes enabling photosynthesis even in adverse light conditions,
- nutrient recycling,
- major energy reserves in the root system, and
- the opportunity of asexual reproduction at locations where conditions are such that sexual reproduction does not work.

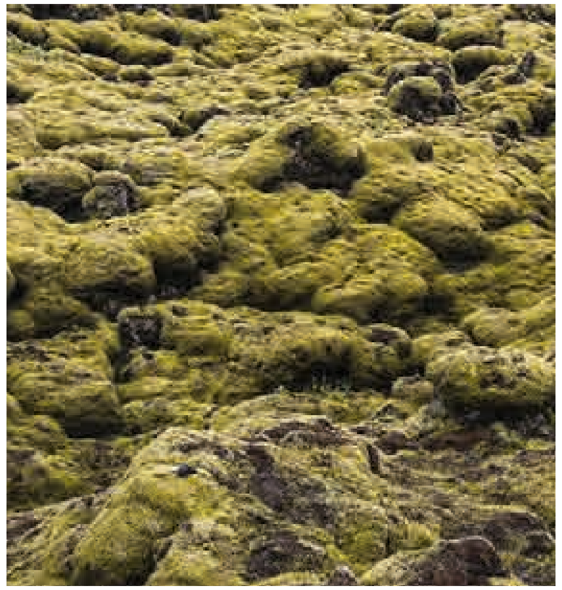
Small is beautiful

Polar plants particularly like to settle in sheltered locations where they are not exposed to the full forces of the wind, ice and cold. A second important survival strategy is to grow slowly and reduce energy consumption especially at times of low resource availability. This approach is known as the Montgomery effect, named after Edward Gerrard Montgomery, a scientist at the University of Nebraska Agricultural Experiment Station (USA). When conducting experiments involving a variety of cereal cultivars he found that in locations offering low environmental resources slow growth does indeed confer ecological benefits onto plants. In the Arctic, for example, the summer and therefore the growth phase is so short that plants such as the Arctic wintergreen *(Pyrola grandiflora)* growing in Iceland and Greenland take several years to grow from the initial sprout to a mature plant capable of seed production. This also explains the longevity of many plants in the polar regions.

The tiny pygmy buttercup *(Ranunculus pygmaeus)* is a species that has perfected prudent resource use. It often grows surrounded by mosses in the vicinity of glaciers, streams or snow drifts and survives even if it is occasionally covered by so much snow in the winter that this snow does not melt in the course of the following summer, resulting in the plant missing out on an entire cycle of growth and reproduction. Other species are so thrifty in their resource use that they can persist for even two or three years in series underneath a snow cover. These include Alpine bistort *(Polygonum viviparum)*, mountain sorrel *(Oxyria digyna)* and polar willow *(Salix polaris)*.

The small and squat stature of many polar plants is not only a result of their drawn-out growth. Plants forming thick ground-covering carpets instead of having their leaves and flowers shoot upwards will escape the icy Arctic winds. The air held inside these carpets or cushions is swirled to a lesser degree and is more easily warmed by the sun. In this manner the carpeting plants create their own microclimate, the temperature of which may reach 25 to 30 degrees Celsius on summer days when the ambient temperature at a height of two metres is a mere eight degrees Celsius. The plants inside the carpet thus enjoy optimum metabolic conditions at such times.

In order to grow and flower during the short and cool summer, polar plants also employ strategies which in warmer regions would lead to immediate death from heat stress. One of the strategies is coloration. Darker colours



4.16 > Mosses colonizing a lava field in Iceland. The Arctic is home to some 900 species of mosses. They can mostly be found in Arctic wetlands and on snowbanks.

4.17 > Alpine bistort *(Polygonum viviparum)* is one of the Arctic plant species that can persist underneath a snow cover for periods of more than two years.

4.18 > Antarctic hair grass *(Deschampsia antarctica)* is one of the two vascular plant species that are native to the Antarctic continent.

4.19 > The white petals of the flowers of glacier buttercups *(Ranunculus glacialis)* reflect sunlight towards the centre of the flowers which makes them very attractive to insects.

4.20 > The white cotton-like plumes of cottongrass are a familiar sight in Arctic wetlands. However, these are not the flowers but only develop along with the seeds. The long perianth bristles form white tufts which also protect the seeds from the cold.

absorb a greater amount of solar radiation than lighter colours. This explains why the vegetative cover in many of the Arctic areas appears predominantly brown instead of green. This is particularly true for plant communities on Arctic beaches where the growing season is particularly short.

Moreover, plants like the glacier buttercup *(Ranunculus glacialis)* are able to align their leaves and flowers at an optimum angle to the sun. Its initially white flowers then function like little parabolic dishes which direct the incoming sunlight directly to the reproductive organs at the centre of the flower. This increases the air temperature inside the flower which in turn results in the reproductive organs developing at a faster rate and in the flowers attracting a greater number of insects. Following pollination the glacial buttercup closes its flowers and the petals turn red, allowing the flower to absorb a greater amount of solar radiation, the heat content of which in turn protects the seeds developing inside the flower.

Other Arctic plants create their own "greenhouse". Female polar willows *(Salix arctica)*, for example, grow fine downy hairs on their leaves and along their inflorescences. This downy cover traps an insulating layer of air close to the leaf surface. The hairs also reduce the leaf surface area which normally would be subject to heat loss as a result of evaporative cooling. The downy hairs so efficiently protect the little willows that the temperature of the leaves may be up to eleven degrees Celsius higher than the ambient temperature.

Northern plants also avoid growing their roots deep into soils where much of the ground stays frozen throughout the year and where meltwater accumulates. Instead they take root in the shallow layer of topsoil which is the first to melt in springtime and generally tends to be waterlogged only for short periods. At the end of the summer, trees and shrubs drop their needles and leaves and overwinter in a dormant bud stage. Before they go dormant, however, they cover their buds in a wool-like substance in order to protect them from the frost.

Many Arctic plant species defy the freezing cold winter temperatures by moving water, among other substances, from their cells into intercellular spaces. In this manner the plants reduce the risk of ice crystals forming inside of cells and damaging these. The plants simultaneously strengthen the cell membranes with certain types of sugars and proteins; the membrane's lipid composition also changes. Special enzymes prevent the cells from suffering damage due to dehydration. However, these cellular frost protection mechanisms are not activated year-round. They only play a role when temperatures drop at the end of summer and the plants are acclimatizing. At the height of winter most plants are so well protected from frost damage that some even survived laboratory trials as part of which they were briefly dipped into liquid nitrogen at a temperature of minus 196 degrees Celsius.

However, problems arise when unusually warm periods and severe frost alternate during the winter or when normally snow-covered areas suddenly become free of snow. These kinds of conditions can damage even the hardiest of Arctic plants. Nonetheless, in most cases the plants will be able to compensate for such damage by growing new leaves and shoots in the spring.

Making the most of the short summer

Plants need active enzymes in order to take up carbon dioxide, to photosynthesise and to generate energy reserves in the form of glucose and starch. Cold-adapted plants of the polar regions contain a particularly high level of active enzymes. Large quantities of the enzyme RuBisCO (Ribulose-1,5-bisphosphate carboxylase/oxygenase) allow the Arctic flora to uphold metabolic activity even at lower temperatures. But even polar vascular plants cannot grow at subzero temperatures. The plants must wait for the short summer in order to develop leaves and flowers and they must be able to make optimum use of this short period. The cells of cold-adapted plants contain particularly high numbers of mitochondria which, as the cells' "power plants", are responsible for energy generation. With their help the plants increase their metabolism to maximum levels during the summer. Not only do they make optimum use of the 24 hours of daylight but they are also able to photosynthesise in unfavourable light conditions.

This strength, however, makes the cold-adapted plants susceptible to heat stress. If the ambient temperature rises to greater than average levels, both metabolism and cellular respiration increase well beyond healthy levels. The plants then swiftly use up all their energy reserves and suffer damage. This explains why polar plants of the Arctic do not spread further south. It also highlights one of the mechanisms by which climate change poses a risk to polar plants. Rising temperatures increase the probability of cold-adapted plants succumbing to exhaustion.

Searching for nutrients

Some plants actively seek out resources so as to have sufficient amounts of nutrients and light at their disposal during the short growing period. They develop small shoots or runners above or below ground which they use to tap into light and nutrient sources away from their original location that are crucial to their survival. This strategy can offer the plants clear locational advantages, as a comparison between two closely related cottongrass species has shown, both of which grow in Arctic wetlands.

Common cottongrass *(Eriophorum angustifolium)* develops runners and actively searches for minerals, an ability that allows the plants to survive in the very wet parts of the marshes. Their runners tolerate stagnant water and allow the species to spread into flooded areas. In contrast, the hare's-tail cottongrass *(Eriophorum vaginatum)* does not send out shoots into its nearby environment. It grows instead as tussocky grasses and thrives in particular in the drier locations where there might be significant water level fluctuations.

The energy reserves produced by the plants by means of photosynthesis during the short summers tend not to be invested into the development of new leaves but are mostly put into subterranean storage in the form of starches in the plants' roots. Therefore the root systems of Arctic plants are generally larger than those of plants of temperate or tropical latitudes. It makes sense for the plants to accumulate significant reserves in the north polar region with its highly variable weather conditions; there is always a possibility that they might miss out on one or even two growing periods while buried under snow, a time during which they must live on their reserves. It is for this reason that plants of the tundra such as bog-rosemary *(Andromeda polifolia)* store up to 75 per cent of their energy reserves in their roots.

Nutrients such as nitrogen, phosphorus and potassium are also particularly valuable to polar plants. Plants such as the dwarf birch *(Bitula nana)* have therefore found ways to recycle them once they have taken up and processed such elements. Shortly before the birch drops its leaves at the end of summer the plant withdraws a major proportion of the nutrients stored in these leaves back into the more permanent plant body. Hare's-tail cottongrass employs the same mechanism; it can recycle 90 per cent of the phosphorus contained in its leaves, which means that in the springtime the plant only needs to newly take up ten per cent of its phosphorus requirements from the soil.

Two ways to reproduce

Most animal species rely on sexual reproduction for their species' survival. In contrast, plants often have the option of asexual reproduction. They may form runners, branches or even seeds, with the latter being produced in the absence of classic pollination (agamospermy). These strategies have allowed several plant species at home in the Arctic to persist for centuries or even millennia, one example being Arctic sedges such as *Carex ensifolia*.

Sexual reproduction in vascular plants may fail either because of a failure to develop flowers or because pollination could not take place. In some species the latter may be caused by even just a brief cold spell. In the northern range of the American dwarf birch *(Betula glandulosa)*, for example, only 0.5 per cent of birch seeds germinate. In order to survive in these regions the species has no choice but to resort to asexual reproduction.

In the springtime shortly after the snowmelt the tundra suddenly bursts into bloom. This spectacle is primarily caused by perennial plants. With very few exceptions there basically are no annual plant species in the polar regions. In order to develop flowers in such a short time-frame, Arctic plants need flower buds which have already been initiated in the autumn and which can immediately kick into action following the snowmelt.

The many flowering plant species of the Arctic are primarily pollinated by flies, which is not very surprising as there are hardly any bees north of the polar circle. When scientists in Greenland took a closer look at the insects responsible for pollinating mountain avens *(Dryas octopetala)*, a characteristic plant of the Arctic, they counted a total of 117 different insect species which visited the plant. However, pollination was primarily performed by a single species, a small relative of the housefly called *Spilogona sanctipauli*.

To spend the winter in the form of a seed in the soil is a globally widespread and highly successful survival strategy of plants – this is no different in the polar regions. When scientists studied the flora of Spitsbergen they found that 71 of the 161 native plant species produced seeds in order to ensure the survival of the species. The same strategy is employed by the only two Antarctic flowering plant species. Plant seed longevity varies around the globe. While the seeds of some species persist in the soil for less than a year, some Arctic plant seeds display surprising levels of resilience. As part of scientific studies, seeds of the sedge species *Carex bigelowii* which were approximately 200 years old were still able to germinate; and in Alaska seeds of the small-flowered woodrush *(Luzula parviflora)* germinated after an estimated 175 years in the ground. If one day environmental conditions were to rapidly deteriorate, these species would therefore be in a position to persist as seeds in the soil for several decades or even centuries, and to germinate once conditions have become more favourable.

Over the past two to three million years, the flora of the polar regions has displayed a remarkable capacity to survive and adapt, and especially in the Arctic a rich diversity of species has emerged. Global warming will now pose new challenges for the cold-adapted flora, and the degree to which the polar biodiversity will be able to persist is uncertain.

4.21 > Autumn in the Arctic: A yellowish-orange carpet of shrubby willows and dwarf birches covers this headland in the Canadian Arctic. This far north the American dwarf birch *(Betula glandulosa)* primarily reproduces asexually.

Marine life

> The productivity of the polar seas and their species diversity verge on the miraculous. To an outsider, living conditions in the Arctic and Antarctic Oceans seem anything but inviting. The constantly cold water inhibits the growth of cold-blooded organisms and slows their every movement. Food is available only during the brief summer – although it is then abundant. But the inhabitants of the polar seas – especially the dwellers of the Antarctic – have developed unique adaptation mechanisms to compensate for these limitations.

In the rhythm of light and ice

Like the land areas of the polar regions, the seas are also classed as extreme habitats. The Antarctic and Arctic Oceans have the coldest and most constant water temperature of all the world's oceans. This temperature is below zero degrees for most of the year and seasonal fluctuation is usually less than five degrees Celsius. In very southerly ocean regions such as the McMurdo Sound, a bay that forms part of the Ross Sea in the Antarctic, the difference between summer and winter temperatures is in fact less than half a degree Celsius. The inhabitants of this region must therefore cope with very cold ambient temperatures throughout the year. For most of the time the water temperature is minus 1.8 degrees Celsius. Furthermore, seasonal changes have a more marked effect on the polar seas than on any other ocean: in summer the sun never sets, while in winter darkness reigns for months on end.

This switch between polar day and polar night has a profound impact on life in the Arctic and Antarctic Oceans. Sea ice forms as the days shorten, so that in winter it covers much of the ocean surface; in summer the ice melts again, retreating to a minimum area. The ebb and flow of light and sea ice determine the rhythm of life in the polar regions. Where the sea ice breaks up in summer, sunlight at last penetrates the upper layers of water and stimulates algae growth. At the same time, the melting floes release microorganisms and other life-forms associated with the ice; these disperse in the water, along with trace elements such as iron that have been encased in the ice or deposited on its surface in the form of dust over the winter.

In the spring and summer, sunlight, iron and other water-borne nutrients such as nitrogen, phosphorus and silicon compounds trigger large-scale algal blooms that provide the basis for the food webs of the polar oceans. In coastal waters in the Antarctic, algal density can peak at a level of 30 milligrams of chlorophyll per cubic metre of water. In winter, by contrast, there are so few algae in these same places that the water's chlorophyll content may fall to less than 0.01 milligrams per cubic metre. In no other ocean are seasonal differences in biomass production so large. In autumn and winter the formation of sea ice inhibits life in the Southern Ocean. When the sea surface cools and turns to ice, key nutrients such as iron have usually been used up by algal growth in the summer. Any substances that remain sink to the sea floor, partly as a result of the thermohaline circulation of the water masses. This means that virtually no food is left in the upper metres of the water column. Algae stop growing and primary production ceases. Moreover, the sea ice shields the water column from the wind and thus prevents intermixing of the upper water layers. As a result of this lack of eddying, algae, faeces and other particles suspended in the water column fall to the sea floor, thereby drastically reducing the nutrient content of the column.

For most of the inhabitants of the polar seas, the seasonal succession of light and ice means that periods of abundance constantly alternate with periods of hunger. In addition, many organisms – particularly those that live on the bottom of the shelf seas – are always in danger of having their habitat destroyed by drifting icebergs or sea ice floating in the shallow waters. An iceberg ploughing across the sea floor in the Antarctic kills more than 99.5 per cent of the established macroorganisms and more than 90 per cent of the smaller meiofauna. In areas in which icebergs are plentiful this can happen more than once a year. In consequence, the biotic communities in these disturbance zones are usually very young and colonize the sea floor only patchily.

Meiofauna
Meiofauna, also known as mesofauna, are a major category of benthic fauna. The term covers all bottom-dwelling organisms of between roughly 0.05 millimetres and one millimetre in size. Smaller organisms are classed as microfauna, while larger ones up to 20 millimetres in size fall under the heading of macrofauna.

A question of iron

Although the marine fauna of the Arctic and Antarctic have much in common with each other, they are not identical. This is partly because of differences in the supply of nutrients and trace elements in the two regions. In the far north, rivers carry large quantities of suspended material into the marginal seas, thus providing the Arctic Ocean with the iron that is vital to living things; the deep south, by contrast, lacks such a reliable source of iron. Although the water masses of the Antarctic are nutrient-rich, they suffer from an almost universal lack of iron. In consequence, algal blooms form mainly in two areas: firstly, in the coastal waters and polynyas (areas of unfrozen sea within the ice pack), where iron comes from sources such as glacier meltwater, and, secondly, on the edges of the continental plate, where iron-rich water wells up from the depths. The largest of these upwelling zones stretches eastwards from the tip of the Antarctic Peninsula to South Georgia. It is a hotspot of life, home to the largest concentrations of krill in the Antarctic and a magnet for krill hunters such as whales, penguins and seals.

By comparison, the upper water layer of the central Arctic Ocean is relatively nutrient-poor. The summer ice melt and the pronounced stratification of the Arctic water masses as a result of the large quantities of freshwater discharged by rivers prevent deep, nutrient-rich water rising to the surface. Brief, intense algal blooms in the spring and summer therefore occur mainly near the edge of the ice and in the marginal seas. The Barents Sea, Chukchi Sea and Bering Sea are among the most pro-

4.22 > Elephant seals, together with king penguins and other seabirds such as petrels and albatrosses, line the shore of Saint Andrews Bay on the north coast of South Georgia. Here the penguins form breeding colonies of up to 100,000 birds.

4.23 > Copepods not only make up the majority of marine zooplankton – with around 13,000 species, they are also the most species-rich group of crustaceans. Polar species are usually somewhat larger and more nutritious than their relatives in the mid-latitudes.

ductive marine ecosystems in the world, providing so much food for bottom-dwellers, fish, seabirds, seals and whales that huge colonies of these creatures can occur.

Despite this, animal numbers in the Arctic are often only a fraction of the size of Antarctic populations. For example, in the area around the North Pole and the adjacent sub-polar regions there are just 13 bird species with a total population of more than a million, while in the south there are 24 polar and sub-polar bird species. The most abundant seal species likewise lives in the Antarctic: it is calculated that there are between 50 and 80 million crabeater seals *(Lobodon carcinophaga)* in the region, although the vast extent of their habitat means that population estimates are uncertain.

The large numbers of birds, seals and whales in the polar seas at one time led scientists to assume that more biomass is produced and passed on in the food web in these regions than is the case at lower latitudes. This was attributed to short food chains formed of a few key organisms. With regard to the Antarctic it was thought that almost all life hinged on diatoms photosynthesizing and being eaten by Antarctic krill, which were in turn hunted by all the larger animals such as fish, penguins, seals and whales.

This simplified point of view is outdated. We now know that the range of primary producers in the polar seas – in this case predominantly the algae – is just as diverse as in the mid-latitudes. Microbes, plankton and other microorganisms interact in complex ways. In addition, it is now recognized that, although krill undisputedly remains one of the key species, there are many feeding relationships in the Antarctic in which it plays no part.

Consideration of the food web in the two oceans reveals two striking features. Firstly, in the polar seas there are relatively few species that serve as food for the large predators. For example, 80 to 90 per cent of the zooplankton in the Arctic consists of fatty copepods, which form the most important link between the primary producers and larger consumers such as fish and baleen whales. In the Antarctic, this role is performed by krill, amphipods and copepods. Secondly, the hunters and consumers of the Antarctic pursue different prey from those of the Arctic. While seals, whales and seabirds in the Arctic Ocean eat mainly fish and organisms that live on the sea floor, the large predators of the Antarctic Ocean feed largely on krill and fish such as the Antarctic silverfish *(Pleuragramma antarctica)*. Sharks, walruses and whales that search for food chiefly on the sea floor are completely absent from the Antarctic.

The survival tricks of cold-blooded sea-dwellers

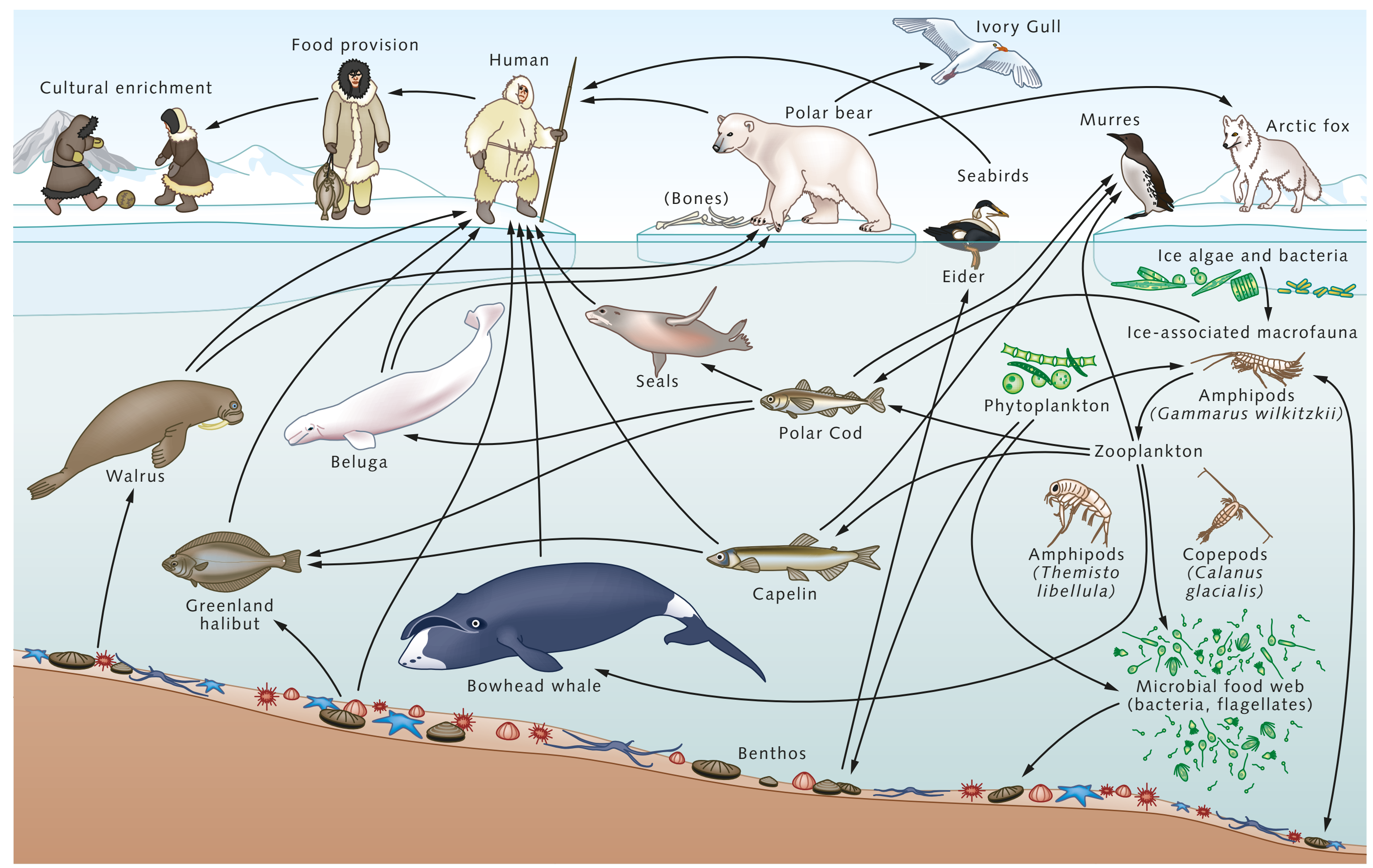
The fauna of the polar seas consists largely of cold-blooded creatures which over millions of years have developed unique mechanisms for adapting to their extreme living conditions. However, because of the geographical isolation of the Antarctic and its longer glacial history, these mechanisms are more marked there than in the Arctic. Notable adaptive mechanisms in the cold-blooded creatures include:

- slower growth, late sexual maturity,
- reduced activity,
- production of antifreeze proteins (especially in fish),
- reduction in red blood cells (also mainly in fish),
- incorporation of unsaturated fatty acids into cell membranes,
- weight savings by doing without calcium deposits in scales and skeleton,
- gigantism,
- smaller clutches with large eggs that contain food reserves to support the growth of the larvae, and
- live births and attentive care of the young.

Temperature and lack of food as brakes on growth

Cold has a persistently adverse impact on the lives of cold-blooded sea creatures. Among other things, it affects their respiration and muscle function and hence their ability to move. It also slows their growth and development, and in consequence there is considerable similarity between the life cycles of polar species. Life in the cold oceans proceeds very slowly, and each developmental step takes longer than in the mid-latitudes. For example, the embryonic

4.24 > Ice algae and free-swimming phytoplankton in the water form the foundation of the food web in the Arctic Ocean. Using sunlight, carbon dioxide and nutrients, these organisms produce biomass that provides nourishment for all consumers, from zooplankton to bottom-dwellers, fish, birds, sea mammals and ultimately humans.



The Methuselah of the North Atlantic

The waters around Iceland and Greenland contain sharks that are thought to have been hunting there at the start of the French Revolution in 1789 – 230 years ago. This hypothesis emerged from a study conducted in 2016 in which researchers determined the age of 28 Greenland sharks *(Somniosus microcephalus)*. The oldest female, which was 5.02 metres long, was found to be at least 272 years old but could have been as old as 512. It was impossible to pinpoint her age more precisely, because Greenland sharks are cartilaginous fish and hence have no bony vertebrae or fin spines whose growth rings the researchers could have counted. Instead, the scientists had to look at the sharks' optical lenses, which are formed at the embryonic stage, and use radiocarbon dating to measure the carbon isotope content. The findings made headlines, because no other vertebrate is known to live as long as these giants of the Arctic Ocean.

Greenland sharks are very rarely seen in the wild. They are predators that prefer regions in which water temperatures are below five degrees Celsius; on their search for carcasses or living prey they roam the coastal waters and deep seas of the Arctic and North Atlantic. To save energy, though, they meander through the Arctic waters at a sluggish pace, swimming at an average speed of 30 centimetres per second (1.08 km/h). They are thus significantly slower than most other sharks, but this does not deter them from hunting fish, seals and beluga whales. The animals reach sexual maturity at the age of 156 (± 22). Their young hatch from the egg while still inside the mother's body; at birth they are thought to be about 40 centimetres long. Since they grow at a rate of less than a centimetre a year, one can only speculate on the age of the Greenland sharks up to 7.3 metres long that have been caught in the past. This is still the figure that scientists quote as the maximum length of this relatively unknown denizen of the deep.

4.25 > Record-breaking fish: Greenland sharks live for hundreds of years.

development of many cold-blooded sea-dwellers in the polar regions takes five to ten times as long as that of thermophilic species in the mid-latitudes. The embryonic stage is often followed by slower growth and delayed sexual maturity. Thus while fish in warmer regions are usually ready to mate after one to four years, the larger fish species in the Antarctic take between six and ten years to reach this point. The Patagonian toothfish *(Dissostichus eleginoides)* does not reach sexual maturity until it is 13 to 17 years old. Some Antarctic ascidians, bryozoans and sponges form an exception to this rule: they are also cold-blooded, but various studies have found that they grow or spread relatively quickly. Nevertheless, even these animals develop more slowly than related species in the mid-latitudes.

The delayed development of polar species is partly attributable to the fact that cold hinders the animals' protein metabolism – i.e. the constant synthesis of proteins and their subsequent breakdown into amino acids in the cells. Continuous protein synthesis is an essential process in growing organisms, enabling protein to be transported to the organs and structural elements. At temperatures of zero degrees Celsius and below, however, it becomes difficult for cold-blooded creatures to maintain their protein metabolism and produce many fully functioning proteins. Researchers have discovered that in the cells of Antarctic species up to 80 per cent of the synthesized proteins are not re-used but are instead broken down again. In thermophilic species the corresponding figure is just 25 to 30 per cent. Polar species have a particularly high concentration of ubiquitin, a protein molecule that is responsible for identifying and removing damaged proteins. These faulty proteins are degraded in a particular part of the cell nucleus, the proteasome. In polar fish the ubiquitin is activated between two and five times more frequently than in fish from the mid-latitudes.

As a result of this and other cellular features, the protein metabolism of cold-blooded animals in the polar seas yields relatively few proteins that can ultimately be used for growth. This means that growing is a particularly energy-intensive process for polar species and in many of them it therefore proceeds very slowly. On the other hand, the cold-blooded inhabitants of the Arctic and Antarctic Oceans reach an unusually advanced age. Larger species of fish such as the Patagonian toothfish, which lives in the Antarctic, have a life span of between 15 and 30 years. The Antarctic bivalve *(Laternula elliptica)* lives for up to 36 years. The ocean quahog *(Arctica islandica)*, a species of clam found in the far north, is a record-holder: in 2006, British scientists found a specimen off the coast of Iceland that was 507 years old.

Researchers also attribute the slow growth of cold-blooded sea-dwellers to the extreme seasonal changes that affect the polar seas. Most cold-blooded animals only grow when they find food – but for many polar species sufficient quantities of food are available only during the periods of algal bloom that occur in summer. In the Antarctic, for example, more than 95 per cent of the species that feed on free-floating phytoplankton or algae growing on the sea floor stop eating in winter, while those that do continue to feed consume only a small percentage of what they would otherwise eat. One of the consequences of this is that the animals' growth is almost entirely limited to the summer.

Always in energy-saving mode

It is not only the development of cold-blooded creatures that proceeds slowly in the polar regions: their everyday lives are also spent in energy-saving mode. This means that they move particularly slowly and avoid unnecessary effort. For example, Antarctic fish do not chase after their prey in the water column but conserve their energy by lying in wait for them on the sea bottom. *Adamussium colbecki*, a bivalve found in the Antarctic, closes its valves only half as often as molluscs in warmer regions, and the predatory snail *Trophonella longstaffi* takes 28 days to bore through the shell of its prey and eat it – a task for which related species in water of ten to 15 degrees Celsius need just ten to twelve days.

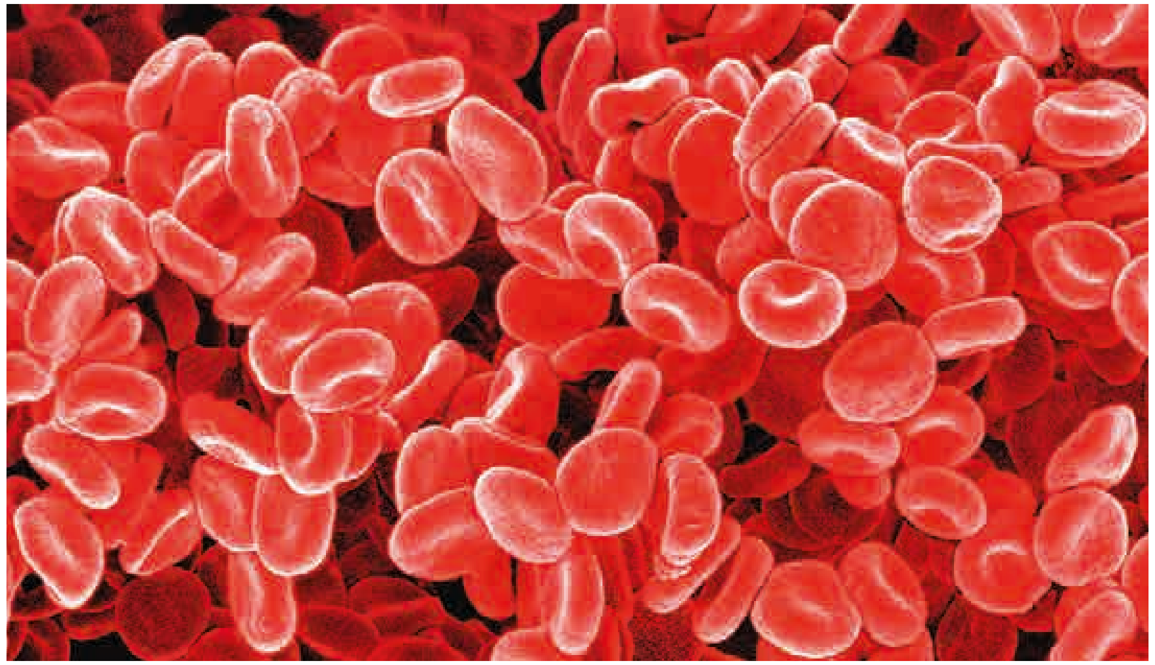
Naturalists currently know of only two adaptations developed by marine creatures in the Antarctic to make up for the disadvantages of the temperature-related effect on movement and enable them to operate at a speed akin to that of their non-polar cousins. The first involves the swimming speed of Antarctic fish. They have around twice as many mitochondria in their muscle cells as related species in warmer seas. This enables Antarctic perch to generate so much energy that they can when necessary swim just as fast as comparable species from the mid-latitudes. The second example is supplied by the Antarctic bivalve *Laternula elliptica*: because its foot muscle is two to three times the size of that of related molluscs in the mid-latitudes and tropics, it can dig itself into the sea floor just as fast as they can.

Radiocarbon dating
Radiocarbon dating, also known as C14 dating, is a method of determining the age of organic matter. Scientists calculate the relative quantities of the radioactive carbon isotope ^{14}C and the non-radioactive isotope ^{12}C in the sample; the resulting ratio indicates how many years have elapsed since the plant or animal died.

Fats, frost protection and colourless blood

The strategies for adapting to life in the polar seas with which people the world over are most familiar are those adopted by fish. All species of fish that live in waters of below zero degrees Celsius prevent themselves freezing to death by producing antifreeze substances in the form of glycoproteins. These are found in all the fishes' body fluids and they are not excreted by filtering organs such as the kidneys. Glycoproteins are sugar compounds that inhibit the growth of ice crystals in the fishes' tissues. As soon as an ice crystal starts to form, the glycoproteins accumulate in this miniature crystal and prevent further water molecules docking on to it. The tiny ice/sugar complex that arises is then excreted via the metabolism. Using this protective mechanism, the fish reduce the point at which their body fluids freeze to below minus 2.2 degrees Celsius and are able to survive ambient temperatures of up to minus 1.8 degrees Celsius. This is an adaptive strategy that fish from the Arctic and Antarctic have developed completely independently of each other; it remains one of the best examples anywhere in the world of parallel evolution – the development of identical characteristics in unrelated species.

A second distinctive adaptive strategy occurs only in the Antarctic Ocean. The Southern Ocean is home to the icefish or white-blooded fish (Channichthyidae), a family of Antarctic fish. Sixteen species of this family of predatory fish have no red blood corpuscles and they also lack haemoglobin, the red pigment that gives blood its colour. Their blood is completely translucent. Haemoglobin is



4.26 > Human red blood corpuscles are shaped like tiny biconcave discs and filled with the iron-rich blood pigment haemoglobin. Their shape enables them to transport oxygen very efficiently. The blood corpuscles also prevent the toxic haemoglobin escaping into the blood stream.

responsible for transporting oxygen in the bodies of many vertebrates, including humans. Each molecule of the pigment has four docking points for oxygen molecules; this is a particularly efficient method of transporting oxygen from the lungs, where it is taken in, to the parts of the body where it is needed. On the return journey the haemoglobin molecules pick up the carbon dioxide produced in the tissues and take it back to the lungs, where it is exhaled.

Excellent as this gas transport system is, haemoglobin is not entirely beneficial. Free haemoglobin in the body can be toxic: that is why it is encapsulated in the red blood corpuscles in humans and many vertebrates. In addition, haemoglobin becomes less efficient at binding oxygen as temperatures fall. Under very cold conditions, the presence of many red blood corpuscles carrying haemoglobin can make the blood more viscous and hence harder for the arteries to transport – especially when miniature ice crystals are also floating in the blood, as is the case in the Antarctic fish.

To prevent this problem, many species of polar fish have in the course of evolution reduced the number of red blood cells in their bodies. The icefish have even managed to do away with haemoglobin entirely. They live only from oxygen that diffuses directly into their blood in their enlarged gills or via their skin. The oxygen then dissolves physically in the blood, which means that the oxygen molecules do not dock on anywhere but are transported as they float freely in the blood.

However, the amount of oxygen dissolved in the blood in this way is fairly small. Icefish such as the blackfin icefish *(Chaenocephalus aceratus)* have to make do with a quantity of oxygen in their blood that is about ten per cent less than that available to red-blooded Antarctic fish. Researchers now think it likely that this haemoglobin-free oxygen supply in icefish only works because the cold conditions in the Antarctic Ocean mean that almost all the fish there have a metabolic rate ten to 25 times slower than that of fish in warm seas of 30 degree Celsius, with the result that the Antarctic fish use less oxygen. Furthermore, the cold water masses of the Southern Ocean are very oxygen-rich, with an oxygen concentration that is almost twice that of tropical seas, making it easier for all inhabitants of the Antarctic waters to take in oxygen. If fish outside the Antarctic had at some point stopped producing haemoglobin, they would have died immediately, but under Antarctic conditions such creatures still have a chance of survival.

Nevertheless, the fish with "white" blood display some specific characteristics that suggest that their circulatory systems must handle very large quantities of blood in order to provide a sufficient supply of oxygen. For example, by comparison with fish with red blood corpuscles, icefish have a heart so large that it pumps four to five times as much blood, arteries that are one-and-a-half times bigger in diameter and a blood volume two to four times greater.

The colder the habitat of cold-blooded sea-dwellers becomes, the more frequently they incorporate unsaturated fatty acids into their cell membranes. This enables the membranes to maintain their fluidity and hence remain fully functioning at low temperatures. Without this protective mechanism, the membranes would become gel-like in the cold and lose the permeability that is vital to survival.

Antarctic fish also have no swim bladder. So that they can nevertheless move with as little expenditure of energy as possible, they store lipids in their liver and other cells. These fats provide additional buoyancy. The fish also reduce their body weight by incorporating relatively little calcium into their skeleton and scales, replacing it where necessary with cartilage. As a result, the skeleton of the blackfin icefish appears almost transparent.

Polar giants

Although most of the cold-blooded inhabitants of the polar seas grow slowly, some of them – especially those in the Antarctic – reach a remarkable size. This has led researchers to coin the term "polar gigantism". The sea spiders (Pycnogonidae) of the Antarctic are a good example: they achieve a diameter of more than 50 centimetres, while the largest sea spiders in moderate latitudes grow to no more than three centimetres across. The amphipods (flea crabs) of the Southern Ocean are up to nine times as long as their tropical cousins, and the cup-shaped glass sponges reach record sizes of two metres in height and 1.5 metres in diameter.

The blue blood of the Antarctic octopus

Haemoglobin is just one of four respiratory pigments used to transport oxygen in the animal world. Invertebrate organisms such as bristle worms use the green pigment chlorocruorin. Peanut worms (sipunculids), penis worms (priapulids) and brachiopods depend on a blood pigment called haemerythrin. When deoxygenated haemerythrin is colourless, but with oxygen on board it is a violet-pink colour. By contrast, molluscs, spiders, scorpions, crabs, lobsters and cephalopods (such as squids and octopuses) form the blue copper-based pigment haemocyanin. It is thought that in cold water that is low in oxygen, haemocyanin is a more efficient transporter of oxygen than haemoglobin. Nevertheless, at cold temperatures it is difficult for the oxygen in the tissues that has been taken in during respiration to separate from the blue pigment again.

The Antarctic octopus *Pareledone charcoti* has two ways of offsetting this temperature disadvantage. Firstly, its blood contains up to 46 per cent more haemocyanin than that of related octopuses that live in warmer water. Secondly, a lot of oxygen diffuses directly into the blood in the animal's gills and dissolves physically there. By these means the little octopod that inhabits the shallow shelf waters of the Antarctic Peninsula ensures that even at temperatures as low as minus 1.9 degrees Celsius its body is supplied with sufficient oxygen right to the tips of its tentacles.

4.27 > The blood of the Antarctic octopus *Pareledone charcoti* contains up to 46 per cent more respiratory pigment than that of its warm-water counterparts.

The factors behind this gigantic polar growth have long been hotly debated by scientists. The reasons that have been put forward include:

- **Low maintenance costs:** Because temperatures in the Antarctic Ocean are low and the metabolic rate of most cold-blooded species is restricted, polar organisms generally need to expend less energy to maintain a large body than similar-sized animals in warmer regions.
- **High oxygen content of the polar seas:** This eases respiration and hence metabolism.
- **High concentration of silicon in the water:** This enables diatoms, glass sponges, radiolarians and other organisms to build up their silicon-based skeletons without expending excessive energy.
- **Abundant supply of food in summer:** The large algal blooms constitute a rich source of food that provides ideal growing conditions for animals with a slow metabolic rate and encourages growth-promoting competition between individuals.
- **Seasonal fluctuations:** In relation to their body mass, larger organisms need less energy than smaller ones. Bigger creatures can also lay down larger energy reserves, which puts then at an advantage at times when little or no biomass is being produced.

Throughout the Earth's history, competition between species has repeatedly led to extreme growth – the dinosaurs are just one example among many. However, the past also shows that these large species usually have difficulty adapting to changes in the environment. This is one of the reasons why scientists believe that global warming may have a greater impact on the giants of the polar seas than on smaller species.

Large eggs, attentive parents

Polar fish lay a relatively small number of eggs, but these eggs are considerably bigger than those of thermophilic species. In addition, Antarctic fish are often surprisingly active in caring for their young: they deposit their eggs on rocks on the sea floor or in the oscula of glass sponges and guard them until they hatch.

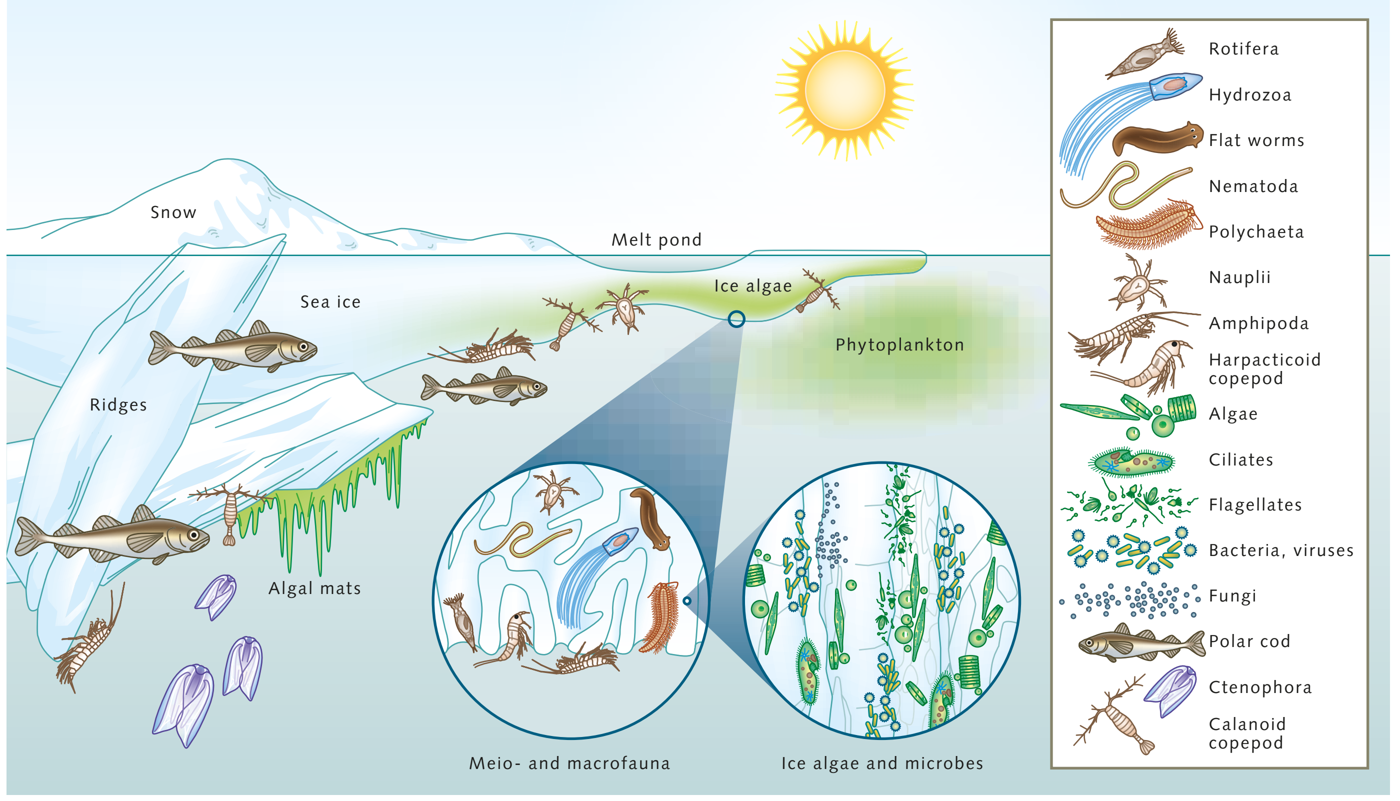
The flea crabs and krill of the Southern Ocean also produce strikingly large eggs that are usually two to five times as big as the eggs of related species in lower latitudes. The trend towards larger eggs in the polar regions is apparent even within a species. For example, the eggs laid by the Antarctic crustacean *Ceratoserolis trilobitoides* in the Weddell Sea are almost twice the size of those spawned by the same species in the vicinity of South Georgia a little further north. Scientists attribute this phenomenon partly to the uncertain availability of food in the polar regions. While animal species in warmer oceans can be fairly certain that their offspring will find sufficient food and grow quickly, this is not the case in the polar seas where food is sometimes hard to come by and the low temperatures make for long development times. For these reasons the young are usually given larger food reserves at the start – that is, in the egg. In addition, the offspring are usually somewhat larger when they hatch, thus increasing their chances of survival at the most critical stage of their lives. Scientists have also discovered that the cold-blooded creatures of the cold, oxygen-rich polar seas have larger cells than related species in warmer waters that contain less oxygen: this is another simple reason why their eggs are larger.

After spawning and fertilization, the life cycle of many polar species again differs from that of their thermophilic cousins. While invertebrate species in warmer regions often pass through a larval stage during which they must actively search for food (planktotrophic nutrition), the young of many Antarctic species are provided with a yolk sac that supplies the larvae with food to last them until they reach the next developmental stage in their metamorphosis; this is termed lecithotrophic nutrition. The main reason for this is once again the extended development time as a result of the cold conditions in the polar seas. The less food the larvae find, the more slowly their already protracted development proceeds; this in turn means that there is a longer period during which the young are at risk of being eaten themselves. The larvae of the Antarctic starfish *Odontaster validus*, however, must search for their own food and may spend up to 180 days in the water column before they settle on the sea floor and complete their metamorphosis to young starfish.

Life in, on and under the sea ice

The sea ice of the Arctic and Antarctic provides a unique habitat for the flora and fauna of the polar regions – even in those parts of the polar seas in which ice cover is present only at certain times of year. Scientists have identified more than 2000 species of algae and animals that live in or on sea ice – the majority of them too small to be seen with the naked eye. In addition to these species there are numerous bacteria, archaea, viruses and fungi that are adapted to the cold. In consequence, researchers now believe that the sea ice harbours a biological community made up of several thousand species, the growth and reproduction of which underpins the survival of all the marine fauna of the polar regions.

At the start of this important food chain are the ice algae: when the seawater freezes, many of these become encased in the ice together with particles, nutrients, a whole host of bacteria and all sorts of microorganisms. Unlike meat and vegetables in the domestic freezer, though, the organisms themselves do not freeze; instead they survive on the underside of the ice or in the vast number of small pockets and channels full of brine and seawater that form in the sea ice. To exist in this extremely salty environment at temperatures as low as minus ten degrees Celsius in the Arctic and minus 20 degrees Celsius in the Antarctic, the ice-adapted microorganisms have altered the composition of the lipids in their cell membranes. This prevents the membranes hardening and ensures that the organisms can continue to absorb nutrients from the seawater. Protein production in the cells is also adapted to the cold so that all the processes vital to survival proceed as smoothly as possible even at low temperatures. Ice algae also form antifreeze proteins and lay down fat reserves in summer that



4.28 > In spring and summer the many pores, pockets and brine channels of the Arctic and Antarctic Oceans support flourishing and species-rich communities of cold-adapted ice algae, bacteria, archaea, viruses, fungi and microorganisms. Scientists have identified more than 2000 species that live in or on sea ice.

enable them to survive the long winter. Despite these survival strategies it is nevertheless the case that the warmer and less salty the sea ice is, the better the sea-ice flora and fauna will flourish.

The ice-algae community consists mainly of diatoms, of which many different species occur in both polar regions. The number of ice algae present in a block of sea ice depends on how much light penetrates the ice, on its salt content and on the nutrients that are encased in the ice or available in the water beneath. Multi-year sea ice usually contains more species of algae than young ice. These relatively old floes also function as a sort of seed bank – especially in the pack ice, which frequently consists of newly formed ice, year-old ice and multi-year floes. In the spring, as temperatures rise and the ice becomes more porous, algae from the multi-year ice migrate to the younger ice and start an algal bloom there.

Ice algae flourish mainly in the lowest layer of the ice, close to the water. Species such as the Arctic diatom *Melosira arctica* also colonize the underside of the ice; in spring they sometimes form algal mats that trail downwards into the water column for up to two metres. Bacteria, on the other hand, are found in almost all layers of the sea ice, although they cluster in the lowest layer and on the ice surface.

The species community of the sea ice spends the long, dark winter in a relatively torpid state. But in the spring, when the sun once again climbs above the horizon, the algae in the lowest ice layer quickly grow and multiply, drawing the nutrients that they need from the seawater. As soon as the ice algae start to bloom, tiny algae eaters such as copepods, amphipods and krill larvae fall on the growing mountain of food. Some of the algal build-up sinks downwards and is devoured on the sea floor by sea cucumbers and other bottom-dwellers.

When the feasting starts in the many niches of the ice, the first zooplankton hunters are already lurking directly below the ice. In the Arctic these species include predatory flea crabs such as *Apherusa glacialis* and *Gammarus wilkitzkii*. But they also need to be careful, because alongside the flea crabs there will be polar cod and Greenland cod hunting for zooplankton under the ice. The fish mainly seek out amphipods and copepods, but they also eat mysids (opossum shrimps). The polar cod actually spawns in the labyrinth of the pack ice. Its millions of young spend the first year of their life concealed in the nooks and crannies of the ice. With the pack ice, they migrate from the spawning areas north of Siberia to the central Arctic. By diving under the ice, scientists have also discovered that jelly-like zooplankton such as comb jellyfish can occur in dense clusters under the ice. These animals seem to gather mainly in areas where the sea ice projects particularly deeply into the water column, thus causing upwelling and downwelling of the water.

Mammals and birds have two strategies for gaining access to the larder under the sea ice. They may use holes and cracks in the ice to break into the feeding grounds; this method of hunting is used in particular by various seal species of the Arctic and Antarctic Oceans. Alternatively, they may wait for the ice-free summer. This is the method adopted by Arctic mammals such as beluga whales and the big baleen whales. They spend the winter outside the sea-ice zone, not travelling north until the ice slowly retreats and large algal blooms form in the marginal ice zone.

Polar bears hunt seals on the surface of the sea ice, thus forming one of a number of end points in a food web the existence of which is directly linked to the sea ice. The life style of each member of this web is so precisely adapted to polar conditions that these species would have little chance of survival elsewhere. For all of them, the shrinking of the Arctic and Antarctic sea ice means a loss of vital habitat.

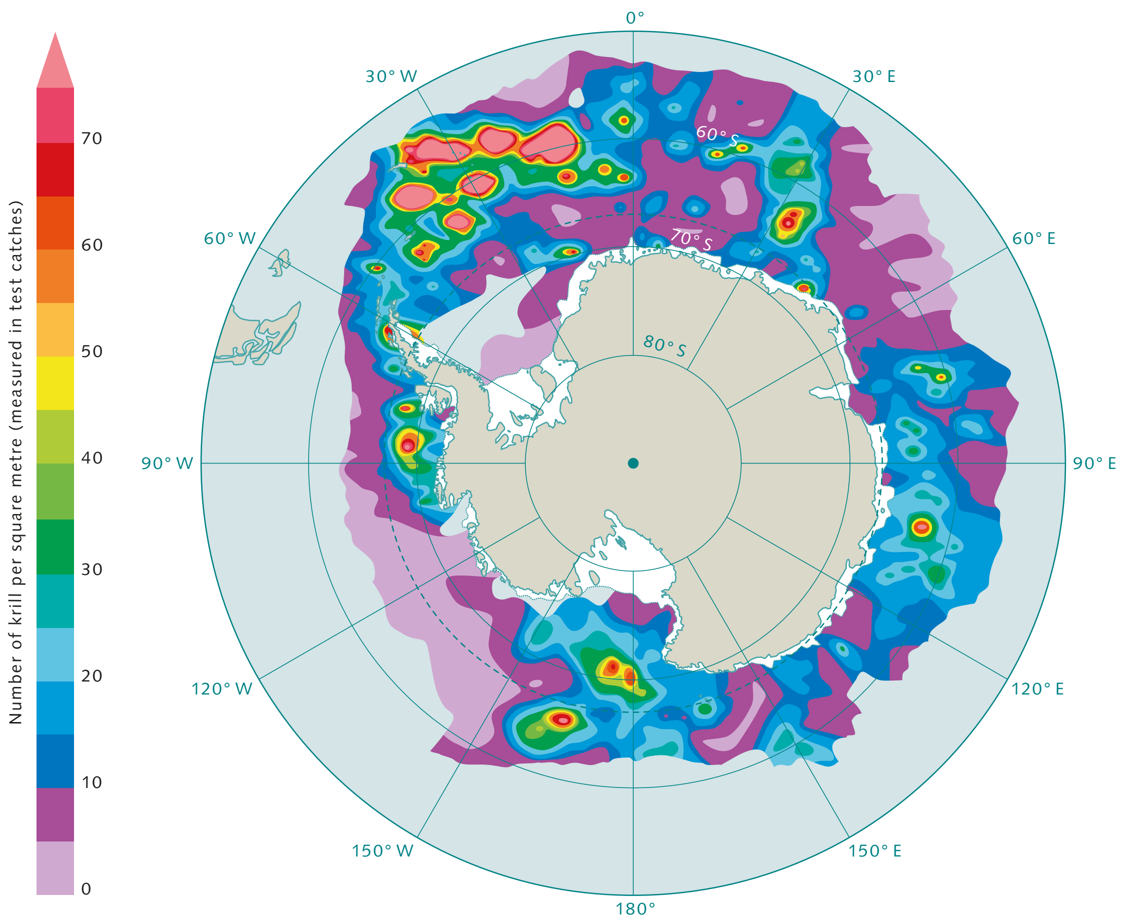
Antarctic krill – the mass phenomenon

A keystone species of the polar regions that depends directly on the sea ice for its survival is the Antarctic krill *(Euphausia superba)*. This bioluminescent crustacean, sometimes referred to as a light-shrimp, is a type of zooplankton that has garnered many superlatives. Its body length of up to six centimetres makes it one of the largest creatures of its type in the Southern Ocean. Individuals can live for up to eleven years and in terms of biomass they are one of the most abundant species on the planet. It is estimated that there are 133 million tonnes of Antarctic krill in the circumpolar regions, excluding larvae.

4.29 > Viewed from below, the Antarctic pack ice forms a rugged landscape in which algae colour the underside of the ice greenish brown in places where the most light penetrates.

Only humans weigh more in total. The term "krill" comes from the Norwegian word for whale food. It used to include other zooplankton species such as winged snails (Pteropoda) and jellyfish, but in everyday language the word is now used to refer only to *Euphausia superba.*

Antarctic krill occur only in the Southern Ocean and are thus one of the many endemic species of the Antarctic. There are five other species of crustacean in Antarctic waters, including *Euphausia crystallorophias*, the ice krill or crystal krill. This species lives mainly in the very cold marine shelf regions in the south, while *Euphausia superba* prefers deep sea areas further north with warmer average water temperatures of between zero and three degrees Celsius. The habitat of *Euphausia superba* is thus limited to somewhat more than half of the extent of the Southern Ocean – more precisely the area between 51 and 74 degrees south. Scientists have identified six large concentrations – one in the northern Weddell Sea and the Scotia Sea, one off Enderby Land, one around the Kerguelen Gyre, two smaller accumulations in the north of the Ross Sea and one population in the Bellingshausen Sea to the west of the Antarctic Peninsula. Because of this patchy distribution, the krill is not the link between primary producers and higher consumers in all parts of the Southern Ocean. Scientists have now identified three zooplankton communities in the Southern Ocean and their corresponding keystone species. The zooplankton in the northern part of the Antarctic Ocean are dominated by the salp *Salpa thompsoni* and the amphipod *Themisto gaudichaudii.* In the southern part, on the other hand, it is mainly the ice krill and the Antarctic silverfish *(Pleuragramma antarctica)* that occupy the key positions in the food web, with the Antarctic krill playing an important but nevertheless subordinate role. In the middle, however, the Antarctic krill and its close relative, the euphausid *Thysanoessa macrura*, plus a number of copepods, are the main prey of hunters such as fish, whales, seals, penguins and other seabirds.



4.30 > Using data from net catches and other sources, scientists have found that populations of Antarctic krill are distributed unevenly around the southern continent. Particularly large swarms occur in the northeast of the Antarctic Peninsula, off the coast of Enderby Land, around the Kerguelen Gyre, in the Ross Sea and in the Bellingshausen Sea.

In the regions where they flourish, the krill occur in swarms of up to 30,000 animals per cubic metre of water. In the Antarctic summer the krill swarms usually occupy the upper 50 to 150 metres of the water column. At the start of winter in April, however, they often sink to a depth of about 200 metres, but they have also been sighted at depths of 1000 to 3500 metres.

The eggs of the crustaceans, which the females lay from January to March, sink to a depth of more than 2000 metres. In the deep sea, free-swimming larvae emerge from the eggs; as the summer draws to a close the larvae rise higher and are carried by the surface currents in the upper part of the water column. Thus the krill larvae that hatched in the Bellingshausen Sea migrate within 140 to 160 days to the waters around South Georgia.

The young krill survive their first winter by hiding in the niches, hollows and cracks of the sea ice, feeding in autumn on the ice algae and in winter mainly on copepods and other microorganisms. Formation of the sea ice early in the winter appears to be an important factor, enabling the larvae to find protection and food for as long a period as possible. When the ice melts in spring, triggering the growth of algal blooms, the crustaceans complete the final stage of their development and become young adults.

The survival prospects of the mature krill are less heavily dependent on the sea ice. Some crustaceans survive the dark part of the year by ceasing to eat and reducing their metabolic rate by up to 50 per cent. During these fasting periods the animals may actually shrink. Other creatures look for alternative sources of food: they eat zooplankton that are still floating in the water column, or they sink to the sea floor, where they eat plant and animal remains that have trickled down. It is the length of the day that determines when the crustaceans' metabolic rate and feeding behaviour switch to the winter pattern. This information is derived in part from laboratory studies which showed that under winter light conditions the animals ate very little, even if plenty of food was floating in the aquarium.

What lived under the Larsen A and B ice shelves?

In 2007, following the sudden collapse of the Antarctic ice shelves Larsen A (1995) and Larsen B (2002), scientists had a unique opportunity to study the animal life in the previously unexplored habitat beneath the great tongues of ice and to observe how the fauna was changing as a result of the loss of ice. Their survey showed that before the collapse of the ice shelves the ocean currents carried so little food beneath the ice tongues that only a few suspension eaters such as the vase sponges *Rossella nuda* and *Rossella racovitzae* were able to exist under the ice. They occurred so sporadically and were so small in size that the researchers thought each animal reminiscent of a solitary tennis ball lying on a tennis court with the next sponge, metaphorically speaking, not on the same court but on an adjacent one.

However, the biologists were surprised to find 16 animal species from the deep Antarctic sea under the ice shelves; most of these were echinoderms such as the sea lilies *Bathycrinus australis* and *Dumetocrinus antarcticus*. As a result of this discovery the scientists concluded that living conditions under the shelf ice probably resembled those in the deep sea and it was this that had enabled the dwellers of the deep to migrate to the shelf-sea zone.

The collapse of the ice altered the supply of light and food in the water. Although the areas were and still are frequently covered by sea ice, algal blooms occurred from time to time. Other organic material was carried in by the currents, enabling pioneer species such as sea squirts and glass sponges to colonize the deserted areas. The vase sponges successfully reproduced and, attracted by the food supply, ice krill, Antarctic krill and Antarctic silverfish swam in the water column. This in turn drew in larger hunters. In the summer of 2007 the biologists found that there were roughly as many crabeater seals and dwarf whales in the former shelf-ice region as would normally occur elsewhere in the Weddell Sea or off the west coast of the Antarctic Peninsula. In other words, the fauna of the Weddell Sea was already reconquering the habitat that had been lost for so long.

Polar ecosystems in retreat

> Global warming is changing the foundations of life in the polar regions – in water and on land. With the diminishing sea ice, the prime food store of the polar seas is shrinking. Rising temperatures are forcing the cold-loving species to take flight, but scarcely any refuges are left. Their territories are being invaded by species from the middle latitudes. Over time, these changes will lead to the disappearance of the unique polar flora and fauna. The first signs of this are already apparent.

Altered environmental conditions due to climate change

Climate change is transforming biological communities throughout the world, but most dramatically in the polar regions. In recent decades, the Arctic and regions along the Antarctic Peninsula have warmed so much that the vital physical determinants of life have changed significantly. For the biological communities in the ocean these include:

- water temperature,
- ocean currents,
- salt and nutrient content of the water,
- carbon dioxide content of the water (ocean acidification),
- oxygen content of the water,
- volume of sea ice, and
- the frequency of iceberg calving.

For the biological communities on land, climate change has had an impact on the following:

- air temperature,
- type and amounts of precipitation,
- duration and extent of snow and ice cover,
- extent of permafrost,
- frequency and intensity of extreme weather events such as heat waves, and
- the amount of coastal erosion.

For the coming decades, climate researchers predict that the polar regions will continue to be subjected to the effects of rising temperatures, increasing acidity of sea water, intensified melting of snow and ice, changing precipitation levels, rising sea level, and large-scale thawing of permafrost soils.

Two types of adaptation

Organisms react to changes in their environment initially by trying to adapt their behaviour to the new conditions within a short time (acclimatization). Depending on their baseline situation, they may accelerate respiration and metabolism, pump more blood or water and nutrients through the body, perhaps eat more or, if they are mobile, migrate to areas where more familiar environmental conditions prevail. But these attempts at adaptation usually require an output of additional energy that the organisms have to generate. If they can do that, they have a relatively good chance of survival. But if they lack the necessary reserves, individuals may quickly reach their physical limits and be at risk of dying.

However, those individuals who succeed in acclimatizing in the short or medium term usually also reach the age necessary for sexual reproduction and, under optimal conditions, have the chance to adapt genetically over a number of generations. The organisms may produce offspring whose genetic make-up is favourably modified such that the new generation can cope better with the altered living conditions than the parent generation (genetic adaptation).

Both of these options are available to the flora and fauna of the polar regions. For two reasons, however, they represent a major, if not overwhelming challenge. In order to survive in the Arctic and Antarctic regions, most polar animals and plants have already reduced their metabolism and energy consumption so drastically at some time in the past that few of them possess sufficiently large reserves to compensate for the expected temperature increases in the long run. Furthermore, the slow evolutionary processes of many polar marine organisms preclude rapid generational changes. So the possibilities for adapting genetically to the new living conditions in a timely manner are very limited, especially for the more highly developed animals and plants. The outlook is different for organisms with short reproductive cycles. Bacteria, viruses and single-celled algae, for example, reproduce so rapidly that their prospects of genetic adaptation are much better than they are for clams, mussels, fish, birds or mammals. Individual adaptive capacity is therefore not as critical for microorganisms as it is for organisms with longer lifespans.

Ecosystems under pressure

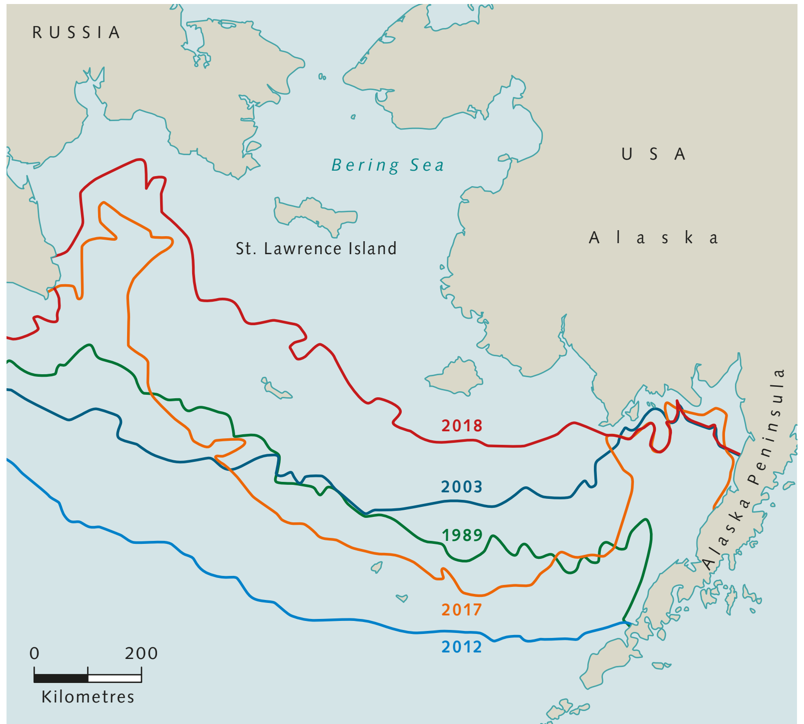
Because the Arctic and some parts of the Antarctic are warming twice as fast as the rest of the world, the highly specialized biological communities in these two regions are under particular pressure. The many species-specific changes that researchers are now observing are represented by the following trends:

- In the two polar regions, depletion of sea ice is reducing the size of the habitat for species that use the ice as food source, resting area or nursery ground. Particularly in the Arctic, this means that feeding grounds are shifting poleward with the retreating ice margin. Birds and mammals here that have hunted or fished on the edge of the ice now have to travel greater distances.
- The spectrum of prey for polar predators is changing in the wake of ocean warming.
- The health and fitness of many animals are deteriorating due to food shortages.
- The decline in sea ice and the rising water temperatures are forcing polar sea dwellers to migrate to the few remaining colder regions. Such migrations will be much easier for mobile deep-sea species than for shelf-sea inhabitants that are adapted to life in shallow water.
- The rising air and water temperatures in the Arctic and Antarctic are paving the way to the polar regions for immigrants from the mid-latitudes. These newcomers may then compete with the native species for food. Or they themselves could become a less nutritious prey than the polar species that they replaced in the food web.
- Climate change affects polar biological communities in many ways due to its interactive processes. Various stress factors can either amplify or diminish each other's effects.
- Exactly how climate-induced changes alter the lives of animals and plants in the polar regions depends to a large extent on regional conditions. The course as well as the degree of change can thus vary greatly from region to region.

Sea-ice retreat – the pantry is shrinking

The retreat of Arctic and Antarctic sea ice is already having a fundamental impact on biological communities, and on the individual species that depend directly or indirectly on the sea ice in any way. The thinner the ice is, the more

4.31 > Body of a dead grey whale north of San Francisco. It is one of more than 200 whale corpses that have been found on the west coast of the USA, Canada and Mexico since the beginning of the year.



4.32 > The winter sea ice in the Bering Sea is steadily retreating. At the end of the winter of 2018 it covered the smallest area of sea since the beginning of satellite measurements. Researchers believe that the causes include increasing air temperatures due to the meandering jet stream, combined with warmer water temperatures.

light is able to reach the ice algae in the spring, and the earlier the important algal blooms begin. Researchers believe that thinner sea ice in the Arctic that also melts earlier will initially boost primary production because the algae in the ice and in the water column will be exposed to more light through the course of the year. But there are two important requirements for increased algal growth. First, the ice and seawater must contain sufficient nutrients. The second requirement is that the amount of snow on the sea ice must not increase. A thick snow cover would prevent sunlight from penetrating through to the ice algae. A more stable stratification of the upper water masses could also inhibit their growth. When sea ice melts, the freshwater content of the upper water layer increases. As a consequence, the low-salinity surface water does not mix as readily with the denser, heavier, more saline and nutrient-rich deep water.

Computer simulations of sea-ice development in the Arctic region indicate that future ice-algae blooms will begin much earlier in the year. This temporal shift, in turn, threatens the survival of copepods as well as many other species of zooplankton whose life cycles have always been closely synchronized with the reproductive cycle of the ice algae. Scientists have been observing a decline in ice-associated amphipods around Svalbard, for example, since the 1980s. Premature ice-algae blooms, or even their complete absence, could initiate a fatal chain reaction such as the one recently observed in the northern Pacific Ocean.

In the past, ice algae have accounted for 60 per cent of the primary production in this region. But in the winter of 2017/2018, the area of sea ice around Alaska attained a size of just half of what was there in 1978. Accordingly, the subsequent ice-algae bloom in that year was also small. As a result, the zooplankton that feed on the ice algae starved first. The next victims were probably the fish species living under the ice, because the following summer the inhabitants of Alaska observed an abnormal number of seabird deaths. Large numbers of the common murre *(Uria aalge)*, which preferentially preys on ice-associated fish such as polar cod *(Boreogadus saida)* and capelin *(Mallotus villosus)*, starved to death. Just a few months later, by August 2019, the bodies of more than 200 starved grey whales had washed onto the west coast of North America. The animals presumably died because they could not find enough food during the previous summer in their Arctic feeding grounds in the Bering Sea and in the Chukchi and Beaufort Seas. Grey whales are the only baleen whales that search for food on the seabed. They filter amphipods, worms, mussels, fish eggs and other bottom dwellers out of the mud, and accumulate an abundance of fat reserves in the Arctic before migrating to the Gulf of California for the birth of their calves.

The ice-related collapse of fish stocks in the Pacific sector of the Arctic Ocean also had an impact on Alaskan fishermen. In the past, they had caught economically important species such as Alaska pollock *(Gadus chalcogrammus)* and Pacific cod *(Gadus macrocephalus)* in the Bering Sea. These species both prefer cold water masses, like those that previously formed a kind of cold-water pool in the Bering Sea. But in 2018 this pool was smaller than it had ever been before, presumably due to the absence of

4.33 > Because there is no longer sufficient summer sea ice off the Arctic coasts of Alaska and Russia, around 100,000 Pacific walruses have come to a beach on the Chukchi Sea to rest from their hunting excursions and give birth to their young. These mass gatherings have also taken place in the past, but as the sea ice recedes further, they are occurring more frequently.

winter sea ice. At any rate, the schools of fish followed the cold water northward and out of the reach of the fishermen. If this chain of events is repeated in the coming years, the continued survival of the lucrative fishing industry in the Bering Sea will be seriously threatened. In 2017 the fishermen still caught and processed Alaska Pollock with a value of 1.3 billion US dollars. However, if the stocks permanently migrate to the north, the operation of the large industrial ships will no longer be profitable.

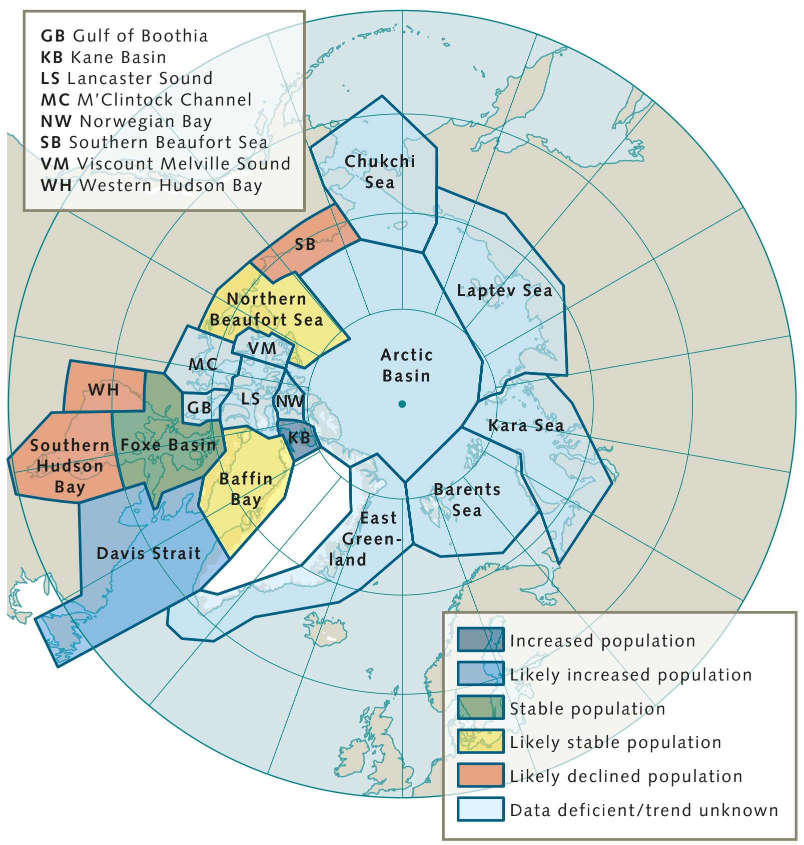
With regard to the continuing decline of sea ice in the Bering Sea, researchers are talking about an imminent regime change. By this, they mean the transformation of a polar marine ecosystem once focused on sea ice as the central component of the habitat and food supply, into a more temperate system, in which sea ice and its associated species play virtually no role.

Too little ice for walruses and polar bears

The retreat of sea ice in the Bering Sea is also altering the living conditions for the Pacific walrus *(Odobenus rosmarus divergens)*. Up to 3.6 metres long and weighing as much as 1900 kilograms, the walruses search for food on the sea floor of the Bering and Chukchi Seas, and in the past they would sleep in small groups on ice floes floating near their fishing grounds. The cows also delivered their calves on the ice and raised them there. But since 2007, researchers have been observing that the walruses are now much more rarely finding ice floes to use as resting platforms. Instead, the animals are forced to make their way back to the land. They often come by the thousands to coastal areas sheltered from the wind and waves. Exhausted and densely packed, they lie on the beaches in groups of up to 100,000 individuals. If the walruses are disturbed in this kind of situation, either by polar bears, airplanes or people, a state of mass panic can result. The heavy animals take flight blindly into the sea, ploughing through any individuals that are not able to get out of the way in time. Many of the calves do not survive this kind of mass panic.

Such stampedes, however, are not the only consequence of climate change for these large pinnipeds. With the increasing water temperatures in the Pacific sector of the Arctic Ocean, the food supply for the walruses is also undergoing changes. Subarctic bottom dwellers and po-tential prey animals like the graceful decorator crab *(Oregonia gracilis)* are migrating from the south into the Chukchi Sea, and are invading new habitats. Furthermore, the distances from the coast to the ice edge are becoming steadily greater for the animals. Native inhabitants of Alaska report that they are increasingly finding deep-sea fish in the stomachs of the walruses they hunt and significantly fewer mussels – an observation that indicates that the spectrum of prey for the large mammals is changing. What impacts these changes will have on the population as a whole remains to be seen. In the case of harp seals and hooded seals on the Atlantic side of the Arctic Ocean, researchers are already recording a decline in the birth rate, diminishing overall health, and dwindling populations. Scientists attribute these developments similarly to the decline of sea ice.

4.34 > The Arctic polar bears are divided into 19 geographic groups whose population numbers are insufficiently known to researchers. In 2019, reliable data was available from only eight regions.

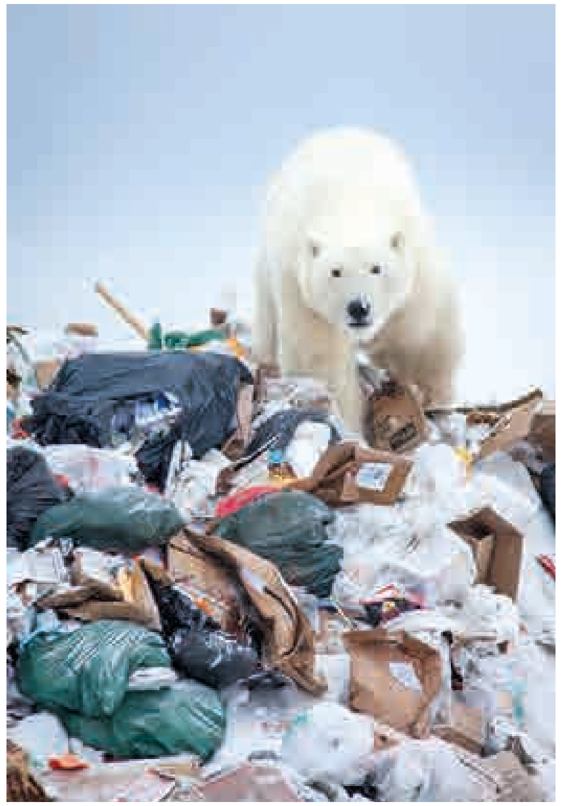


The outlook for polar bears is also discouraging. With the disappearance of sea ice, climate change is destroying the only habitat on which they can find sufficient food. Recent findings indicate that the bears require 60 per cent more energy than was previously thought. Even on days when the animals hardly move, they still burn more than 12,000 calories. This basic requirement can only be met by preying on ringed seals *(Pusa hispida)* and bearded seals *(Erignathus barbatus)*, which the bears hunt on the sea ice. Any other food source would not be sufficient to ensure the survival of the bears. In recent years, young polar bears in particular have been observed searching for alternative food sources on land. These animals were eating berries and kelp, chasing ducks and small mammals, and raiding the nests of snow geese *(Chen caerulescens)* and thick-billed murres *(Uria lomvia)*.

Scientists therefore assume that, in the long run, the unchecked decline of Arctic sea ice will lead to extinction for the polar bears. The hunt for seals can only be successful on the ice, where they initially prey on young animals in the late spring. These are still unable to escape into the water at this time, and as prey they have a fat content of 50 per cent. Then, when the new generation of seals are able to take refuge in the sea, the bears wait to ambush them at one of their many breathing holes.

Polar bears that have year-round access to the ice can hunt for seals at any time. Animals that live in regions where the sea ice melts extensively in summer have to spend the ice-free time on land and must fast most of the time. The longer these bears are unable to hunt at sea, the greater the danger of starvation becomes. In computer models, biologists have calculated mortality rates for adult bears in the western Hudson Bay. These indicate that three to six per cent of all adult males will die when the summer fasting period lasts 120 days. If the period is extended by 60 days, to a total of 180, 28 to 48 per cent of the bears will be threatened by starvation. Extended periods of fasting have also been shown to disrupt the reproductive capacity of these carnivores. In years when there is little sea ice, female polar bears give birth to fewer and smaller cubs, and mortality rates for the offspring increase.

4.35 > A hungry polar bear preys on a colony of breeding seabirds on Coburg Island in Nunavut, Canada.



4.36 > As long as the absence of sea ice deprives the polar bears of access to the seal hunting grounds, they will search for food on land, for example in the garbage dumps of Arctic communities.

The decrease in average sea-ice thickness is a further factor causing problems for the polar bears, because thinner ice floes drift faster. The increased drift speed means that they will have to make a greater effort to continue hunting in their traditional territory. The greater effort, in turn, means an increased energy demand that the animals will have to meet. This is a challenge that is driving the bears increasingly closer to human settlements, or into regions where they have rarely been seen before. In June 2018, for example, a polar bear visited Summit Camp, a US research facility on the Greenland ice sheet. The station lies at an elevation of 3200 metres, and is located more than 400 kilometres from the nearest coast.

Estimates say that there are around 25,000 polar bears in the Arctic today, comprising 19 different populations. Information on developmental patterns is available for eight of these populations. Only in the Kane Basin southeastern of Ellesmere Island is the number of bears known to have increased. Scientists suspect that the case is similar for the population in the Davis Strait. So far, the populations in Baffin Bay, the Foxe Basin (Canadian Arctic Archipelago) and the northern Beaufort Sea appear to have remained stable. Conversely, the researchers are reporting declines in the southern Beaufort Sea as well as in the southern and western regions of Hudson Bay. If the scientific predictions are correct, polar bears will die out in these two regions within the next 30 to 40 years. During the same period, the total number of polar bears in the Arctic is expected to plummet by two thirds.

Not enough ice in the krill nursery

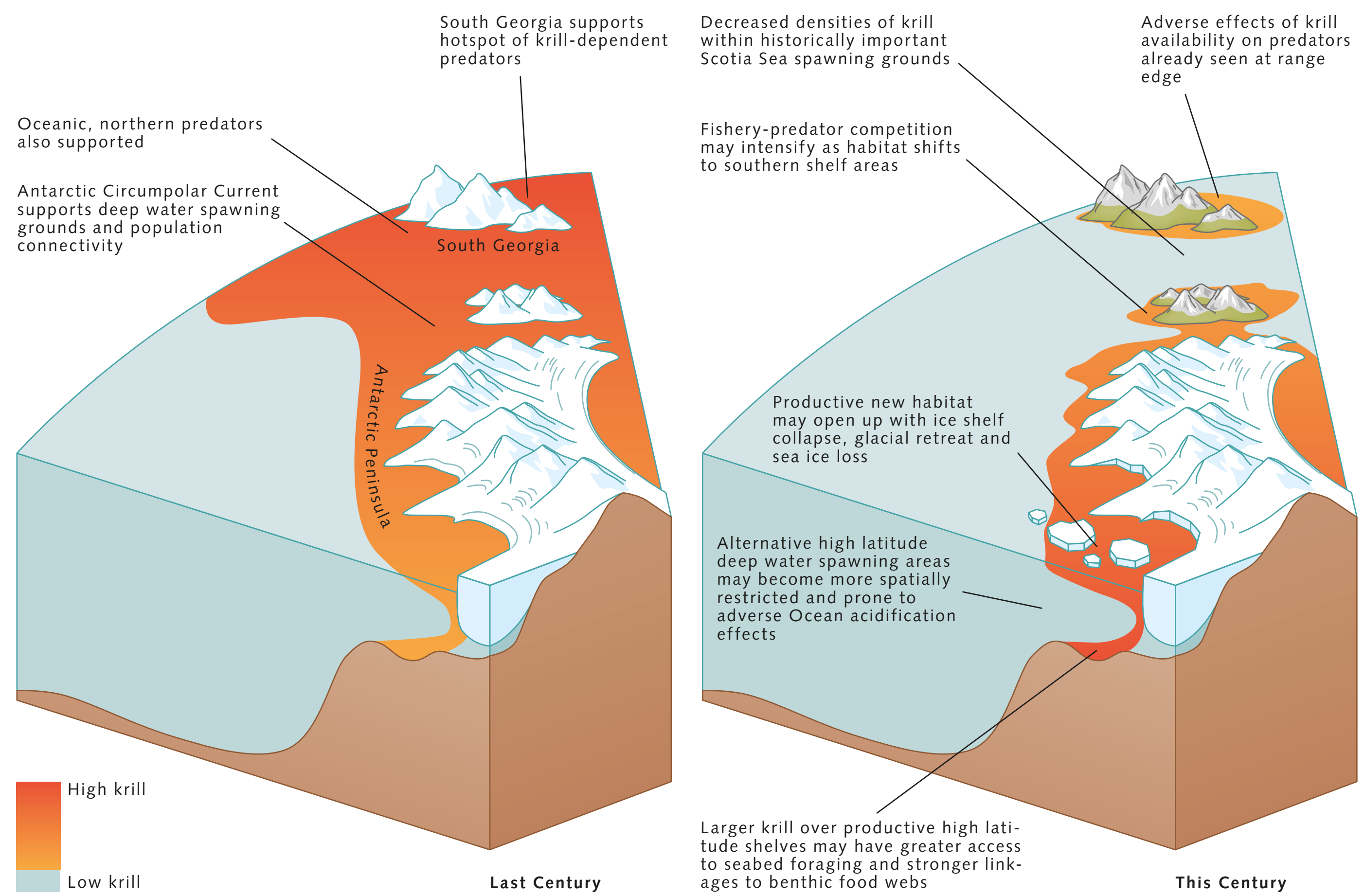
In the Antarctic, shrinking of the sea-ice cover has so far been occurring primarily on the western side of the Antarctic Peninsula, which is the nursery area for the krill population of the southwest Atlantic sector of the Southern Ocean (20° to 80° West). This community accounts for more than half of the total population, and is thus the largest concentration of krill in the Antarctic region. Scientists have analysed catch and size data for the krill over the past 90 years and found evidence of very fundamental change. Not only has the total number of krill decreased by more than 50 per cent, the large swarms today are located much further to the south than they were in the 1920s. At that time, the largest summer occurrences were around South Georgia. Now, however, these crustaceans live mainly along the northern and western coasts of the Antarctic Peninsula. Furthermore, the individual animals today are an average of six milli-metres longer than they were in the 1970s. This observation implies a demographic change within the krill swarms. The populations are now much older than they were earlier, which means that the Antarctic krill are producing fewer offspring, or that fewer of the offspring survive the larval stage.

The primary reason for this is presumed to be the retreat of sea ice on the western side of the Antarctic Peninsula. When ice is scarce the algal blooms are smaller, and the zooplankton species such as krill cannot find enough food in the springtime at the beginning of their reproductive cycle. A deficient food supply in the spring affects egg production and the hatching success of the offspring. In the past, the krill larvae and juvenile animals have been able to hide in the winter from predators, like the Antarctic silverfish, in the cavities, cracks and niches of the sea ice. Without this refuge, however, the crustaceans are at the mercy of their hunters.

Furthermore, the krill, also known as "light-shrimp", encounter altered living conditions in many fjords along the Antarctic Peninsula. Where glaciers have retreated onto the land, meltwater streams wash large quantities of sediment into the fjords and create turbidity in their waters. This pollution impacts krill in two ways. First, turbid water means less light for the various kinds of algae that live in the water column. These are no longer able to carry out a sufficient level of photosynthesis and thus grow much more slowly or die within a short time, and are no longer available as food for the krill. Second, when ingesting food, krill cannot actually distinguish between phytoplankton and sand particles. They consume whatever they filter out of the water. If their food consists mainly of sand grains, the light-shrimp starve. For this reason, the Antarctic krill has already disappeared from Potter Cove, an intensively researched glacial bay on King George Island. Its place in the food web has been taken over by salps, which can cope much better with the murky fjord waters.

The changes in the krill population in the southwest Atlantic sector have clearly left a mark on the species structure of the Southern Ocean. For example, the seals of South Georgia now give birth to calves that

4.37 > Warming of the Southern Ocean has led to the migration of Antarctic krill from their former territorial waters around South Georgia. They are now found further to the south in the coastal waters of the Antarctic Peninsula. The food webs in both areas have been permanently altered as a result.



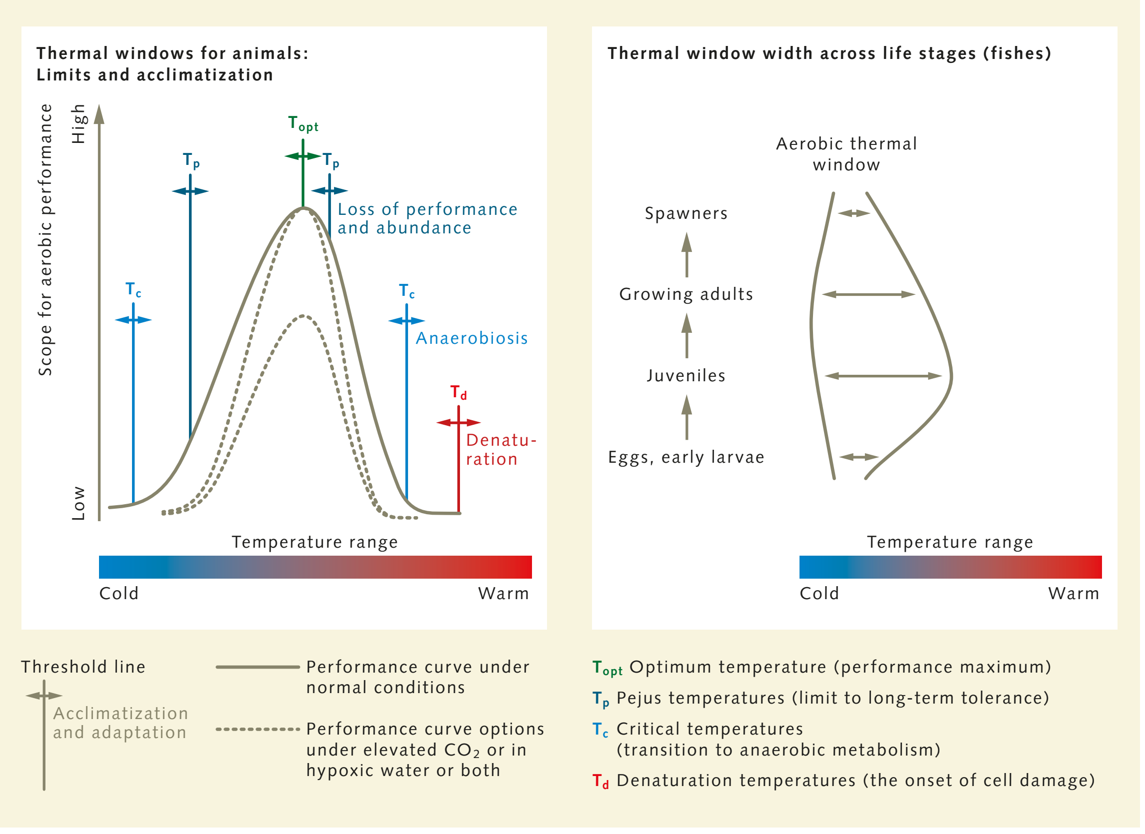
are much lighter than they were when the krill swarms were still abundant around the island. The southward migration of krill swarms is also making it difficult for Adélie penguins on the South Shetland Islands and along the west coast of the Antarctic Peninsula to find food. In recent decades their colonies have shrunk by as much as 50 per cent, although the declining krill population is not the only reason for this. Changes in the weather conditions on the Antarctic Peninsula have also played an important role.

Adélie penguins nest on snow-free and ice-free ground. If the breeding birds are caught off guard by rain or heavy melting of snow, their nests may be flooded and eggs or chicks lost. In the past, such losses have contributed to a decrease in the number of Adélie penguins along the Antarctic Peninsula, as have the diminishing krill population and the decline of the ice-associated Antarctic silverfish, another favourite food of the penguins.

Life at the thermal limit

In recent years, using a wide variety of methods, scientists have been studying how marine organisms respond to rising temperatures. Most of the laboratory studies indicate that cold-loving, ectothermic organisms native to the northern and southern polar seas are much less able to survive a period in warmer water than related species from temperate marine areas. Antarctic invertebrates like the bivalve *Limopsis marionensis*, the brittle star *Ophionotus victoriae*, and the brachiopod *Liothyrella uva* died at water temperatures of only three to four degrees Celsius. This places them among the most heat-sensitive marine organisms in the world.

In order to evaluate the adaptability of an ectothermic marine dweller, scientists determine the size of its thermal window. This refers to the range between the upper and lower temperature limits at which the organism can function smoothly. The width of this window varies depending on the species and the habitat. Animals from more temperate latitudes like the North Sea generally have a wider thermal window. This is necessary because they live in a marine region where the water temperatures vary greatly with the tides and seasons. This means that the animals have to endure the warm temperatures of summer as well as the cold winter conditions. The thermal windows of organisms in the tropics or polar regions, on the other hand, are two to four times smaller than those of the North Sea dwellers.



4.38 > Every organism has a limited temperature range within which it can function and exist. Researchers refer to this range as the thermal window. An organism performs most effectively when the ambient temperature is near the midpoint of its temperature window. If it gets warmer or colder, the functionality of the organism diminishes, even to the point of death. For most organisms, the size of the thermal window changes with increasing age. Fish, for example, can usually tolerate greater temperature fluctuations as young animals than they could in the embryonic stage.

The temperature limits for a particular species also vary with the age of the individual animal. It has long been assumed that larvae or juvenile animals have the smallest thermal window. It is often stated that a species cannot colonize in places where it gets too warm for them. This statement is true for the Atlantic cod and polar cod, among others. For these two species, a slight increase in water temperature is enough to kill a large proportion of their eggs. Research on a variety of invertebrate animal species from the Southern Ocean, however, indicates that their offspring react very differently to heat. In some studies, the mortality rates of juvenile animals did not increase until the temperature reached a level that was also dangerous for the adult animals. In others, the young animals were even more resistant to heat than the mature generations.

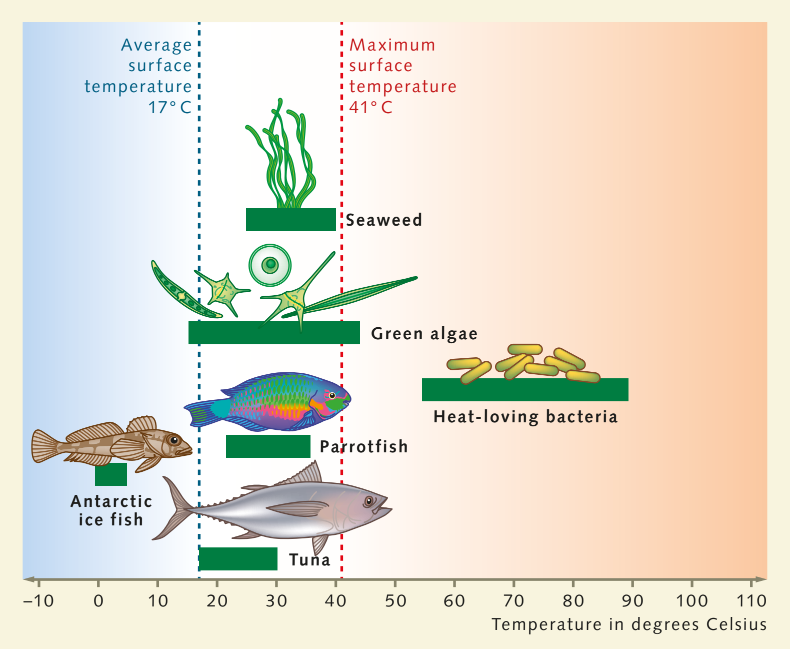
But it was also revealed that the offspring of polar species develop more rapidly in warmer water. If, for example, the Antarctic sea urchin *Sterechinus neumayeri* reproduces in water that is 0.5 degrees Celsius warm, the larvae sink to the seabed within 90 days after egg fertilization, where they then metamorphose into young sea urchins. In colder water, at minus two degrees Celsius, the animals require 120 days for this process, whereby the larvae also have more time to drift with the current to more distant regions. If the duration of the larval stage is shortened, there could be ramifications for the lateral distribution of the species.

There is now a basic assumption that most ectothermic animals in the polar regions would be able to survive over the long term in water that is as much as three to four degrees warmer. But if the warming exceeds this upper value, it would cause an increase in mortality and a greater number of deformities in juvenile animals. Another result would be that, for various reasons, the organisms would no longer be able to meet the increasing energy and oxygen demands that accompany rising water temperatures. When the water becomes warmer, all of the natural body processes of ectothermic marine organisms progress faster and therefore require more energy. Among other things, the animals digest the food they consume more rapidly, and a larger proportion of the energy they take in is used for their basal metabolism – the maintenance of basic normal body functions. If the animals ingest the same amount of food under these conditions as they did previously, they end up with less energy reserves for growth and reproduction than they had under colder conditions.

4.39 > The embryos of the Atlantic cod require water temperatures of three to seven degrees Celsius in order to develop optimally. The eggs, about 1.5 millimetres in diameter, will die if the water is only slightly warmer.

These and similar interactions are particularly threatening during the winter, when there is virtually no primary production in the polar seas due to the paucity of light. In the past, most cold-loving species have simply lowered their metabolism in winter. However, if global warming of the oceans continues, the energy demands will also increase during the polar night when food is scarce. The only individuals that will survive are those who are able to build up sufficient reserves.

From long-term studies on fish and other ectothermic organisms in the Antarctic region, it is also known that these species require a relatively long time to adapt to new



4.40 > Over generations, ocean dwellers have adapted to the conditions in their native waters, and have developed a corresponding range of temperature tolerance. The range is generally larger for species from the middle latitudes (tuna) than for species in the tropics or polar seas. Tropical and polar organisms commonly live at the upper or lower limits of their comfort zone.

environmental conditions. In laboratory experiments, up to nine months passed before the animals were able to restructure the fatty acids in their cell membranes to match the adjusted temperatures. This delayed acclimatization weakens the animals over the long term, because it means that many of the processes in their bodies do not function optimally for several months if the external conditions change quickly, as with a change of season, for example. Researchers are assuming that the water temperatures in the Antarctic will continue to fall to near the freezing point for the next one hundred winters. But they also believe that the winters will become shorter and the summers warmer. The cold-loving ocean dwellers will therefore be in a constant state of adaptation and will only rarely experience optimal conditions in the future.

Migration towards the pole

The easiest way for organisms to adapt to global warming is presumably to migrate to areas where familiar temperatures still prevail. For organisms living on land, this would be either the high mountain areas or regions further to the north or south. Sea dwellers, on the other hand, can migrate to greater depths or toward the poles. Researchers have been observing these temperature-induced migrations in plankton, invertebrates, fish and seabirds for decades, including in the peripheral areas of the polar oceans. Phytoplankton in the North Atlantic, for example, have been shifting poleward since the 1950s by a few hundred kilometres per decade. In the Southern Ocean, calcareous algae are found much further south today than they were 20 years ago.

Since the beginning of industrialization, the zooplankton populations of the world's oceans have migrated an average of 600 kilometres towards the poles to evade rising water temperatures. In regions that have become particularly warm, the ranges of microorganisms have shifted by as much as 2550 kilometres.

The Atlantic cod *(Gadus morhua)* has already advanced so far to the north in its flight from the heat that it can now be found in large numbers in the waters around Svalbard in the summer. The warm Atlantic water masses overlie cold Arctic waters from the Barents Sea at this time of year, so the cod finds optimal conditions with water temperatures of around four degrees Celsius. Its Arctic relative, the polar cod *(Boreogadus saida)*, on the other hand, has to flee this temperature. As a cold-loving species it prefers water temperatures around zero degrees Celsius. The Intergovernmental Panel on Climate Change predicts that these and other cold-adapted inhabitants of the northern and southern polar seas will see their habitats continue to shrink because there are no other areas of refuge for them in the long run.

When immigrants from the middle latitudes advance into the polar regions, they may have to compete with established species for food resources. For example, Atlantic and Pacific killer whale populations are now also hunting seals in Arctic waters, and are thus competing with polar bears. Because of the northward migration of the Atlantic cod, the polar cod is confronted with a further competitor for food. Where these two fish species share the sea, they may hunt the same prey.

Immigrating species also change the food structure of the polar regions by becoming prey themselves while being significantly smaller and less nutritious than the

4.41 > Calcareous algae and other phytoplankton bloom in the spring and summer in the nutrient-rich waters of the Barents Sea, colouring this Arctic marginal sea bright green to milky blue. Researchers are noting that the magnitude of this algal bloom is increasing in the wake of climate change. At the same time, the blooms are occurring further to the north than they did at the beginning of the 21st century. This is due to the retreat of the Arctic sea ice.

native species they have displaced. One example of this is the Atlantic copepod *Calanus finmarchicus*. It is advancing into the Arctic Ocean via the North Atlantic Current, and in its northern range is now replacing more fat-rich Arctic species such as *Calanus glacialis* and *Calanus hyperboreus*. For the predators of copepods, this species substitution means that they have to consume larger volumes of the newcomers in order to obtain the usual amount of energy. Scientists are observing very similar patterns in amphipods.

The polar seas are acidifying

By acting as a gigantic carbon sink, the oceans have absorbed around a third of the carbon dioxide that human activities have released into the atmosphere since the beginning of industrialization. Thus the world's seas have slowed global warming. However, this absorption also leaves traces, because when carbon dioxide from the atmosphere dissolves in seawater, a profound chemical change occurs in the surface water. Seawater normally has an average pH value of 8.2 and is therefore slightly alkaline. This is because of the mineral components in the water, calcium carbonates such as calcite and aragonite, which were at one time dissolved from weathered stone on land and then washed into the sea.

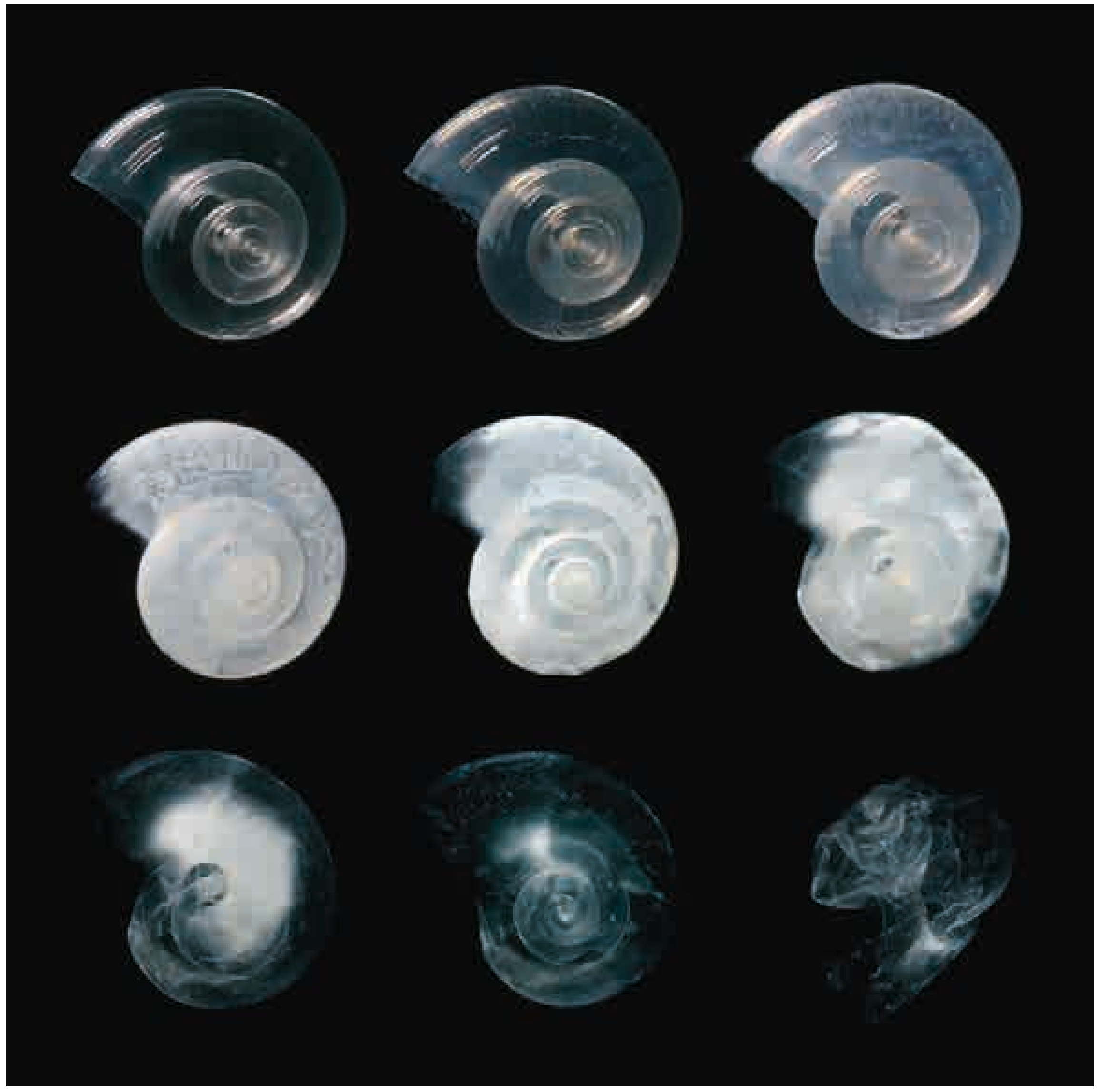
If the oceans absorb carbon dioxide, however, this gas, unlike oxygen, does not simply dissolve in water. On the contrary – a proportion of the carbon dioxide binds with the water, so that carbonic acid is produced. Anyone who makes their own sparkling water at home in a Sodastream understands this principle. When the button is pressed, carbon dioxide is injected into a bottle of tap water and immediately produces in it the bubbles typical of carbonic acid. To a certain extent, the same thing happens in the sea, but the carbonic acid in the sea is not stable: it breaks down into bicarbonates, the carbonic acid salts, and protons (hydrogen ions). The latter increase the acidity of the water and the ocean becomes more acidic.

The measure for the concentration of hydrogen ions in a solution is known as the pH value. However, this numerical value shows the concentration as a negative common logarithm. That means that the more hydrogen ions there are in a solution, the lower the pH value is. Since 1860 the mean pH value of the ocean surface has fallen from 8.2 to 8.1. This apparently small gradation on the logarithmic pH scale corresponds to an actual rise in acidity of 26 per cent – a change that the world's seas and their inhabitants have not experienced in millions of years. By the year 2100 the pH value of the oceans is predicted to fall by a further 0.3 to 0.4 units, and seawater thus to become one hundred to 150 per cent more acidic. That does not mean that the oceans are actually acidic, as even with values around 7.7 they are still alkaline from a chemical point of view, but they are – in relative terms – more acidic than before.

All marine creatures that breathe in water, such as fish, bivalve molluscs and starfish, have five to 20 times less carbon dioxide in their blood than land-dwellers. That is why scientists assume that water containing more carbon dioxide will affect sea creatures in a different, probably more dramatic way than species that breathe air. If the carbon-dioxide concentration in the bodily fluids of an animal rises, this leads to acidification there too and among other things impairs the transport of substances through cell membranes.

Especially at risk are calcifying organisms such as bivalve molluscs, corals, echinoderms and certain species of plankton, since they need calcium carbonates to form their shells and skeletons. The concentration of these minerals in seawater is falling as acidification increases, however. For the organisms, this means that the more acidic the water becomes, the more effort they have to expend to construct their shells and skeletons. However, the more energy the creatures invest in calcification, the less they have left for other processes essential for survival, such as growth and reproduction. Therefore, in the long term, the size, weight and overall fitness of the organisms decline. Moreover, as acidity levels rise, so too does the danger that the more acidic water will attack existing mollusc and snail shells, and coral reefs, and will damage or even totally destroy them.

Ocean acidification thus affects organisms quite directly – especially in the polar regions, where most organisms already only survive because they have reduced their energy consumption to the absolute minimum. This means that many marine dwellers have almost no energy reserves to cope with the extra pressure of acidification. What makes matters worse is that acidification and warming of the seas go hand in hand. The interaction of the two processes can either increase or decrease the impact of acidification in the ocean, depending on the species. Be that as it may, the effects on individual members of the food web indirectly influence the entire marine community.

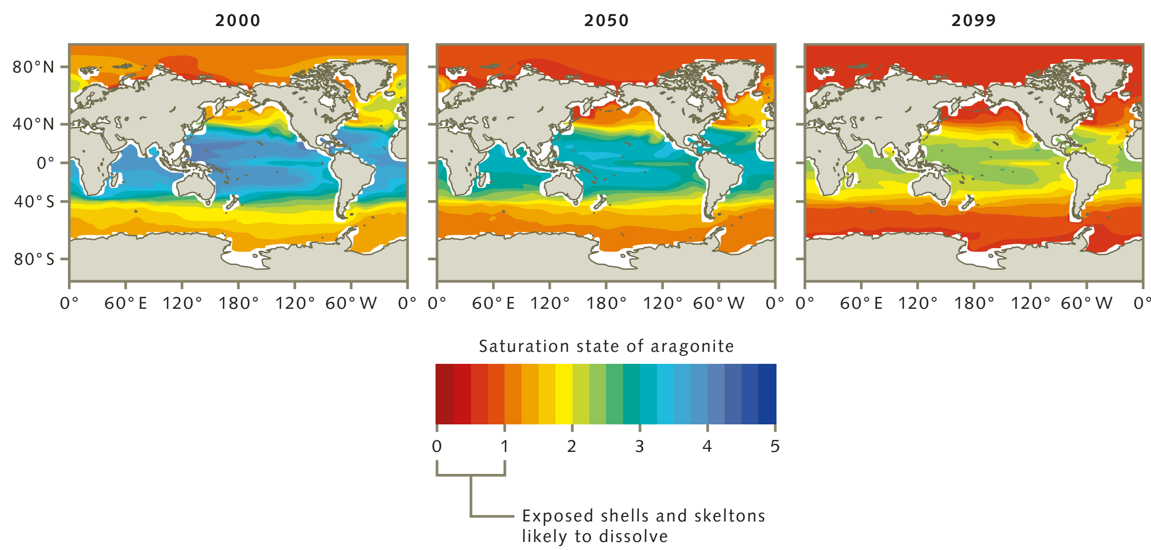


4.42 > Researchers set up a laboratory experiment in which they kept the Antarctic pteropod *Limacina helicina antarctica* under the acidified conditions predicted for the year 2100 – assuming that humans do not cut their carbon emissions. The finding: the sea snail's calcareous shell dissolved within 45 days.

Ocean acidification hotspots

The ice-free areas of the Arctic and Antarctic Oceans absorb more carbon dioxide from the atmosphere than the global ocean overall and acidify more quickly than warmer ocean regions. This is primarily due to the still comparatively low water temperatures of the polar seas. Gases such as oxygen and carbon dioxide dissolve more readily in cold water. In addition, the major rivers of the Arctic

4.43 > Because gases such as oxygen and carbon dioxide dissolve more readily in cold water, the polar seas are acidifying significantly more rapidly than water bodies in the mid- and tropical latitudes. As acidity levels in the polar seas rise, the concentration of vital calcium carbonates in the water falls.



carry large quantities of organic material into the marginal seas. If this is broken down by microorganisms, more carbon dioxide is produced, which accelerates the acidification of the Arctic Ocean. This is particularly true for the Laptev, East Siberian and Chukchi Seas. The melting of the great ice sheets also exacerbates the trend, since if meltwater flows into the sea, it dilutes the water masses. That means that the concentration of calcium carbonate ions falls as well. However, when algae blooms occur, carbon dioxide is removed from the sea and the pH value of the water rises again. Because of this, the pH of seawater is subject to natural fluctuations, especially in the polar seas.

Scientists can already see clear indications that the polar seas are becoming more acidic, but the response of the marine creatures there to the falling pH of the water varies considerably. For example, researchers conducting laboratory and field trials were surprised by the remarkable level of resistance shown by viral and bacterial communities. Some of the bacteria species even grew better in more acidic water than in water with a normal pH value. The phytoplankton proved similarly robust. However, the scientists do not see this as a reason for optimism because once the algae in the experiment reacted to the rising acidity levels, shifts in species assemblages fundamental to the entire food web generally followed.

Organisms benefiting from acidification include large algae such as the Arctic kelp *Saccharina latissima*, also known as sugar kelp. The increasing carbon-dioxide content of the water facilitates photosynthesis to a certain degree, so that the algae grow better. Moreover, experiments show that Arctic cold-water corals can also construct their calcareous skeleton in a more acidic environment – provided that they find enough food to meet the greater energy demand. However, scientists fear that in the long term the acidification of the water could lead to signs of decay at the base of the reefs. These are composed of limestone formed from dead corals, which could dissolve if acidity levels rise in the Arctic Ocean.

The losers from acidification, on the other hand, include the Arctic and Antarctic sea butterflies (Pteropoda). These animals secrete a calcium carbonate shell. In experiments, researchers observed that the shells were generally smaller and less stable in more acidic conditions, and exhibited greater damage than in water with a normal pH value. The green sea urchin *Strongylocentrotus droebachiensis* produces fewer young in more acidic water, because the eggs are less well fertilized. Furthermore, the number of deformities among the embryos increases. There is also a gloomy outlook for the echinoderms of the Antarctic shelf seas. These regions of the ocean are predicted to acidify so rapidly that echinoderms such as sea

urchins and starfish will have to migrate into deeper waters to avoid being harmed by the higher acidity.

Second to marine mammals, fish are among the most highly developed creatures in the oceans. They have complex regulation mechanisms that enable them to adapt to changing temperatures and carbon-dioxide concentrations in the water. Fish neutralize the surplus carbon dioxide in their bodies using acidity-regulating processes in their gills, intestinal tract and liver. Biologists have studied this effect extensively and established that fish can compensate for a lower pH value within a few hours.

However, the scientists also discovered that these mechanisms only function fully in adult fish. Juvenile fish, on the other hand, are not yet able to protect themselves adequately, and react significantly to acidification of the sea; this is the case with juvenile cod, for example. In acidification experiments, smaller numbers of fish larvae were released from the egg; they were noticeably smaller at this stage than in normal environmental conditions and needed more oxygen. At the same time, twice as many juvenile fish died in the first 25 days of life at the pH values forecast for the end of the 21st century than under today's conditions. Studies using young Atlantic herring *(Clupea harengus)* showed that the juvenile fish exhibited organ damage and deformities more often in acidified water. These became more severe as the acidity of the water in the test basins increased.

Such species-specific consequences of ocean acidification indirectly alter the entire species structure of the polar seas, for example, when one species experiences a clear competitive disadvantage as a result of acidification, while its rivals remain unaffected. Biologists believe, for instance, that in the future non-calcifying algae will have considerably better conditions for growth than calcifying algae. In the long term, a development of this kind could mean that in places where large kelp forests exist today, dense carpets of a more mat-like algae will flourish in the future. Another consequence of acidification could be, however, that important limestone structures in the sea disappear – and with them the species that live on or in these structures. Especially at risk are cold-water coral reefs and mussel and maerl beds. The latter are coastal sand or shingle banks made up of more than 50 per cent ramified living and dead red algae. Mussel beds provide a source of food for many seabirds, and for marine mammals such as the walrus. Should they die as a result of acidification, a vital livelihood base will be lost, not only for the more highly evolved animals, but for humans as well.

The situation is exacerbated by the interaction of ocean acidification and rising sea temperatures. A major meta-analysis has shown that Arctic marine dwellers react more sensitively to more acidic water if their environment becomes warmer at the same time. This is the case with sea butterflies and fish. For example, if the acidification and warming of the Barents Sea continues as it has to date, the cod population there, which is of enormous importance for the fishing industry, will probably collapse by the end of this century. On the other hand, studies on Antarctic fish and sea urchins showed clearly that temperature changes put the animals under considerably more stress than the increasing acidity of the water, to which many creatures in the trials were able to adapt. Nevertheless, to do this they required a great deal of time, which they are unlikely to have in their natural environment.

The wide variations in the responses of individual species to the ongoing acidification and warming of the polar seas make it difficult for scientists to draw general conclusions. Moreover, there are no conclusive long-term studies, especially for the Antarctic, that consider multiple environmental factors. However, all findings and prognoses so far indicate that the falling pH of the water will be accompanied by fundamental changes to the biotic community, which, in the Arctic at least, will also have a direct effect on human societies.

Changes for animals on the land

Climate change is also altering the land areas in the polar regions, and therefore the habitats of their occupants, especially in the Arctic. In many regions today, the snow cover is melting much earlier in the year, the sea ice is retreating earlier and for longer durations, and the vegetation is beginning to sprout earlier in the year

4.44 > Reindeer in the Svalbard Archipelago have developed the habit of eating seaweed washed up by the sea in winters with frequent rain and frozen snow or ice covers.

because of the warmer temperatures. These changes have consequences. Researchers note that the distributional ranges of polar species are shifting northward as subarctic species advance into the southern reaches. The entire tundra is in motion; even the elk are on the move, as a Siberian reindeer herder observed more than five years ago.

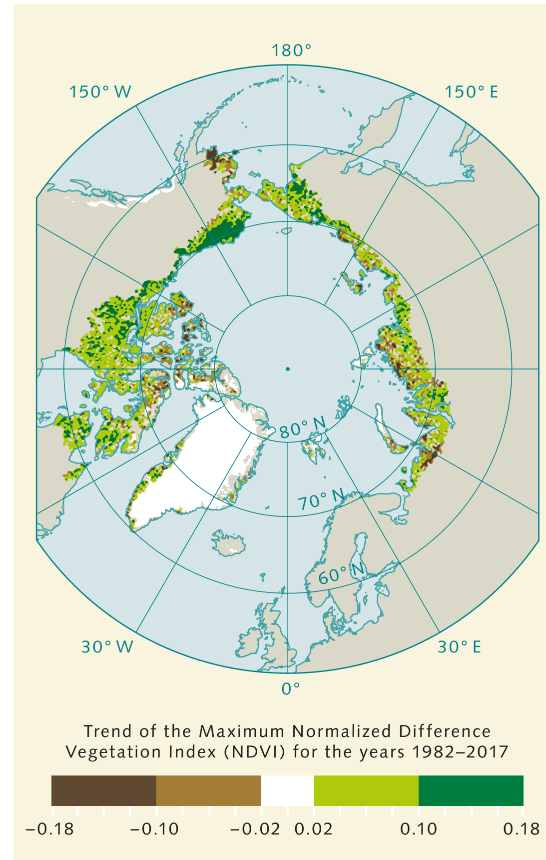
In the future, the changes will probably be even more dramatic because, even if humankind is able to limit average global warming to two degrees Celsius, the air temperatures in the Arctic region will rise by 2.8 to 7.8 degrees Celsius and pave the way for species from more southern realms. The unique biological communities of the high Arctic lands are threatened with extinction in the long run because their northward retreat is limited by the Arctic Ocean. Only those polar species that are able to migrate to higher elevations or to remote islands will have a prospect of survival.

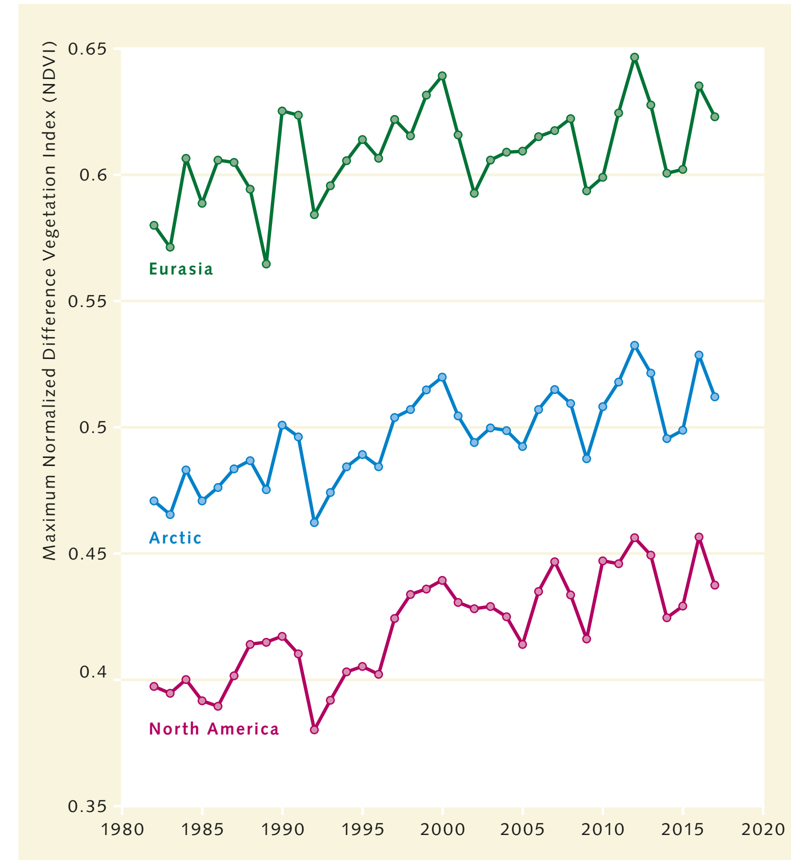
Which species survive in the Arctic in the future will primarily be determined by the winter conditions. Temperature stress and flooding due to strong rains or sudden snow melt, for example, threaten small rodents like lemmings, which in the past have been able to find protection from cold and predators beneath the snow. Ice-rain or freezing of the snow cover also hinders caribou, reindeer and musk oxen in their search for food. In this situation, the lichens, which are essential for their subsistence, are so firmly embedded in the ice that the animals cannot scratch them free with their hooves. The animals are threatened with starvation, especially the herds living on Arctic islands or in very isolated areas where there is little chance of migrating to other regions. The reindeer in western Svalbard have begun to look for food on the beaches in winters when the ground is heavily iced over. The animals wander along the coast and eat washed up kelp and other seaweed. The salty algae, however, appear to be just a stopgap solution, because in winters with normal polar weather conditions the animals again take up the search for lichens.

Increased warming in the Arctic is also disrupting nature's basic calendar. The sequence of important biological processes is undergoing a shift in time. The vegetation in some regions of Greenland is now beginning to grow 30 days earlier in the year. But the reindeer calves are still being born at the usual time because the reproductive cycle of the animals is determined by the length of the days and not by temperature. So, while the reindeer cows and their offspring were previously finding the qualitatively best food at exactly the right time, they are now showing up too late, and this has resulted in higher mortality rates for the calves.

Changes in polar vegetation

With regard to vegetation, researchers have been considering for several decades the question of whether the combination of warming and higher atmospheric carbon dioxide levels will boost plant growth in the northern polar region, or whether the increasing heat will be harmful to cold-adapted plants and rather lead to a long-term decrease in species diversity.





The answer so far has been: both, because developments are not homogeneous. In some regions of the Arctic tundra researchers have observed an increase in plant biomass (Arctic greening). This means that the plants are experiencing a boost in their metabolism, especially in response to the higher summer temperatures. They are emerging earlier and growing stronger, and they are expanding northward. This pattern is especially prevalent on the North Slope of Alaska and in the southern tundra regions of Canada and East Siberia. In these areas, bushy willows and alders grow much higher today than they did in the past. The shoots of the shrubs are thicker and the plants develop more branches and twigs. Plants like the mountain sorrel *(Oxyria digyna)* appear earlier in the year and bear larger and greener leaves, and grasses are now sprouting in many exposed sites where previously only gravel was found.

However, there are also areas where the opposite trend is prevalent, where vegetation density and biomass are declining despite the rising summer temperatures (Arctic browning). These regions include, for example, the Yukon-Kuskokwim Delta in western Alaska, the High Arctic in the Canadian Arctic Archipelago, and the northwestern Siberian tundra. Various extreme events here, such as episodes of winter heat with sudden snow melt, icing over due to unusual winter rains, tundra fires, persistent drought or plagues by various pests in the neighbouring forests have created adverse conditions for the plants. Furthermore, with the thawing of permafrost the

4.45 > Researchers have been using satellite data since the 1970s to observe the development of vegetation patterns in the Arctic region. With the help of this data from space they have created the Normalized Difference Vegetation Index (NDVI). The more vascular plants grow in a region, the higher this value is (Arctic greening). But when the vegetation dies, the index falls (Arctic browning).

dangers of flooding, standing water in depressions, and erosion have increased.

Because of these varied developments, scientists are certain that climate change will generate complex interplay among the vegetation, the atmosphere, the permafrost soils, and plant-eating animals. The amount of warming alone does not determine whether the vegetation cover becomes denser and greener in a certain region. What increased plant growth does indicate is that an area is responding in its entirety to warming.

Looking to the future, it is still uncertain whether plant growth in the Arctic region will generally increase if climate change progresses to a degree such that the temperature is no longer a limiting factor for the vegetation. Computer simulations predict that the vegetation will continue to advance northward. If humankind does not drastically reduce its carbon dioxide emissions, there will only be a few areas in the Arctic by the end of the 21st century where it will still be cold enough to prevent the growth of plants. But even then, the Arctic region will probably not be a favourable environment for an abundance of plants. As long as the Earth's axis maintains its tilt, the winters in the polar regions will continue to be long and dark, and the summer growing season will be so short that it will present a huge challenge to plant growth.

Risk escalates with rapid change

It has taken millions of years for the Arctic and Antarctic animal and plant worlds to adapt to the extreme living conditions in the polar regions. By comparison, the present climatic changes driven by global warming are happening so fast that the polar ecosystems and their highly specialized organisms are in danger of not being able to adapt quickly enough. Human-induced climate change therefore poses a massive threat to the diversity of polar biological communities and to their functionality.

Today, we know that the feeding interrelationships in the polar ecosystems are much more complex and diverse than was previously understood. Similarly, we still know relatively little about the biodiversity of many groups of polar organisms. In 2014, for example, scientists had sufficient information on less than two per cent of the Arctic organisms to be able to recognize climate-induced changes in their behaviours. The researchers are therefore still unable to say much about the possible reactions of the affected biological communities. In the areas that have been well researched, however, one thing is very clear: Where climate change is already having an impact, the natural polar biological communities look different today than they did prior to industrialization.

4.46 > On Herschel Island in far northern Canada, plant growth has increased in the wake of climate change, as these two photographs illustrate. The image on the left was taken in 1987 and the one on the right two decades later.

Conclusion

Highly specialized and greatly threatened

Cold, light and ice determine the course of life in the Arctic and Antarctic. On land, these parameters are the reason that the growth or reproduction cycles for most organisms are very short, and that many animals leave the polar regions at the end of the summer. In the sea, the cold makes energy-efficient slowness essential, which in turn can make many organisms quite long-lived. The amount of sea ice, the food supply, and access to open water change in rhythm with the polar day and night.

Under the pressure of extreme environmental conditions, highly adapted biological communities with amazingly high biodiversities have developed in both polar regions, although the number of species does not begin to approach the dimensions of the tropical regions. In the Arctic, the greatest biological diversity is found on the land because of the relative distribution of the ocean and con tinents. In the Antarctic, on the other hand, almost all life is dependent on the sea. The degree of adaptation here and the number of endemic marine species are both significantly higher than in the Arctic. This is due to the geographic isolation of Antarctica and to its longer and more diverse glacial history.

The recurrent growth of Antarctic glaciers and ice shelves out to the continental margin has often brought the dwellers of the shelf seas to their physiological limits. Over time, this has resulted in the development of many new and highly specialized species, a process that scientists refer to as a species diversity pump. The inhabitants of the Arctic Ocean, on the other hand, were able to migrate to the North Pacific and North Atlantic in times of extensive icing. Today researchers can distinguish the Atlantic and Pacific sectors with regard to the marine ecosystems of the Arctic Ocean.

Plants overcome the cold and the shortage of light in various ways. These include cellular frost-protection mechanisms, a compact size, slow growth, heat-optimizing characteristics such as hairs or flower shapes, accumulation of large reserves, improved photosynthetic performance, largely asexual reproduction and multiple utilization of nutrients.

In endothermic animals, an insulating winter coat or plumage prevents the loss of valuable heat. They build large reserves of fat, warm each other when necessary, and survive extreme weather conditions in sheltered locations. Many ectothermic marine organisms utilize anti-frost proteins, move in energy-saving mode, grow slowly and produce comparatively few offspring, which they provide with the best possible conditions in early life.

But due to climate change, the physical foundations of life in the Arctic and Antarctic are shifting. Their polar ecosystems and highly specialized organisms face the imminent risk that they will not be able to adapt rapidly enough to survive. With the disappearance of sea ice, a habitat is vanishing that serves many species as a sanctuary, food source and hunting ground. These organisms are now threatened with extinction. Rising water temperatures are increasing the energy requirements for ectothermic organisms, while also paving the way for immigrant species. Food webs are becoming destabilized, and competition for food is intensifying. Acidification of the polar seas also makes survival more difficult for organisms that build calcareous shells or skeletons. Climate change thus poses a massive threat to the biodiversity and functionality of polar ecosystems.

5 Polar politics and commerce

> As a result of climate change, ice and cold in the polar regions are diminishing. This is particularly noticeable in the Arctic. Here shipping routes are opening up and mineral deposits are becoming accessible, arousing the attention of industry. In the Antarctic, too, ever more countries and companies are pursuing commercial interests. Here, however, the imperatives of environmental policy have kept commercial activities within bounds up to now.

The Arctic and Antarctic as political arenas

> Historically, cooperation and willingness to compromise have characterized the political agenda of the polar regions. Since the signing of the Antarctic Treaty in 1959, the southern polar region has been managed on a collective basis. The countries with a stake in the Arctic have since 1996 coordinated fundamental policy issues in the Arctic Council. Yet both dialogue forums face challenges as a result of climate change and global geopolitical developments. The more the ice retreats, the louder do calls for commercial exploitation of the polar regions become.

Paradigm shift and new geopolitical interests

The polar regions are currently undergoing a fundamental shift in their significance. With the advance of climate change and the growing sophistication of the technology behind ships, aircraft, buildings, information channels and communication methods, humans are becoming ever more successful at enlarging their range of activity in the Arctic and Antarctic. In both regions significantly more states and stakeholders are now active than was the case just a couple of decades ago – and each is pursuing its own interests. Climate change has set in motion something akin to a geopolitical chain reaction that is presenting both the countries surrounding the Arctic and the member states of the Antarctic Treaty System with new challenges.

Easier access as the sea ice retreats

The shrinking of the sea ice makes it easier for people and ships to access the Arctic and Antarctic regions. In August 2014, for example, unusual ice conditions in the eastern central Arctic enabled the German cruise ship *Hanseatic* to reach a position 85° 41' North, thus setting a new record for passenger ships. According to observers, there are also large parts of the Antarctic that can no longer be regarded as remote and untouched. Decades of whale and seal hunting, the ozone hole caused by human activity and the many traces that scientists, fishermen and tourists have now left in the Antarctic provide confirmation of this statement.

5.1 > An icebreaker escorts tankers and cargo vessels through Russia's Arctic waters. This escort service is expensive yet is required by the Russian authorities: This is one of several reasons why shipping companies have until now made little or no use of the Northeast Passage as a route between Europe and Asia.

5.2 > The buildings of a new military base erected by Russia on Alexandra Land, an Arctic island that forms part of Franz Josef Land, stand on stilts. The base, which covers 14,000 square metres, houses air-defence units.

Commercial interests

The larger the areas of water and land that are laid bare by the shrinking ice masses of the Arctic and Antarctic, the more eagerly do a whole range of commercially oriented stakeholders and interest groups – travel companies, fishing fleets, mineral exploration companies, shipping companies and the like – covet the newly emerging opportunities. For example, the United States Geological Survey (USGS) calculates that 22 per cent of the world's unconfirmed oil and gas reserves lie north of the Arctic Circle. Shipping companies such as the Danish conglomerate Mærsk are already testing the feasibility of using the Northeast Passage as a route for cargo vessels travelling between northern Europe and the Indo-Pacific – in the hope that this will one day save considerable time and money.

Security concerns

As the sea ice melts, the countries with an Arctic coastline are losing a natural barrier that some observers regard as having protected them from military invasion from the north. This new security situation is said to be causing the Nordic countries some concern: Alongside increasing economic activity in the Arctic there is also a growth in military operations and latent conflicts could re-erupt. For example, during the Cold War the Arctic was a key theatre of military confrontation between the two then superpowers, the USA and the Soviet Union. Both sides maintained large military bases and rocket launching pads north of the Arctic Circle. Almost all these sites were shut down under the policy of détente of the 1990s, but climate change and the current debate on sea routes and rights of passage could result in a renewed build-up of military presence in the northern regions of the countries bordering the Arctic.

Attracting international attention and research

At the same time, the extent of climate change in the Arctic and Antarctic is attracting the attention of scientists and environmentalists. With a constant stream of new research findings, scientists are making the public ever more aware of the state of the polar regions, while environmentalists worldwide are campaigning for their protection. Their core message is that it is in the Arctic and Antarctic that the future of our planet is being decided.

All these developments indicate that the polar regions – especially the Arctic – are becoming geopolitical arenas in which a growing number of stakeholders have ambitions and concerns. At the same time, the superpowers have resumed their competition for power and influence in these regions: This sometimes hampers what used to be extremely well-functioning international cooperation in both the Arctic and the Antarctic.

Munich Security Conference
The Munich Security Conference (MSC), a globally important forum for debate on international security policy, is held in Munich every February. It aims to promote peace through dialogue and provides politicians and representatives of business, industry and civil society with a platform for official and unofficial diplomatic initiatives. The main conference is accompanied by side events at which specific issues and regions are discussed. One such event is the Arctic Security Roundtable.

Who governs the Arctic?

The question of who has a political say has a different answer in the Arctic than in the Antarctic, which is managed collectively. The reason for this is once again the differing location of the two regions. The Arctic is geographically delimited by the Arctic Circle. Large parts of the Arctic region lie within the territory of eight counties: Canada, Russia, the USA (via the state of Alaska), Norway, Denmark (because of its close links with the actual Arctic state, Greenland), Iceland, Sweden and Finland.

Among these eight countries, Iceland, Sweden and Finland differ from the others in that they have no direct access to the Arctic Ocean. The only Arctic states in the narrower geographical sense – i.e. with direct access to the Arctic Ocean – are therefore Denmark (Greenland), Canada, Norway (Svalbard), Russia and the USA (Alaska). They are termed the Arctic Five, as distinct from the group of eight countries with territory inside the Arctic Circle.

Although the Arctic states are spread across three continents, all eight nations are part of a community of culture, norms and values and are linked in various ways – whether as a result of environmental and climate-related concerns, because of economic, security-related and social issues or on account of their indigenous populations in the Arctic territories. The nations therefore debate important matters of common interest in the Arctic Council: since the 1996 **Ottawa Declaration** this has been the leading intergovernmental forum for the Arctic and has promoted and coordinated cooperation among the Arctic states, the indigenous population and other inhabitants of the Arctic. In its work the Arctic Council focuses largely on sustainable development of the Arctic region and on environmental issues. Military and security issues are explicitly excluded from its agenda: these are instead discussed in forums such as the twice-yearly meetings of the Arctic Security Forces Roundtable (ASFR), at events of the Arctic Coast Guard Forum (ACGF) or at the Arctic Security Roundtable organized by the Munich Security Conference in collaboration with various partners.

In addition to the eight member states, six organizations that represent the interests of indigenous Arctic peoples have the status of Permanent Participants on the Council. Decisions require the approval of all members and involve close consultation with the Permanent Participants. However, the Council's guidelines and recommendations are not legally binding: implementation of any resolutions is entirely at the discretion of individual member states.

Many observers, though, regard the fact that the decisions of the Arctic Council are not legally binding as a strength rather than a weakness, since it allows for swift and flexible adaptation in a rapidly changing environment. Moreover, the Arctic Council has in the past initiated the signing of three legally binding multilateral agreements. In 2011 the Arctic states signed the Agreement on Cooperation on Aeronautical and Maritime Search and Rescue in the Arctic; this was followed two years later by the Agreement on Cooperation on Marine Oil Pollution Preparedness and Response and in 2017 by the Agreement on Enhancing International Arctic Scientific Cooperation.

Meetings of the Arctic Council are attended not only by representatives of the member states and the Permanent Participants but also by the spokespersons of the working groups, of which there are currently six. The working groups regularly draw up comprehensive and groundbreaking status reports on various social and environmental aspects of the Arctic. These provide the Arctic states with recommendations for action and are also used as an important source of information worldwide.

Representatives of 13 non-Arctic states, 14 intergovernmental organizations and twelve international non-governmental organizations are also permitted to attend the Council's sessions as observers. The countries with observer status currently include Germany, China, France, India, Poland, Japan and the United Kingdom. These observer states hope that their participation will increase their international visibility and give them direct access to information on Arctic issues. In return, the Arctic Council expects them to become involved in the various working groups and support their work.

For example, Germany now sends scientists and experts to all six of the Council's working groups and, with the Netherlands, it funds the post of coordinator of the bird conservation programme operated by the Conservation of Arctic Flora and Fauna (CAFF) working group. The observers are required to report regularly on their activities. On the basis of these reports, the eight members of the Arctic Council then decide whether or not a state's observer status should be retained. However, no state has yet had this status withdrawn.

A zone of peace

The founding of the Arctic Council in 1996 was to some extent due to the then General Secretary of the Central Committee of the Communist Party of the Soviet Union, Mikhail Gorbachev. In his famous speech in Murmansk in 1987 Gorbachev termed the Arctic a zone of peace and called for greater cooperation between the Arctic states.

This inspired Finland to get the Arctic states around a table and, in the course of several conferences held in 1991, persuade them to adopt the Arctic Environmental Protection Strategy (AEPS). The aim of the AEPS is to strengthen cooperation between the Arctic states on research into environmental protection issues, focusing in particular on pollution of the Arctic by oil, heavy metals and persistent organic pollutants. The initiators were also concerned about the effect of ocean noise pollution on marine creatures, about radioactivity and about acidification of the Arctic Ocean. Various working groups were set up to investigate these issues. They include:

- the Arctic Monitoring and Assessment Programme (AMAP),
- the Working Group on Protection of the Arctic Marine Environment (PAME),
- the Working Group on Emergency Prevention, Preparedness and Response (EPPR),
- the Working Group on the Conservation of Arctic Flora and Fauna (CAFF).

Other working groups have been added over time. Together they provide the basic structure of the Arctic Council and deliver input that underpins all the Council's discussions and decisions.

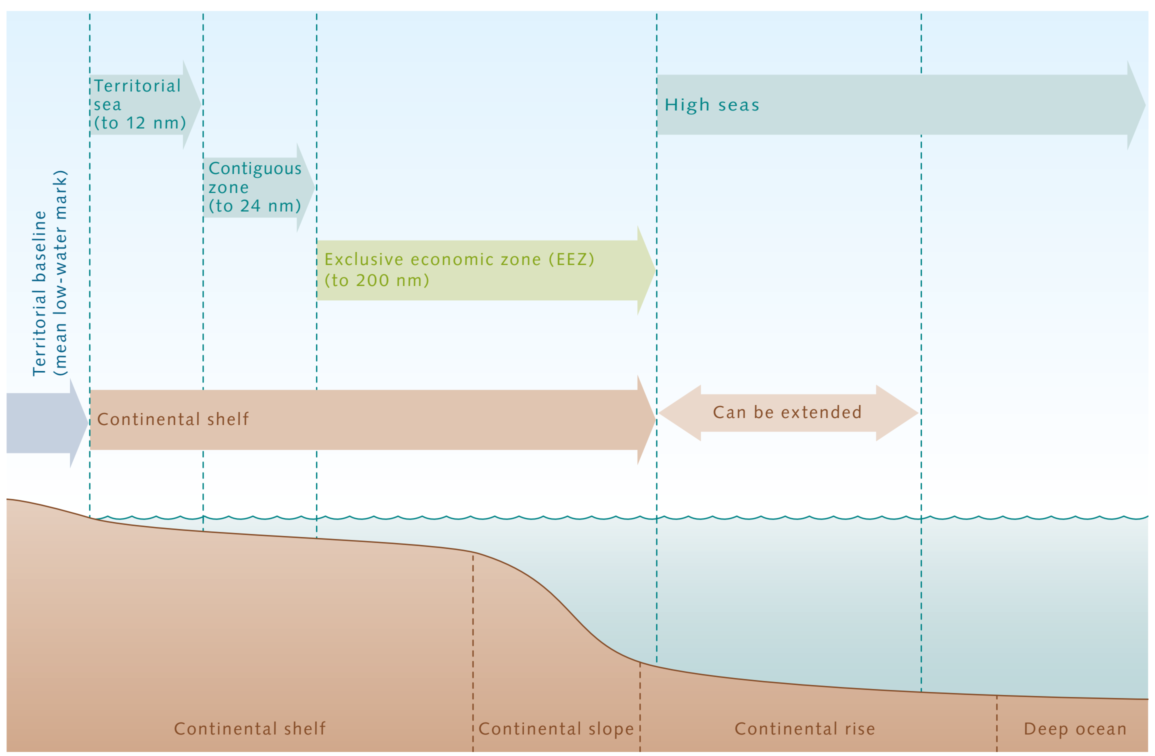
5.3 > Meeting of the Arctic Council in Rovaniemi, Finland, May 2019.

The issues on which the Arctic Council focuses are determined mainly by the programme of the member state that is chairing the Council. The chairmanship rotates among the eight Arctic states every two years. In May 2019 Finland handed the chairmanship of the forum over to Iceland, which has adopted "Together Towards a Sustainable Arctic" as the theme of its two-year term.

Some experts now consider that the basic principle of the Arctic Council, namely that it is a forum for discussing issues of common interest on the basis of scientific recommendations and agreeing uniform recommendations for action by all members states, is a success story. In January 2018 a group of political scientists and security experts even nominated the Arctic Council for the Nobel Peace Prize, arguing that in view of the international impact of the growing political tension between the superpowers, it is important to highlight the cooperation that the Arctic Council can achieve.

Defining boundaries in the Arctic

Despite the key position of the Arctic Council and its eight member states, there are areas of Arctic management and decision-making in which the five littoral states have a particular role. In particular, the United Nations Convention on the Law of the Sea (UNCLOS) gives them extensive sovereignty and jurisdiction over the coastal waters, the exclusive economic zones and large areas of the seabed on the Arctic continental shelf.



5.4 > The United Nations Convention on the Law of the Sea (UNCLOS) divides the sea into various legal zones, with the state's sovereignty decreasing with increasing distance from the coast. Adjacent to the internal waters is the territorial sea, also known as the 12-nautical-mile zone. In this region the sovereignty of the coastal state is already restricted, as ships of all states enjoy the right of innocent passage through it. In the exclusive economic zone (EEZ), which extends for up to 200 nautical miles from the coast, the coastal state has the exclusive right to explore and exploit living and non-living resources. This means that it is entitled to utilize any oil and gas fields, mineral resources and fish stocks found here. On the continental shelf, which is a natural prolongation of a country's land territory and may extend beyond the exclusive economic zone, the coastal state can explore and exploit the resources on the seabed. Beyond the exclusive economic zone is the maritime zone known as the high seas.

UNCLOS, which was concluded in 1982, is a comprehensive set of rules on the use and protection of the seas; for this reason it is sometimes called the "constitution of the seas". Of the five Arctic coastal states, only the USA has not yet ratified this convention. In May 2008, however, the US government signed the **Ilulissat Declaration**, thereby undertaking to settle all issues affecting the Arctic Ocean jointly and peacefully with the other Arctic coastal states on the basis of the law of the sea.

The UN Convention on the Law of the Sea sets out the definition of various maritime zones and the corresponding extent of certain sovereign rights of the coastal states. These zones are:

- internal waters and the territorial sea,
- the contiguous zone,
- the exclusive economic zone,
- the continental shelf and
- the high seas.

Internal waters and the territorial sea

Saline waters landward of the baseline or low-water mark are defined as internal waters. The territorial sea, by contrast, is on the seaward side of the baseline and extends for up to twelve nautical miles (one nautical mile is 1852 metres). States have complete sovereignty over their internal waters because – like the territorial sea – they form part of its territory. Nations also have wide-ranging sovereignty over their territorial sea; this includes rights to the airspace above, the water column, the seabed and the ground below the seabed. However, a coastal state may not prohibit the innocent passage of foreign ships through its territorial sea.

Passage is considered innocent if, while passing through the territorial sea, the ship in question does not use or threaten violence, does not spy on the coastal state and does not at any time pose a threat to the security of the coastal state in any other way. The UN Convention on the Law of the Sea defines potential threats in detail: for example, submarines must surface for the passage and hoist their flag. The Convention also prohibits unlawful discharges and other forms of marine pollution. The coastal state may designate shipping channels that must be used for passage and can levy charges if it provides services that enhance the safety of shipping. However, when designating shipping channels and traffic separation schemes, it must heed the recommendations of the International Maritime Organization (IMO).

Baseline
The baseline normally runs along the coastal low-water line and thus corresponds to the mean low-water line as marked on official charts.

Article 37 of the Convention on the Law of the Sea stipulates that the coastal state must grant foreign ships right of transit passage if the territorial sea is part of a strait or waterway that links parts of the high seas or different exclusive economic zones with each other and is used by international shipping. Coastal states have less scope for restricting the right of transit passage than for curbing innocent passage: in principle, transiting ships have the same freedom as on the high seas. Transit passage can be suspended or restricted only in the event of the threat or exercise of military force by the ship. Submarines can be submerged while passing through straits.

The question of whether foreign ships have a right to undisturbed transit passage is a regular source of dispute in the Arctic. This occurs, for example, in connection with the territorial waters of Canada's Arctic Archipelago, through which the Northwest Passage runs, and the waters off the Russian Arctic coast, where the Northeast Passage routes pass through. Ships wanting to traverse Russia's Arctic waters must comply with conditions laid down by the Russian government. The conditions that apply to foreign warships are particularly strict. For example, NATO military ships must notify their intention 45 days before the passage and must let a Russian pilot on board – something that, on account of security concerns, the US government categorically refuses to do. Washington argues that the law of the sea gives American warships the right to free, undisturbed (transit) passage. There is no sign of an end to this dispute.

The contiguous zone and exclusive economic zone

The contiguous zone adjoins the territorial sea, extending a maximum of 24 nautical miles beyond the low-water line. In this zone, coastal states may exercise certain powers of inspection and, for example, enforce customs regulations vis-à-vis third countries. Beyond the contiguous zone is the exclusive economic zone (EEZ), which can extend up to 200 nautical miles from the low-water line. This zone does not form part of the coastal state's sovereign territory. However, the coastal state has exclusive rights to fish in this area and to approve, erect and operate artificial islands and facilities such as oil drilling platforms and offshore wind farms. In this zone the coastal state has jurisdiction over marine conservation and marine research. This means that foreign states must obtain the consent of the coastal state if they wish to conduct scientific studies in the exclusive economic zone. However, a coastal state may not assert any territorial claims in its exclusive economic zone. Foreign nations have freedom of navigation in this area and may also lay submarine pipes and cables.

The Arctic states have defined the limits of the exclusive economic zones and have since the 1970s set out where they run in various bilateral and trilateral agreements. In only a few regions are these boundaries disputed. For example, Canada and the USA disagree about the precise course of their maritime boundaries in the Beaufort Sea.

The extended continental shelf

The United Nations Convention on the Law of the Sea sets out special rules on the continental shelf, which in large part lies below the exclusive economic zone. Like the exclusive economic zone, the continental shelf is an area of jurisdiction in which only the coastal state has the right to explore and exploit the natural resources. Under maritime law, any coastal state can declare the continental shelf in the exclusive economic zone of up to 200 nautical miles in width, even if in geological terms the shelf is narrower than this.

If the geological continental shelf extends beyond this 200-nautical-mile limit of the exclusive economic zone, the coastal state can under Article 76 of the Convention on the Law of the Sea extend the outer limit of the shelf. To do so it must make a submission to the Commission on the Limits of the Continental Shelf (CLCS), setting out the scientific data that show that the relevant part of the seabed and the ground beneath it constitute a natural extension of its land territory.

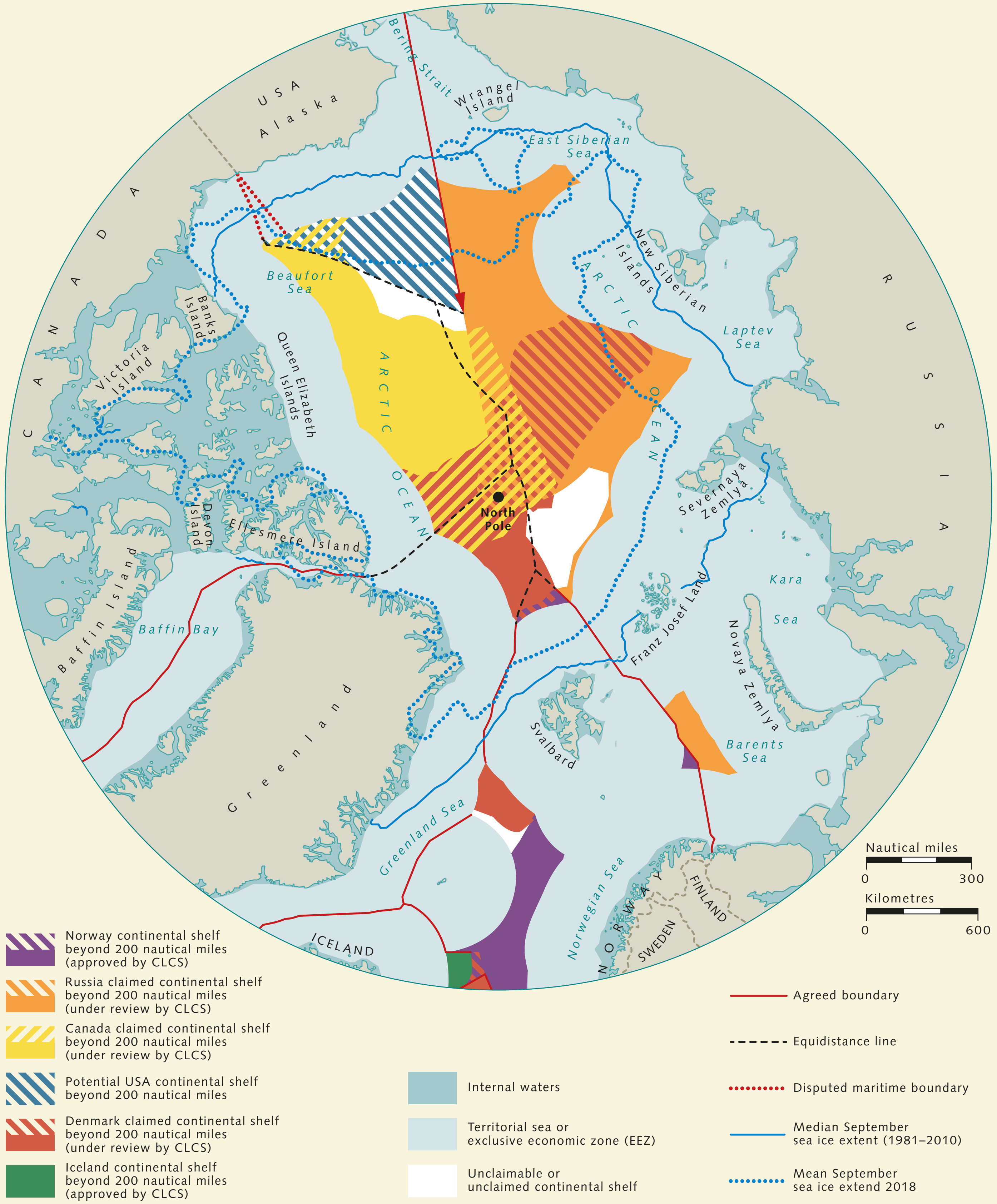
However, there are limits to this sort of extension: the new outer limit of the continental shelf must not be more than 350 nautical miles from the coastal state's baseline or more than 100 nautical miles from the 2500-metre isobath. A combination of the two methods is permitted.

The delimitation of boundaries in the Arctic is complicated by the fact that three underwater ridges – the Lomonosov Ridge, the Gakkel Ridge and the Alpha-Mendeleev Ridge – run along the floor of the Arctic Ocean and necessitate a special ruling in the Convention on the Law of the Sea. Article 76 of the Convention distinguishes between submarine ridges and submarine elevations.

Depending on whether a ridge or an elevation is joined to a coastal state's continental shelf, differing rules apply. If parts of the continental shelf run over a submarine ridge, only the 350-nautical-mile rule can be applied; the rule on the 2500-metre isobath cannot be invoked. However, if the continental shelf extends over a submarine elevation, both rules apply, since it can be assumed that the submarine elevation consists of the same material as the continental shelf. Submarine ridges, by contrast, usually consist of volcanic rock and are therefore of a material different from the continental shelf.

These complex rules in the Convention on the Law of the Sea make the work of the UN Commission on the Limits of the Continental Shelf more difficult. The Commission considers all submitted applications and makes a recommendation. If the coastal state adjusts the outer limit of its expanded economic zone in accordance with the recommendation, this outer limit is final and binding. What is not clear is what happens if a coastal state opposes the Commission's recommendation and sets an outer limit that is not in accordance with the recommendation. The

5.5 > A territorial bone of contention in the Arctic: both Denmark and Canada lay claim to Hans Island (in the middle of the picture). The island, 1.3 square kilometres in size, lies in the Kennedy Channel of the Nares Strait that separates Canada's Ellesmere Island from the north coast of Greenland.



5.6 > In the central Arctic there are overlapping claims from Arctic coastal states to areas of the seabed outside their 200-nautical-mile zones. There are just two small regions to which no country lays claim because they lie too far from the coasts for a claim to be made.

Commission is not a body with judicial powers: its purpose is only to ensure that the delimitation of boundaries complies with scientific standards.

The prospect of extending the continental shelf and with it the exclusive right to mineral deposits in the seabed has resulted in all the Arctic coastal states that are parties to the Convention on the Law of the Sea applying for extensions. Norway was granted an extension of parts of its continental shelf in 2009. Russia, Denmark and Canada have spent many years attempting to prove – on the basis of seismological studies – that the Lomonosov Ridge and the Alpha-Mendeleev Ridge are submarine elevations and hence natural geological continuations of their continental shelves. On 23 May 2019 Canada submitted to the UN Commission a 2100-page application in which it lays claim to an area of the sea covering 1.2 million square kilometres and including the geographical North Pole. Russia and Denmark had previously submitted similar-sounding claims in their applications. As yet, however, the Commission has not issued recommendations on any of the applications, because it takes several years to consider them and reach a decision.

Moreover, the Commission is not responsible for situations in which two coastal states with opposing or adjacent coastlines argue over the precise boundary of their continental shelves or over overlapping areas to which they lay claim. In such cases the Convention on the Law of the Sea requires the countries involved to conclude one or more boundary agreements. In other words, the states need to sort out these disputes among themselves. If this were to fail, the dispute could be settled by an international court such as the International Court of Justice or the International Tribunal for the Law of the Sea – provided that the countries involved recognize its legal authority.

In the past, the willingness of the Arctic coastal states to negotiate and compromise has enabled boundary disputes and border conflicts to be resolved. Thus in September 2010 Norway and Russia signed an agreement that put an end to four decades of argument over the boundary of their adjacent economic zones and continental shelves in the Barents Sea, which is rich in minerals and resources. The boundary that has been agreed upon gives equal weight to the claims of both countries. The two parties also agreed that any new, previously undiscovered resource deposits that straddle the boundary would be exploited jointly.

The high seas

The high seas commence at the outer limit of the exclusive economic zone. Here all states have the freedom of the high seas: ships have free passage and aircraft have the right to overfly. In addition, anyone can fish or conduct research in these areas. However, all activities must be peaceful in nature. By contrast, the seabed beyond the coastal states' continental shelf and all the resources it contains are part of the common heritage of mankind to which no state and no natural or judicial person can claim sovereign rights. This area and its resources are managed by the International Seabed Authority (ISA). In the Arctic, however, this status applies only to two small regions in the central Arctic Ocean; all other marine areas are claimed by one or more coastal states.

In addition, Svalbard plays a special role in Arctic agreements. The sovereignty of this archipelago east of Greenland is regulated in the Spitsbergen Treaty of 1920. While Svalbard is formally under the governance of Norway, all parties to the Spitsbergen Treaty have the same rights as the Norwegians to make peaceful use of the archipelago's resources and to work, trade and engage in shipping there. In addition, citizens of all treaty signatory countries enjoy free access to the archipelago. To date, 46 countries have signed the treaty. However, the situation with regard to the marine areas around Svalbard is unresolved. On the one hand, the exclusive economic zone around the archipelago is indisputably under the jurisdiction of Norway. On the other hand, there is as yet no answer to the question of whether the Spitsbergen Treaty, with its agreed principle of equal resource rights for all signatory states, also applies to this marine area. The question is an important one, especially with regard to the future use of the predicted oil and gas reserves in the northern Barents Sea. Oil companies do not yet have access to this region, but there is considerable long-term interest in opening up the area for oil and gas exploration, which means that there is potential for conflict.

The club of the Antarctic nations

Unlike the Arctic region, the continent of Antarctica is a long way from the coasts and borders of any nation states. This is often used as a reason to portray the southern continent and the surrounding ocean areas as detached from international politics and commercial activities. Upon closer consideration, however, it quickly becomes clear that the southern polar region is indeed a political arena whose complex history must always be viewed against the backdrop of international politics – then as now.

The legal framework of Antarctica as a political arena is set out in the Antarctic Treaty System (ATS). This consists of the Antarctic Treaty itself, augmented by the Protocol on Environmental Protection to the Antarctic Treaty, and by two conventions dealing with the conservation of Antarctic seals and the conservation of Antarctic marine living resources. Negotiation of the Antarctic Treaty was prompted by the USA; the document was signed by twelve nations on 1 December 1959 and entered into force roughly 18 months later, on 23 June 1961. The twelve original signatories were Argentina, Australia, Belgium, Chile, France, Japan, New Zealand, Norway, the Union of South Africa, the United Kingdom, the United States and the USSR.

Conclusion of the treaty represented a historical breakthrough on two fronts. Firstly, in the middle of the Cold War that succeeded the Second World War, the Antarctic Treaty was the first international agreement to bring the divided and highly militarized eastern and western powers together around the negotiating table, where they agreed on joint use of the area south of 60° South for peaceful purposes and research. Both sides had previously threatened to station rockets and military personnel in Antarctica.

Secondly, to enable the treaty to come about, the United Kingdom, Norway, Australia, France, New Zealand, Chile and Argentina suspended their earlier territorial claims to Antarctica. The signing of the treaty therefore ended the smouldering territorial conflict in Antarctica and paved the way for peaceful cooperation among nations with very different interests. In addition, the Antarctic Treaty runs indefinitely. While some of the subsequent agreements can be renegotiated after a certain time, the Antarctic Treaty never expires. The signatory states undertake to protect Antarctica and ensure its peaceful use for ever.

The idea of joint management of Antarctica as a research continent isolated from the rest of world politics worked for decades. Since the treaty was signed, the region has been peaceful. Fifty-four nations have now joined the Antarctic Treaty System and have committed themselves to peaceful use of the southern polar region. The states that actively conduct research in the Antarctic are known as Consultative Nations; they each pursue their own national research programmes but they also cooperate on many levels. They share their findings, plan joint expeditions, collaborate on the very complex logistics involved in operating research stations on the southern continent and provide assistance in emergencies – regardless of any conflicts that may be keeping the states at loggerheads with each other elsewhere in the world.

However, the success of international cooperation in Antarctic research obscures the fact that the territorial conflicts of the past are still smouldering today. None of the seven nations with territorial claims have abandoned these claims since the treaty was signed. On the contrary: Norway and Australia, for example, have submitted applications to the Commission on the Limits of the Continental Shelf, requesting the relevant Antarctic territories to be assigned to them. It has been agreed that these applications will not be considered by the UN Commission until the Antarctic Treaty is one day terminated, but the mere fact that the applications have been made illustrates the seriousness with which the parties involved continue to pursue their national interests in the region south of 60° South.

The territorial claims also hinder international cooperation in the Antarctic, for example in connection with the negotiations on designating marine protected areas in the Southern Ocean. States with territorial claims have been involved in all the designated protected areas and proposals for protected areas to date; observers see this as an attempt to consolidate these claims. An exception is the proposal for a protected zone in the Weddell Sea put forward by Germany and the European Union. However, this proposal was opposed by Norway, which wants to pursue additional research in some of the potential protected areas east of the prime meridian (in the part of the Antarctic claimed by Norway) and draw up separate protection measures on the basis of this. Meanwhile Australian politicians are regarding with suspicion the fact that China has now established three of its four Antarctic research stations in the part of the eastern Antarctic that Australia is laying claim to.

Who invests has a say

The parties to the Antarctic Treaty System meet once a year to share information and discuss issues of common interest. These Antarctic Treaty Consultative Meetings (ATCMs) are attended by:

- representatives of the Consultative Nations, of which there are currently 29. These are countries that have signed the Antarctic Treaty and are actively pursuing substantial research in the Antarctic;
- representatives of the 25 non-consultative nations. These countries have joined the Antarctic Treaty System but generally do not pursue their own active research in the southern polar region;
- observer organizations such as the Scientific Committee on Antarctic Research (SCAR) and the Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR);
- invited experts from the Antarctic and Southern Ocean Coalition (ASOC; a global alliance of environmental protection organizations) and the International Association of Antarctica Tour Operators (IAATO).

Decisions at ATCM meetings must be unanimous. Only the 29 Consultative Nations are entitled to vote: all the other

Rights from the age of whaling and exploration

The first territorial claims in the Antarctic were made in 1904, at a time when whalers were discovering the Southern Ocean as a hunting ground and the whaling nations were starting to compete for the best whaling sites.

That was the year in which the Norwegian whaler and captain Carl Anton Larsen hoisted the British flag on the newly built whaling station of Grytviken on South Georgia, the building having been partly financed with British capital. Until then the island had been regarded more or less as no man's land.

Shortly afterwards Britain officially staked a claim to South Georgia, and in 1908 the United Kingdom declared the entire Antarctic peninsula between the 20th and 80th meridians west of Greenwich to be British territory – and that was just the beginning.

In 1923, more than 80 years after the discovery of the Ross Sea by the Englishman James Clark Ross on 5 January 1841, the United Kingdom used his achievements and those of other British explorers as a basis for further claims.

Great Britain first annexed the sector of the Ross Sea between longitudes 160° East and 150° West, making it a dependency of its colony New Zealand. Three years later it laid claim to a further 40 per cent of the Antarctic continent (45° East to 160° East), this time in the eastern Antarctic. In 1933 this sector – with the exception of a small segment (136° East to 142° East) that France had already claimed as its property – was handed over to Australia, a former British colony.

Norway, which was then the biggest whaling nation, observed Britain's expansionist activities with great concern. The Norwegians feared that their ships would be prohibited from whaling off the coast of the annexed areas.

To prevent such a ban, they organized expeditions of their own in the Southern Ocean, giving the ships' crews clear instructions to annex any new land that was discovered. Two islands were initially annexed in this way. By 1939 Norwegian explorers had explored and annexed the entire Antarctic sector between 16° 30' West and 45° East, including the coastal waters, the interior of the territory and the geographic South Pole. This region, which is now called Queen Maud Land, covers an area of almost three million square kilometres.

Following Norway's example, the countries at the most southerly tip of the American continent – Chile (1940) and Argentina (1942) – then laid claim to Antarctic territory. The designated territories not only overlap but also include areas claimed by Britain, but all these territorial conflicts are suspended until the Antarctic Treaty is terminated.

parties present may participate in the preceding discussions but cannot vote. Because of this, critics accuse the Antarctic Treaty System of a lack of openness, fairness and transparency and call for reform. However, the Consultative Nations are assertive. In their view, countries should not be entitled to influence affairs in Antarctica unless they actively conduct research and contribute financially to the logistics and infrastructure that this requires. This is why international organizations such as the European Union and the United Nations are not represented at the meetings of the Antarctic Treaty states. Among the reasons put forward for their exclusion is the argument that these alliances would represent the interests of countries that have not yet joined the Antarctic Treaty System.

5.7 > At the start of each year the position of the geographic South Pole is recalculated and marked with a post and the flags of the twelve original signatories of the Antarctic Treaty. This has to be repeated annually because the ice moves by about ten metres a year.

International agreements on the protection of the Antarctic

The second pillar of the Antarctic Treaty System is formed by several international agreements on environmental protection in Antarctica, the provisions of which are legally binding on all member states. However, each member state implements these agreements through its own national legislation. The agreements include:

Agreed Measures for the Conservation of Antarctic Fauna and Flora

This first common set of measures to protect the Antarctic environment was agreed in Brussels in 1964 with the aim of strengthening international research and cooperation in connection with the conservation of Antarctic flora and fauna. It also established a system of special protected areas within the Antarctic. However, at the ATCM meeting in 2011 the Consultative Nations agreed that the measures would be replaced by the Environmental Protocol.

The Convention for the Conservation of Antarctic Seals (CCAS)

The Convention for the Conservation of Antarctic Seals was signed in 1972 in order to regulate the commercial slaughter of seals that was still taking place in Antarctica. The Convention entered into force in 1978 but it makes few demands on the signatories because seal hunting in the Antarctic has now ceased. All activities recorded under the CCAS are collated by the United Kingdom – the depository state of the CCAS – and reported at the annual ATCM meetings.

The Convention on the Conservation of Antarctic Marine Living Resources (CAMLR Convention)

The CAMLR Convention was adopted in 1980, after the then Soviet Union had severely overfished the marbled rockcod *(Notothenia rossii)* in just two fishing seasons and commercial interest in Antarctic krill had boomed. The Convention entered into force two years later and was the first marine convention to adopt an ecosystem approach to the conservation and management of marine living resources. This means that possible fishing plans and quotas are always evaluated in terms of the impact of this removal of fish and other marine resources on the related ecosystems.

The Convention covers all the marine organisms, including seabirds, living in the convention area; its aim is to conserve the marine ecosystems of the Antarctic. Fishing is not banned, but it must be sustainable. Implementation of the convention is coordinated and monitored by the Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR), which is based in Hobart, Australia. Acting on the recommendations of a scientific committee, the Commission sets fishing quotas, places species under protection if necessary and is responsible for designating marine protected areas in the Southern Ocean. The Commission currently has 25 members, including the European Union. Commission decisions must be unanimous. The area to which the Convention applies is delimited by the **Antarctic Convergence,** which means that in some areas it extends to 50° South. The convention area represents around ten per cent of the Earth's oceans.

The Protocol on Environmental Protection to the Antarctic Treaty

The Environmental Protocol was concluded on 4 October 1991 in Madrid, Spain, and so is also known as the Madrid Protocol. According to the German Environment Agency, it is the strictest and most comprehensive set of rules for a region of the Earth ever enshrined in an international agreement. Since it entered into force in 1998 the Protocol has prohibited the mining of mineral resources in the Antarctic. The signatories are obligated to preserve the Antarctic as a nature reserve devoted only to peace and science (Article 2 of the Protocol).

Within the territory of the Antarctic Treaty, the Protocol regulates all activities that could have adverse impacts on the environment and dependent and associated ecosystems. It also sets out for all parties to the Protocol the procedures and rules governing the awarding of consent for an activity in the Antarctic. The regulations in the five annexes to the Protocol deal with the conducting of environmental impact assessments, the protection of Antarctic flora and fauna, the disposal and treatment of waste, the prevention of marine pollution (for example from the discharge of oil, harmful substances or sewage, or the disposal of waste), and the special protection and management of selected areas.

The Environmental Protocol can be renegotiated after 50 years – that is, in or after 2048. However, it does not expire automatically after 50 years but remains in force unless the contracting states agree to modify it. The prospect of the Environmental Protocol being renegotiated in 2048 is a matter of concern to environmental organizations. They fear that new negotiations might lift the moratorium on the mining of mineral resources in Antarctic waters. The exploration of Antarctic mineral deposits was already considered in the 1980s. In June 1988, after negotiations that continued for six years, 19 countries concluded a set of rules on the mining of mineral resources. However, the agreement – which was entitled the Convention on the Regulation of Antarctic Mineral Resource Activities (CRAMRA) – was rejected by some states. The Convention did not enter into force as planned in December 1988. This was largely because of opposition from France and New Zealand: both countries were of the view that the environmental provisions in the text as it then stood did not go far enough.

Negotiations on a comprehensive environmental protection agreement for Antarctica then commenced. The Environmental Protocol that is currently in force was drawn up in just four years. The discussions, occurring as they did shortly after the end of the Cold War, took place in an era of détente during which many participants displayed a new willingness to compromise on environmental issues.

At this time the countries represented in the United Nations negotiated and concluded not only the sustainable development action plan Agenda 21 but also the Convention on Biological Diversity (CBD), the United Nations Framework Convention on Climate Change (UNFCCC) and the United Nations Convention to Combat Desertification in Those Countries Experiencing Serious Drought and/or Desertification, Particularly in Africa (UNCCD).

In negotiating the Environmental Protocol, the members of the Antarctic Treaty System agreed that their activities in Antarctica would be geared towards protecting the environment and that they would for the time being completely abandon the idea of exploiting resources there. This was a remarkable change, as present-day observers still note.

New players, new views

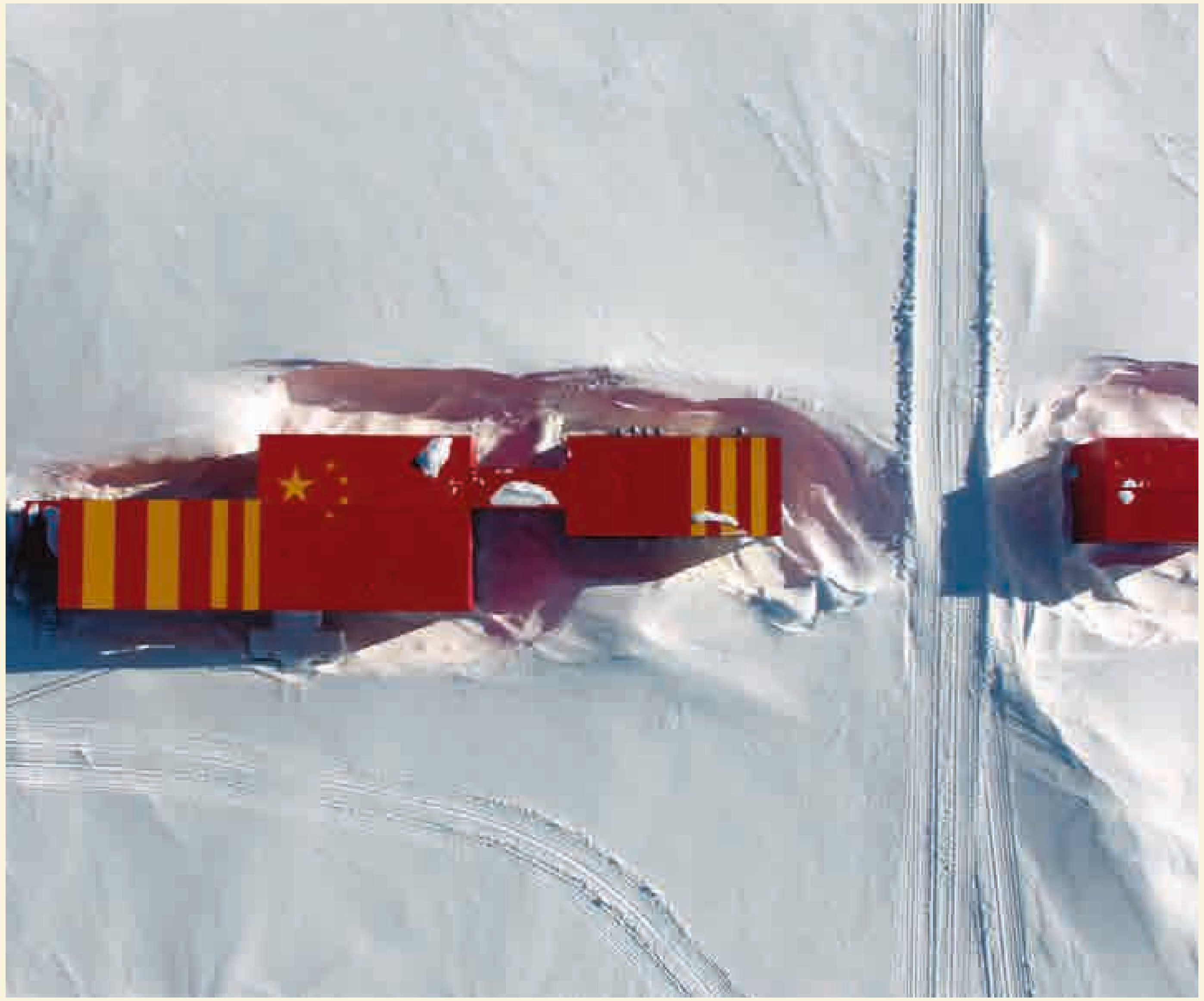
The era of détente is now past. Since the Environmental Protocol entered into force in 1998 there have been major changes not only in the extent of human activities in the Antarctic but also in the geopolitical world order. The superpowers are once again competing for power and influence. The economies of former developing and newly-industrializing countries such as China, India and South Korea are now sufficiently strong for these states to express their growing political and economic interests by boosting their research presence in the Antarctic. These countries are also increasing their involvement in important scientific and technical bodies such as the Scientific Committee on Antarctic Research (SCAR) and the Council of Managers of National Antarctic Programs (COMNAP). COMNAP is the international association which brings together all the national associations and institutes that pursue research in the Antarctic. It coordinates transport logistics and research projects and participates in the meetings of the Consultative Nations as an advisor.

Some of the original signatories of the Antarctic Treaty see this development as posing a geopolitical risk and suspect the emerging countries of acting primarily on the basis of strategic and commercial interests. However, all the western states, too, have in the past expressed interest in the Antarctic's resources and minerals. Political scientists therefore warn against stigmatizing the new arrivals on the scene, which could in the long term jeopardize peaceful cooperation in the Antarctic.

Instead, critics propose that the requirement for unanimity at important meetings such as those of the ATCM and CCAMLR be abolished and replaced by the principle of a democratic majority. This would have the advantage of enabling voting to take place on controversial issues (such as the designation of marine protected areas under CCAMLR) that have in the past been blocked by the veto of a small number of member states. However, an argument against this proposal is the fact that the decisions would have to be implemented in national law by member states. Countries that had voted against a measure would not be bound by the decision taken and would presumably have no interest in enshrining the corresponding requirements in their national legislation. There would thus be a risk that key players would not abide by the decisions.

5.8 > The Antarctic Treaty officially entered into force on 23 June 1961. Shortly afterwards, from 10 to 24 July 1961, representatives of the twelve original signatory states met in Canberra, Australia, for the first official meeting of the members of the Antarctic Treaty. These meetings are still held annually, although there are now significantly more members.

China's growing interest in the polar regions



5.9 > Kunlun is a Chinese research station located about 1200 kilometres inland in East Antarctica and at an elevation of 4087 metres above sea level. It is occupied only during the Antarctic summer, when scientists take ice cores and record atmospheric and geophysical measurements.

January 2018 saw the publication of a strategy paper that had been long awaited by the countries most involved in Arctic and Antarctic affairs: China, the second-largest economic power in the world, was for the first time publishing an official Arctic strategy in which it sets out its aims and interests in the northern polar region. As a non-coastal state, China has no legal rights in the Arctic but must instead depend on bilateral cooperation with Arctic coastal states. It was not until 2011 that China started attending the meetings of the Arctic Council as an observer nation.

Nevertheless, China's role in both the Arctic and the Antarctic has changed dramatically in the past ten years. The country sees itself as an emerging superpower with economic and strategic interests that extend far beyond the Asian-Pacific area. It wants to pursue these interests and play a part on the world stage. The polar regions are a key aspect of this.

In the Arctic, China is interested primarily in newly emerging shipping routes and the region's rich resource deposits. China and Russia are negotiating the development of a polar Silk Road involving a number of different transport and communication routes that would give China access to the Arctic. Shipping routes are key to this and the focus is on the Northeast Passage routes through Russian waters. For ships travelling from the port of Rotterdam in the Netherlands to Dalian in China, this northern route is ten days shorter than the traditional southern route via the Suez Canal. Moreover, use of the Northeast Passage would enable oil and gas supplies to be shipped from virtually any Arctic port to China in ten to 14 days.

At present, most of the resources that China so urgently needs come from Russia: China has entered into long-term supply contracts worth hundreds of billions of US dollars with Russian oil companies. The Chinese oil giant CNPC and China's Silk Road Fund also have stakes in Russia's liquefied natural gas project Yamal LNG. The project is based in the north-east of the Yamal Peninsula in Siberia, where natural gas is extracted and then liquefied to enable it to be more easily shipped. The Chinese government is also strengthening relationships with other Arctic states. It concluded a free trade agreement with Iceland in 2014 and is currently negotiating with Norway. With Finland it is discussing the laying of a submarine telecommunications cable, and on Greenland it is interested in deposits of valuable metals and rare earths.

Furthermore, in April 2019 China and Russia signed a cooperative agreement that provides for the construction of a joint research centre in the Arctic. This will be the third Chinese research base in the Arctic. China has operated a station in the research village of Ny-Ålesund on the island of Spitsbergen since 2004. In October 2018 China and Iceland opened a jointly operated Arctic observatory in northern Iceland. And since 2003 China has regularly despatched its research icebreaker *Xue Long* ("Snow Dragon") on scientific expeditions to the Arctic. A second polar research ship, *Xue Long 2*, was launched in September 2018 and is due to enter service before the end of 2019. China is thus actively involved in expanding its research infrastructure in the Arctic. However, it also stresses in its strategy paper that it wants to advance technical innovation in connection with resource mining, the use of renewable energies and environmental monitoring in the Arctic. China has also increased its involvement in the Arctic Council's working groups. Independent experts consider these political and economic ambitions to be legitimate. Provided that China abides by all the international norms and regulations, its investment in the Arctic should be viewed as an opportunity and not as a threat.

In Antarctica, China has in recent years spent more money on the expansion of its research infrastructure than any other nation. The country, which signed the Antarctic Treaty in 1983 and has been a Consultative Nation since 1985, now has four research stations – one on the Antarctic Peninsula and three in the eastern Antarctic. A fifth station is currently being built on Inexpressible Island in the Ross Sea; it is expected to open in 2022 and will then be operated year-round.

In May 2017 China organized an ATCM meeting for the first time. It presented its first strategy paper on research in Antarctica on the same occasion. The government used the opportunity to emphasize the importance of partnership and its respect for the laws and standards of the Antarctic. Nevertheless, the country wants to be seen as a strong Antarctic nation. And if the Antarctic Treaty should one day lapse, China would be on hand – with at least five Antarctic bases and clearly articulated claims.

China is interested not only in mineral deposits but also in the marine living resources of the Antarctic. It became a member of the Convention on the Conservation of Antarctic Marine Living Resources (CAMLR) in 2006. The Chinese representatives are now vocal at the annual meetings of the associated commission, CCAMLR. They and the Russian representatives view the creation of marine protected areas as a threat to the future use of krill, the Antarctic toothfish and other living resources of the Southern Ocean. To preserve these economic interests, China accepted the Ross Sea as a marine protected area but then blocked all other CCAMLR proposals for protected areas.

An economic boom with side effects

> The polar regions have always been rich in raw materials and natural resources, and have always exerted a great fascination. In the past it has been difficult to make profit from them because ice and cold has hindered access. Due to the dramatic changes in climate, however, the gates are now opening for gold miners, investors and tourists, especially in the Arctic region. While the Arctic countries view this development as an opportunity, scientists and environmentalists are warning of grave consequences.

The great hunt

The first profitable ventures in the polar regions were those of seal hunters and whalers. Whales have been caught on a commercial scale in Arctic waters since the 17th century. For example, whaling began on Spitsbergen in the year 1612, only 16 years after the discovery of the Svalbard Archipelago by the Dutch seaman and explorer Willem Barents (1550–1597). In the early years, the hunters mainly stalked Greenland whales and the North Atlantic right whale. These species both have a thick fat layer and swim so slowly that the whalers could pursue them in rowboats and kill them with hand-held harpoons. Unlike humpback or blue whales, Greenland whales and North Atlantic right whales do not sink to the seabed after dying. Instead, their bodies float on the surface, making it easy for the whalers to retrieve their prey.

The blubber of the slain animals was boiled down and used in Europe as lamp oil and in the production of soaps. Corsets and parasols were made from the flexible whale baleen. At the end of the 17th century, the prospect of "liquid gold", as whale oil was then called, attracted 200 to 300 whaling ships to the waters east of Greenland from all the seafaring nations of Europe. It has been estimated that the Dutch whalers alone caught around 73,000 whales in the Arctic region between 1661 and 1823. It is therefore not surprising that the Arctic whale stocks were heavily depleted by the end of the 18th century.

At this time, the first reports of large seal populations in the South Atlantic were beginning to circulate. The ships set a southerly course and began to slaughter seals on South Georgia half a century before the discovery of the Antarctic continent. They started by hunting the Antarctic fur seal *(Arctocephalus gazella)*. There was a lot of money to be made from their valuable furs in North America, Asia and Europe. Soon afterward the elephant seals were added as prey. They were slain for their thick, oil-rich layer of fat.

During the next ten years, expanding from South Georgia, the seal hunters discovered new hunting grounds on the South Atlantic island groups, from the region of the Scotia Arc to as far as the South Shetland Islands near the tip of the Antarctic Peninsula. At the same time, in the southern Indian Ocean, the ships advanced to the Kerguelen and McDonald Islands, where they mainly hunted the Subantarctic fur seal *(Arctocephalus tropicalis)*. After 20 more years of radical hunting the most important hunting grounds for southern fur seals were practically depleted.

Nevertheless, the hunt for these animals did not cease until around 1900. Only a few hundred to a thousand of these two species survived in some inaccessible island bays. The hunt for elephant seals had already slackened 30 years earlier because the demand for seal oil had fallen with the introduction of petroleum as a preferred lamp oil.

Unlike the fur seals and elephant seals, the four seal species living in the pack ice of the Southern Ocean (crabeater seal, Weddell seal, Ross seal, and leopard seal) have rarely been hunted and thus have been spared commercial exploitation. The exact opposite has occurred with the large whales of the Antarctic seas. Their slaughter gained pace in 1904 when the first land-based station for whale corpse processing was constructed in South Georgia. The use of steam engines, and the invention and refinement of the harpoon gun by the Norwegian Svend Foyn (1809–1894) between 1864 and 1870, made it possible to kill and retrieve the faster rorquals such as the fin whale *(Balaenoptera physalus)*, the blue whale *(Balaenoptera musculus)*, the sei whale *(Balaenoptera borealis)* and the minke whale *(Balaenoptera acutorostrata)*, as well as humpback whales *(Megaptera novaeangliae)*. In addition, in 1925 the first shipboard cookers and stern slipways were employed. With the introduction of these factory ships it was no longer necessary to bring the whale corpses to land stations for processing.

Equipped with this technology, the whalers killed significantly more animals in less than 80 years of hunting in the Southern Ocean than were slain in 300 years of whaling in the Arctic Ocean. In the southern summer of 1930/1931 alone, whalers in the Antarctic seas killed and processed 14,923 blue whales, 28,009 fin whales, and 2079 humpback whales. The idea of protecting whales first began to slowly take hold only after the end of the Second World War. In December 1946, the International Convention for the Regulation of Whaling was signed and the International Whaling Commission was created.

However, it failed in its mission to effectively reduce whaling activity. Although the catch of blue whales declined due to a population collapse, whalers in the Antarctic waters began to hunt more fin whales and sei whales and, beginning in 1973, the much smaller minke whales.

Whaling for commercial purposes was not banned until 1982, when a moratorium was adopted for the protection of large whales in response to strong public pressure. It went into effect in 1986, but is being circumvented by countries such as Norway, Iceland, Japan and South Korea. Some indigenous peoples in Greenland, on the Siberian Chukchi Peninsula, in Alaska and the US state of Washington, as well as on the Caribbean islands of St. Vincent and the Grenadines, are permitted to kill a certain number of whales in consideration of their livelihood and culture.

Resource extraction in the polar regions

The more accessible the polar regions become for people, the more frequently questions arise about the deposits of raw materials there and how they can be used. Around the world the demand for oil and gas, metals and rare-earth elements is increasing, and with it the price and the willingness to invest more money in exploring for them, especially in the Arctic region.

However, resource extraction from areas that are poorly developed and difficult to access involves many incalculable factors that drive up costs and thus the investment risk, and which in the past have already led to the abandonment of extractive activities and plans. In 2015, for example, Shell Oil Company terminated its exploration activities in the Chukchi Sea because costs and benefits were disproportionate, and the company's reputation had suffered as a result of the project.

Incalculable factors relating to resource extraction in the Arctic include:

- Lack of infrastructure in the Arctic results in long development times: Up to 17 years can elapse between the discovery of a deposit and the start of production. And even then, the remoteness of mines or production platforms will continue to pose problems for companies. For example, Chinese mining companies investing in Greenland complained that they could only bring their employees to the site by helicopter, which increased operating costs enormously.
- Difficult climatic and weather-related conditions: Extreme temperatures, strong winds, mobile sea ice and the instable Arctic permafrost grounds are difficult to predict and require the use of special and expensive technology. Mines, streets, railways and buildings have to be protected against the thawing ground. Offshore facilities such as oil platforms and tankers must endure the constantly changing ice conditions.
- Long and sometimes difficult transport routes: The production sites are very far away from the consumers.
- High personnel costs for specialists willing to work in the inhospitable and remote areas.

- Shifts in the world market and fluctuating raw-material prices: The extraction of raw materials in difficult areas such as the Arctic is only profitable if there are correspondingly large markets and a sufficiently high price for the materials.
- Geopolitical developments: Raw-material exploration in the Arctic requires technology and expertise that a state alone cannot usually provide. Russia, for example, had to postpone some of its planned exploration projects when a number of countries imposed economic sanctions following its occupation of the Crimea.
- Environmental damage: Polar ecosystems react extremely sensitively even to minor fluctuations, and they regenerate very slowly after accidents. Because of the ice cover and the extremely low temperatures, at which oil residues break down much more slowly than in warmer regions, many experts consider the environmental risks to be inestimable.

5.10 > In the Diavik diamond mine, located in the sub-arctic part of the Canadian Northwest Territories, high-quality diamonds for jewellery making have been mined since 2003. Since 2012 the mining has taken place entirely underground.

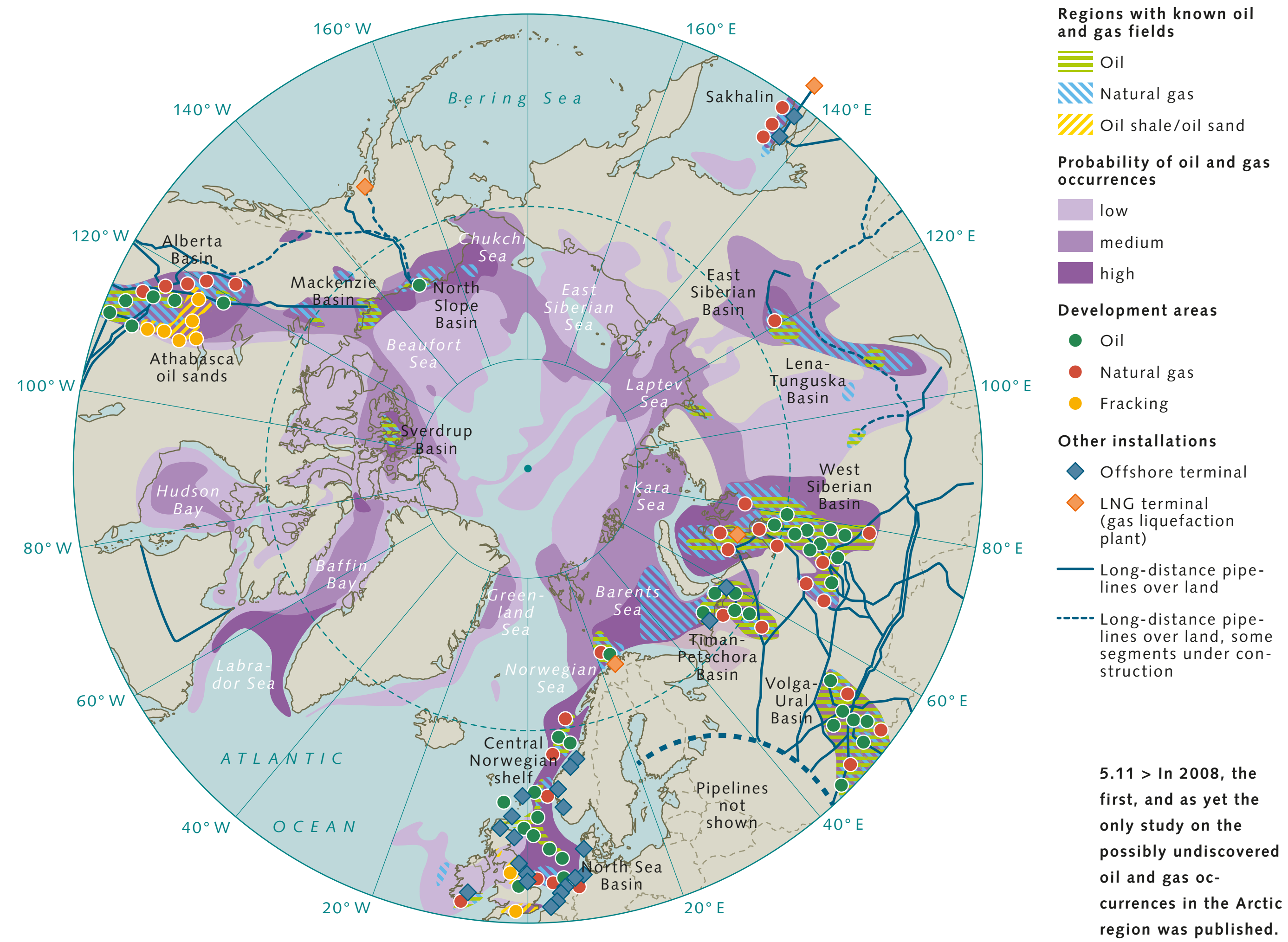
- Public pressure: Complaints or campaigns by environmental organizations and the local populations can delay or even prevent the approval processes for exploration operations in the Arctic region. For instance, in April 2019 the Norwegian parliament withdrew approval of a planned oil and gas drilling project in the waters around Lofoten. The decision followed global campaigns by environmental organizations such as SeaLegacy, which warned of the consequences of resource extraction for the environment, fisheries and tourism.

Geological conditions

Experts distinguish between mineral raw materials and hydrocarbon deposits, or energy resources. The former category includes metals and minerals such as iron ore, uranium, gold, diamonds and many others. The latter refers to natural gas and oil. The distribution of these raw-material deposits in a region depends primarily on the plate-tectonic history of the area. The three large and geologically very old Canadian, Baltic and Siberian continental shields, for example, are situated in the vicinity of the Arctic Ocean. These are composed primarily of crystalline rocks, but also contain some sediment series, and their ages range from one to 2.5 billion years. The prevailing geological conditions were conducive to the formation of mineral raw materials such as gold, copper, iron ore, molybdenum, lead, zinc, platinum, nickel, diamonds and rare-earth elements.

Oil and gas deposits, on the other hand, are more likely to be found in Arctic areas where rivers and seas once deposited sediments over millions of years, producing sediment layers several kilometres thick. This has taken place over the past 350 million years, primarily in the shelf regions. In some areas, the shelf layers contained abundant organic material, which is a necessary condition for the formation and concentration of oil and gas.

In contrast to the shallow, broad shelf seas of the Arctic region, the typically narrow shelf regions of Antarctica are only marginally suited for offshore oil and gas exploration. The weight of the ice cap forces the Antarctic continent downward, so that the sea floor of the continental shelf in large part lies at a depth of more than 500 metres. If production were allowed, oil companies would have to invest a great deal of time and effort in drilling for oil and gas there.



5.11 > In 2008, the first, and as yet the only study on the possibly undiscovered oil and gas occurrences in the Arctic region was published. It suggested that the largest deposits are located in the West Siberian Basin, in the Timan-Petschora Basin, in the North Slope Basin of Alaska, and in the central Norwegian shelf.

Energy resources in the Arctic

Oil and gas have been produced in the Arctic region for decades. Since the beginning of the search for these two resources in the mid-1930s, over 450 significant oil and gas deposits have been discovered north of the Arctic Circle, both on land and in the shelf areas. Around ten per cent of the oil and 25 per cent of the gas production worldwide is now taking place in the Arctic region, although it comes almost exclusively from deposits on land. For the Arctic states, the development of oil and gas reserves in their northern territories is already vital or is becoming an increasingly important economic sector. For example, Russian natural gas is being delivered to Germany, which receives a full one-third of its natural gas from Western Siberia.

In spite of the high production volumes, there are large portions of the Arctic that are still undeveloped, especially the offshore areas. Indeed, many possible deposits have not yet been discovered. In 2008, the United States Geological Survey (USGS) attempted to estimate the size of the probable undiscovered deposits of these two resources in the Arctic in its major CARA study (Circum-Arctic Resource Appraisal). According to the calculations, around 30 per cent of all probable undiscovered natural gas reserves in the world and 13 per cent of the undiscovered oil reserves are located to the north of the Arctic Circle. A large proportion of these undiscovered fields are presumed to be located in the shallow shelf areas of the Arctic Ocean, in water depths less than 500 metres.

The USGS study investigated a total of 25 Arctic provinces. It found that 90 per cent of the probable reserves are located in only ten of these areas. The possible oil and gas deposits are thus concentrated in just a few regions. Furthermore, the amount of probable natural gas is three times as great as the expected amount of oil. The largest occurrences of energy resources are presumed to be in the West Siberian Basin, the Timan-Petschora Basin, Alaska's North Slope Basin and on the central Norwegian shelf (Barents Sea). Of these, the richest oil areas are off the north coast of Alaska and in the Arctic waters off Canada and Greenland. The largest natural gas reserves are presumed to be in Russia's West Siberian Basin, especially in the southern part of the Kara Sea.

The prognoses of the USGS clearly indicate that some Arctic states have especially large reserves. According to the study, two-thirds of the probable reserves lie in the Eurasian part of the Arctic region and the remaining one-third are in the North American part. Around 90 per cent of the reserves in the Eurasian Arctic are natural gas, while the deposits in the North American sector presumably have more oil. Russia is at the top of the ranking for the Arctic states richest in these resources, with about half of the yet undiscovered deposits. With Alaska's potential, the USA is in second place with one-fifth of the probable reserves, followed by Norway, Denmark/Greenland and Canada.

To date, the USGS study is still the only Arctic-wide survey of possible oil and gas reserves and, due to its methodology, it is fraught with large uncertainties. In many areas the estimates of the American scientists are based on very vague geological information. For many parts of the Arctic region there is simply not enough data. Researchers therefore expect the estimates to change significantly as new geological data become available.

Furthermore, the authors point out that their statistical calculations did not take into account either the technological and economic conditions or possible exploration risks. For this reason it is very likely that a substantial portion of the presumed reserves will never be developed or produced. Furthermore, detailed knowledge of a reservoir does not necessarily mean that it will be exploited. Throughout the Arctic region there are many reserves that have been known for 40 to 50 years but have not yet been developed for economic or environmental reasons. This is particularly true for deposits in the North American Arctic sector where oil and gas production is controlled exclusively by market demands, and thus purely by the price that can be expected.

In Russia, on the other hand, resource production also has strategic and political significance. A strategy paper by the Russian government considers resource exploitation in the Arctic to be an essential basis for the social and economic development of the country. The export of crude oil and products produced from it accounts for over 50 per cent of total Russian exports. In addition, resource development in the Arctic serves to build infrastructures in the northern regions and symbolically enhances Russia's self-image as an Arctic nation.

The Russian government is therefore promoting the exploitation of resources, for instance through tax incentives. Large state-owned corporations such as Gazprom and Rosneft dominate the industry. They produce natural gas and crude oil in far more areas than is done in North America, for example. The number of production facilities continues to increase. In April 2019, following a meeting with President Vladimir Putin, the Russian oil company Rosneft announced that it was planning to develop several oil and gas fields in the Russian Arctic, which would make it possible to recover 1.5 billion tonnes of oil. The project would also serve to expand the Northern Sea Route along the Russian Arctic coast. In order to realize these plans, Rosneft not only has to invest in new icebreakers and ice-capable tankers and construct an oil pipeline from its Vankor oil fields west of the Yenisei River to the Arctic

5.12 > With the help of the specially designed, ice-resistant oil drilling platform *Prirazlomnaya*, the Russian oil company Gazprom succeeded for the first time in producing oil from Arctic offshore deposits in 2013. The platform is still in operation today in the Prirazlomnoye oil field south of the island of Novaya Zemlya.

5.13 > The Russian company Novatek and its partners have built the Yamal LNG liquefied natural gas plant on the north-eastern shore of the Yamal Peninsula. In three production lines, natural gas is produced, liquefied and shipped to Europe and Asia via the port of Sabetta.

coast. It has also begun to build accomodation for the expected 20,000 workers. In addition, the company is seeking international partners who will invest in this large project in spite of all the risks and the uncertain price outlook for energy resources.

At almost the same time, the Russian Ministry for Natural Resources and Environment announced that it intends to fund more than a hundred projects for oil and gas production in the Arctic and for the expansion of infrastructure and tourism with a sum equivalent to 164.2 billion US dollars. These include major projects already underway such as large oil- and gas-production sites on the Yamal Peninsula and in eastern Siberia.

On the Gyda Peninsula on the eastern shore of the Gulf of Ob, for example, Russia's largest private petroleum company Novatek is currently building its second facility for the production and shipment of liquefied natural gas (Arctic LNG 2). Construction of the harbour terminal and the accompanying industrial facilities and buildings will cost around 21 billion US dollars, and additional funding is being provided in part by Saudi Arabia, the French oil company Total, and Japanese commercial companies. The industrial complex, with an annual capability of 19.8 million metric tonnes of liquefied gas, is scheduled to start operations in 2023 and supply liquefied gas to customers in Asia and Europe. The list of investors is indicative of the increasing international cooperation in the exploration and exploitation of raw materials in the Arctic region. Because oil and natural gas production in the northern polar region is technically difficult and involves enormous costs, even experienced players such as Rosneft, Gazprom and Novatek depend on cooperation with American, European and Asian companies.

In the USA, the Trump administration is now pushing ahead with the sale of oil-drilling licences in the once-protected coastal area (called the 1002 Area) of the Arctic National Wildlife Refuge – for example, by allowing the administration to carry out required studies on the impacts of oil exploration within a very short time. Caution would be advisable here. Because of its climatic and geographic situation, the Arctic is a high-risk region for economic activities, especially for major projects such as oil and gas production. Accidents and risks cannot be ruled out even when the mining and oil companies comply with environmental regulations and employ modern safety technology. There is always a danger of degrading the environment with oil pollution, garbage and noise, all of which are especially damaging in the Arctic. This is particularly so in the case of tanker accidents or pipeline leaks, because oil and other hydrocarbons remain in the ecosystem much longer due to the low temperatures.

Experts also agree that measures to remove oil slicks or spills in the Arctic are very difficult and protracted, if not impossible. They say that clean-up techniques that have proven useful in other regions are less effective or even useless in Arctic waters. Ice could clog the oil suction systems, or oil booms could freeze. During the polar night, darkness would also hamper any clean-up operations. Furthermore, many regions in the Arctic are only accessible by airplane, helicopter or ship. This means that there is a lack of the important infrastructure and personnel necessary to rapidly and effectively combat an oil spill in the event of an accident along the Arctic coast.

Mineral raw materials in the Arctic

While the mining of mineral raw materials is prohibited in Antarctica by the Protocol on Environmental Protection to the Antarctic Treaty, mineral resources such as coal, zinc, copper, gold, diamonds, platinum, nickel, palladium, iron ore and rare-earth elements constitute important economic branches in many regions of the Arctic, or they are considered to be a basis for future economic development, as in Greenland. Since the discovery of diamond deposits in the Northwest Territories, for example, Canada has become one of the top five diamond producers in the world. The largest zinc mine in the world, called Red Dog Mine, is located in Alaska. It has the largest known zinc deposits on Earth to date and alone accounts for ten per cent of the global production of this metal.

The development of mineral raw materials in the Arctic region has a long history. The iron ore mine in Malmberget, Sweden, in the Lapland region, opened in 1745 and is still the second largest in the world. In Greenland, minor amounts of copper, lead, zinc, silver, gold, marble, graphite, olivine and cryolite have been extracted since the middle of the 19th century. Beginning in 1896, the goldrush on the Klondike River attracted more than 100,000 gold prospectors to Alaska and flooded the world market with gold. Just two decades later Russia began construction of its largest mining and metallurgy complex in the Siberian Arctic (Norilsk mining district in the Krasnoyarsk region). Because of the unfiltered emissions from metallurgical plants, Norilsk was for a long time a city with one of the highest levels of air pollution in the world.

Today the mining of mineral raw materials in the Arctic still takes place exclusively on land and is therefore less affected by the consequences of climate change as it relates to diminishing Arctic sea ice. There are at present slightly over 20 mining operations that are extracting mineral resources. There are over a dozen in Russia alone, because the Russian Arctic region is rich in ferrous, non-ferrous and precious metals, rare-earth metals and fertilizer raw materials, as well as precious and semi-precious stones.

5.14 > One of the worst oil catastrophes of all time occurred on the night of 24 March 1989, when the tanker *Exxon Valdez* struck a reef in Prince William Sound in the Gulf of Alaska and lost 39,000 tonnes of crude oil. At least 400,000 birds and mammals died as a result of the oil spill, and fishing activity came to a standstill. The coast is still polluted with oil today.

5.15 > Researchers report that climate change could open up a new source of income for Greenland. When ice masses melt, the meltwater streams and rivers transport large amounts of sediment to the coasts where they are then deposited. As a raw material, sand is in demand worldwide, and its export could be economically viable if the mining can be carried out in an environmentally sustainable manner.

In conjunction with these activities, according to the Arctic Economic Council (AEC) there is a lot of prospecting taking place in the Arctic in order to find out exactly where, and especially how abundantly the raw materials occur. It has been known for years, for example, that there are very large deposits on Greenland. Of particular significance here are gold, platinum-group metals, rare-earth elements, uranium and celestine. Economic planners and a large proportion of the Greenland population hope that the mining of minerals will generate large revenues in the future, and that the island will become an important supplier in the long term. The necessary mining licenses have already been issued, including some to Chinese mining companies. But so far a number of factors have prevented profitable large-scale mining because Greenland, like other parts of the Arctic, still lacks important infrastructures like roads, railways, harbours and housing for the mine workers. The average temperatures on the icy island are so low that the extraction of mineral resources is only possible during the short summers. In addition, Arctic sea ice often blocks the paths of transport ships to mining sites such as the Citronen Fjord in the far north. Furthermore, the Arctic states have agreed in the Arctic Council to develop their Arctic territories as sustainably as possible. This means that every country now imposes requirements on mining companies with regard to environmental protection, occupational health and safety, and interaction with the local populations, all of which drive up exploration costs. Because of the low, or at least fluctuating world market prices for raw materials such as lead, zinc and rare-earth elements, most mining projects in Greenland are still in the planning or development phase.

There is presently only one producing mine. The Norwegian company Greenland Ruby has been extracting pink rubies in Aappaluttoq in southwest Greenland since May 2017 and selling them in the form of jewellery to Greenland tourists and on the Scandinavian market. The Canadian company Hudson Resources, Inc. is also apparently near the start of production. It intends to mine calcium-rich feldspar (anorthosite) in the White Mountain region of Kangerlussuaq Fjord in western Greenland and sell it to fibreglass producers. Production of the industrial mineral, however, will only be possible during the short summer, so it is questionable whether the mine will be profitable over the long term.

In other parts of the Arctic, on the other hand, the exploitation of natural resources and development of the necessary infrastructures are progressing rapidly. The opening of a new port terminal near the Russian port city of Murmansk is planned for the end of 2019, through which nine million tonnes of coal will be shipped annually. According to the plans, this volume will double when further construction phases are completed by 2023. In February 2019, the Norwegian government agreed to the construction of a copper mine in the Arctic municipality of Kvalsund despite protests by local fishermen and reindeer herders against the plans. The mine operator Nussir ASA estimates the copper deposits in the area at 72 million tonnes. There is no larger copper deposit known in Norway.

In southwestern Alaska, environmentalists and members of the indigenous population are currently challenging plans by the Canadian company Northern Dynasty Minerals to open a large gold and copper mine in the Bristol Bay region. The area, with its many lakes and rivers, is considered to be one of the most important spawning grounds for red salmon *(Oncorhynchus nerka)*. According to the mining company, however, it is also presumed to have the second largest copper deposits in the world as well as large amounts of gold, silver, molybdenum, palladium and rhenium.

Shipping in the Arctic

The drastic decline of Arctic sea ice, especially to the north of the Russian coasts and in Alaskan waters, is opening new shipping routes that may be of interest to operators from Arctic countries as well as to many companies from outside the Arctic region. In areas where the sea ice completely disappears, or where it is only present in winter, possibilities are opening up:

- Vessels can venture into previously untapped fishing grounds.

Mineral resources beneath the Antarctic ice

Antarctica is the only continent on the Earth where no mining has ever taken place. This unique situation is due on the one hand to the extreme temperatures and the extensive continental ice cover, which make geological investigations of the subsurface extremely difficult. And on the other hand, the Madrid Protocol on Environmental Protection to the Antarctic Treaty prohibits any commercial exploration activities south of 60° South latitude. However, drilling or sampling of rocks for research purposes is permitted.

The geology of the land masses in Antarctica is therefore sufficiently well known in some regions to make assumptions about the potential for raw materials. Researchers now know, for example, that there are coal deposits in the Transantarctic Mountains and iron ore deposits in the Prince Charles Mountains in eastern Antarctica. It would be logistically and technically very difficult to extract these, so from a practical point of view they are of no economic interest. In addition, there is little information available about the quality and total size of these deposits.

The presence of other mineral raw materials is presumed but so far has not been conclusively proven. These include metals such as nickel, copper and platinum. The presumptions are based on the knowledge that the coastal regions of Antarctica have strong geological similarities to the resource-rich margin areas of South America, Africa and Australia, all of which abutted the southernmost continent 250 million years ago. The gold-rich mountain range of Witwatersrand in South Africa, for example, may have the same geological features as some parts of Queen Maud Land in Antarctica. The Antarctic Peninsula is an extension of the South American Andes, where metals such as molybdenum, gold and silver are mined. Minor occurrences of these minerals have also been discovered on the peninsula. And in Dufek Massif in the Pensacola Mountains, a highland region in Queen Elizabeth Land in western Antarctica, researchers suspect the presence of platinum-group metals, chromium and other mineral resources like those mined in the geologically similar Bushveld complex in South Africa.

Oil and gas reserves are presumed to be present in the Antarctic shelf areas. The thick sediment layers necessary for the formation of these two resources could be present on the shelves of the Ross and Weddell Seas as well as in the Amundsen and Bellingshausen Seas. But possible deposits would very probably be too small to make production economically feasible. Moreover, in the shelf areas of Antarctica there are many floating icebergs, some of which are very large. These would present a serious danger for drill ships and platforms, and because of the huge masses of ice below the water surface, they could destroy technical installations on the seafloor without warning. The risk of spills and environmental pollution would be very high.

5.16 > At sites with no ice cover, there is evidence of the presence of mineral resources. The distinct black line at the bottom of this sandstone outcrop in the Transantarctic Mountains is a coal seam that was formed more than 250 million years ago.

- Drilling ships or platforms can exploit the marine gas and oil deposits that were previously not accessible.
- Trading and shipping companies can save considerable time and costs by shipping their goods from Northern Europe to North-East Asia via the shorter Arctic sea routes.
- Travel companies can attract new customers with cruises in the Arctic.

In the public discourse, however, the fact that shipping in the Arctic is not a new phenomenon at all is often overlooked. On the contrary, large parts of the northern polar region were developed by ship. Regular shipping connections were established more than a hundred years ago in ice-free Arctic marine regions like the western and northern coasts of Scandinavia, and wherever governments or companies had invested in Arctic sites and people needed supplies. This was the case, for example, in Svalbard, where coal mining began around 1900, and ships were the only possible way to bring machines and vehicles to the Arctic archipelago and to transport the coal off again.

In large parts of the Arctic today, shipping connections are still the lifelines for the local populations. The people built their settlements near the coasts because the sea route is the only way to receive essential goods. In many regions there are no streets or railways.

Regional instead of international

The Arctic waters are primarily utilized today for fishing, transporting extracted materials, supplying Arctic settlements and mining sites, passenger shipping, tourism, and polar and marine research. Most of these voyages are carried out in the summer or autumn, when large areas are ice-free and the risks are as small as possible. Many ships avoid the ice-covered regions. They operate mainly in the peripheral areas of the Arctic Ocean, for example along the Norwegian coast, in the largely ice-free Barents Sea, around Iceland and the Faroe Islands, to the southwest of Greenland, and in the Bering Sea.

Most Arctic shipping lines are operated by domestic or state-owned shipping companies. Along the Norwegian coast, for example, seven coastal vessels of the Hurtigruten shipping company transport freight and guests to 34 ports of call between Bergen in the southwest and Kirkenes in the northeast. On Greenland, the ship-based transport of goods and fuel is managed by the government-owned shipping company Royal Arctic Line. Its vessels sail between Greenland's 13 largest ports and also supply smaller settlements. In Russia, icebreakers commissioned by the government have been keeping the coastal waters between the Kola Peninsula and the mouth of the Yenisei River navigable year-round since 1979, enabling regular shipping in the region.

Shipping in the Arctic seas is therefore carried out rather more on a regional than international basis. However, when it comes to Arctic shipping, the general public is primarily interested in trans-Arctic routes. These are generally limited to two main routes. A third course, which runs directly across the Arctic Ocean, practically crossing the geographic North Pole, is not realistic considering the still prevailing ice and weather conditions in the central Arctic, and it is only discussed theoretically.

The Northwest Passage

The Northwest Passage comprises seven large routes between the Atlantic and Pacific Oceans. They run from the Bering Strait and the coastal areas of Alaska, through the island maze of the Canadian Arctic Archipelago, and finally through Baffin Bay and the Labrador Sea into the North Atlantic. The first documented crossing of the Northwest Passage was made by the Norwegian Roald Amundsen in the early 20th century. 80 years later the first passenger ship, the Swedish vessel *Lindblad Explorer*, crossed through the passage. This was followed in 2008 by the first container ship, and in 2017 by the first cruise liner.

Transarctic voyages through the Northwest Passage are still exceptional events, however. Firstly, this is because the approximately 36,000 islands in the far northern reaches of North America make navigation difficult, and secondly the sea ice in the Canadian Arctic Archipelago is generally thicker and, due to local conditions, it recedes in summer to a lesser extent than it does,

5.17 > Most ship movements in the Arctic are for regional transport in the coastal waters of the bordering states. Or they are tanker and freight transport to ports south of the Arctic Circle (destination-related transport).

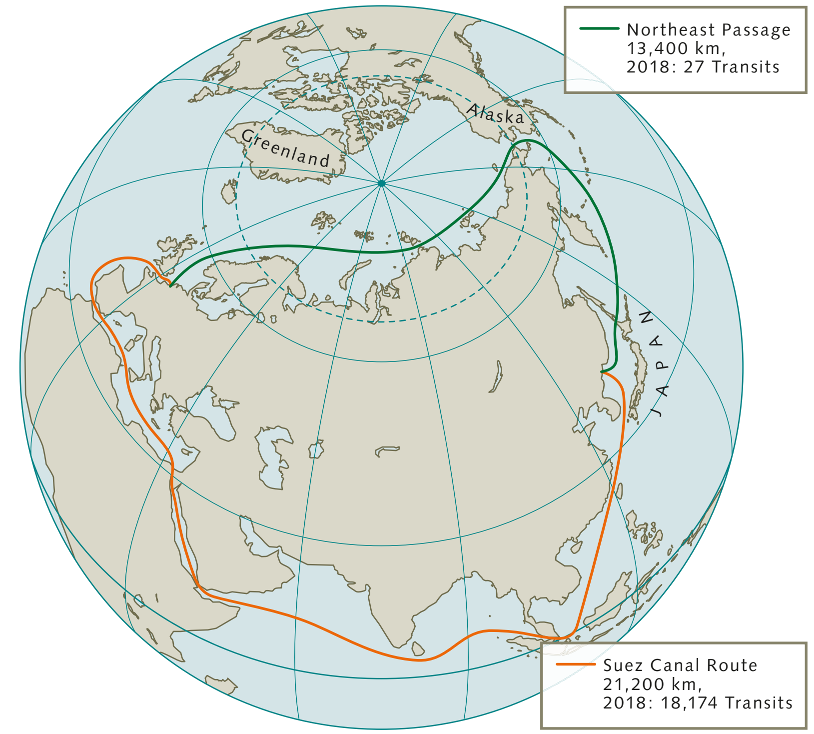
for example, in the Bering and Chukchi Seas. Ships that undertake this voyage are generally coast guard icebreakers or private yachts. The latter are taking a fairly high risk because the ice conditions in the Canadian Arctic are difficult to predict. For this reason, experts also believe that ship voyages in the Canadian Arctic Archipelago will continue to be high-risk in the coming decades. Nevertheless, several cruise operators are offering voyages through the Northwest Passage in the summer of 2020, including Hurtigruten of Norway and Hapag-Lloyd of Germany.

There has also been an increase in the traffic of fishing boats and cargo ships, at least in the Canadian portion of the passage. The latter transport goods to the Canadian north, or are loaded with raw materials in the Arctic ports. The Baffinland Iron Mines Corporation shipped five million tonnes of iron ore in 2018 alone from a new harbour on the north coast of Baffin Island – a record amount for the Canadian Arctic. Over the long term the company wants to increase its annual production to twelve million tonnes of ore. The diminishing sea ice could help it realize that goal. The season during which the waters around Baffin Island are navigable has already lengthened from four to five months.

The Northeast Passage

The Northeast Passage consists of several routes that lead from north-western Europe along the northern coasts of Scandinavia and Russia into the Bering Sea and then into the Pacific Ocean. A portion of this passage, from the Kara Strait to the Bering Strait, is also known as the Northern Sea Route. It passes through the Exclusive Economic Zone of Russia and is administered by the Russian Ministry of Transport. Until about 30 years ago, this sea route was prohibited for ships from countries outside the former Soviet sphere of influence. The Soviet Union used it for military purposes and developed it into an important supply line for its Arctic mining and oil industries.

Since 1 July 1991 the Northern Sea Route has been open for all countries. However, ships must register their passage and meet certain conditions, requirements that are criticised by the USA and other countries. They insist that the routes of the Northeast Passage and the Northwest Passage be regarded as international straits through which all states have the right of transit. This would deprive the individual coastal states of the right to impose strict rules and conditions. The context of this demand is that of all three possible sea routes through the Arctic, the Northeast Passage is currently regarded as a particularly promising shipping route. Ice and wind conditions are favourable for the first permanently navigable channel to open along the northern coast of Russia.



5.18 > A voyage by ship from Rotterdam to Yokohama is much shorter through the Northern Sea Route than by the southern route. But because of the high costs and the unpredictable ice conditions in the Arctic seas, shipping companies still use the longer route through the Suez Canal.

Russia's plans

Russia is making a strong effort to develop the Northern Sea Route into one of the most important shipping routes in the world. In line with its stated transport and traffic strategy, the country intends to commission the construction of new nuclear-powered icebreakers, modernize ports along its Arctic coast, install search and rescue infrastructures, and establish a monitoring system for maritime traffic.

5.19 > The 300-metre-long liquid-gas tanker *Christophe de Margerie* is one of 15 double-acting tankers built by the operators of the Yamal LNG liquefied natural gas plant. It can run backwards through ice up to 2.1 metres thick and thus operate year-round without icebreaker support.

These investments are justified by the fact that cargo ships from northern and north-western Europe would save up to 40 per cent of the distance to Japan or China by travelling through the Northeast Passage instead of the classic southern route via the Suez Canal and Indian Ocean. In this way, ships would also avoid dangerous southern marine areas such as the Horn of Africa or the Strait of Malacca (Malaysia, Indonesia). In these two regions terrorism and piracy are considered serious threats for international shipping traffic.

But for now, the Northern Sea Route is only relatively safe for ships during the summer, and even then cargo ships must often be accompanied by icebreakers, a situation that significantly increases the costs of the transit and severely limits the current development potential for Arctic shipping. Like all commercial ventures this one, first and foremost, has to be economically feasible. Whether this is the case depends, among other things, on the possible saving in distance, the question of what freight is most suitable for the Arctic routes, time management, and the progress and development of the other major trade routes.

Experts warn against overestimating the potential of Arctic shipping and underestimating the risks. Trans-Arctic voyages such as those of the ice-class cargo ship *Venta Mærsk* in August 2018 had a high level of show appeal but were not economically profitable. Accordingly, the number of transit voyages through the Northern Sea Route has been minimal. After a boom between 2010 and 2013 they declined again in 2014, and since then the number of crossings has remained below expectations.

The lack of interest in the shipping industry is primarily due to the economics. In scientific surveys, shipping companies and merchant enterprises have specified that Arctic shipping entails major commercial risks. The risk factors stated by the companies include:

- high costs for the construction of high-ice-class ships, on-board equipment suited to polar conditions, ship insurance (20 to 100 per cent higher than standard prices), and trained personnel: To make matters worse, the ice-capable tankers and cargo ships are not commercially viable in other waters because their thicker hull means that they have an insufficient capacity;
- high costs for special fuel: Ships in the Arctic need a fuel that is suitable for cold temperatures. Moreover, fuel consumption increases enormously when the ship makes its way through sea ice;
- high charges for the escort by Russian icebreakers as well as the services of the Northern Sea Route Administration: Additionally, the ships may not be wider than 30 metres (the icebreaker's channel). On the southern route through the Suez Canal 60-metre-wide ships are possible;
- the limited number of available icebreakers: This complicates long-term planning for shipping on the Northern Sea Route;
- the risk of delays and associated penalties due to unpredictable ice conditions: For this reason, for container ships in particular, whose goods have to be delivered punctually, the Northeast Passage is still not an alternative to the classic southern route;
- the high probability of sea ice and extreme weather conditions, and the associated risks;
- the remoteness of the shipping route and absence of infrastructure for search and rescue measures;
- the restriction of the maximum draught to twelve metres: Because of the shallow water depth, ships often cannot be fully loaded, which lowers the profit margin for the companies and shipping lines;
- fluctuating world market prices for raw materials and fuels: If prices fall the expensive transit through the Arctic becomes less attractive for businesses than the proven southern route;
- upgrading of the Panama and Suez Canal systems is making the southern routes more economically attractive again for the shipping companies: Since June 2016, with the completion of ten years of improvement work (widening and deepening), the Panama Canal is navigable for 96 per cent of the world merchant fleet. The Suez Canal was also improved. Since August 2015, twice as many ships can cross through it as before.

New ship types, detailed traffic analyses

To increase the profitability of Arctic shipping, some companies are beginning to rely on new technology. This includes ice-strengthened cargo ships and double-acting ships.

The latter are a cross between icebreakers and traditional cargo ships. They have a conventional bow for navigating on the open sea and a stern that is equipped with an icebreaking function. In ice-free waters the ship cruises forward. But when sea ice is encountered the ship turns around and runs backward, with the ice-breaking stern leading the way.

These new types of ships are mainly used for transporting raw materials along the Russian coast. But these voyages are usually not included in the transit statistics. When analysing Arctic shipping traffic, experts distinguish between four categories of traffic:

- *Destination transport:* This category includes, for example, oil tankers that deliver oil or liquid gas from Norway or north-west Russia to harbours outside the Arctic.
- *Intra-Arctic transport:* This refers to shipping that connects two or more states within the Arctic region with each other.
- *Trans-Arctic transport:* This is ship transport that passes through the Arctic waters and delivers goods, for example, from a Pacific port city to a harbour on the Atlantic or on the North Sea.
- *Ship transport in the coastal waters of one state bordering on the Arctic Ocean:* This ship movement is also referred to as regional traffic, and includes the regular transport of raw materials in Russia between the port of Dudinka in the northern reaches of the West Siberian lowlands and the harbour city of Murmansk lying on the Kola Peninsula north of the Arctic Circle.

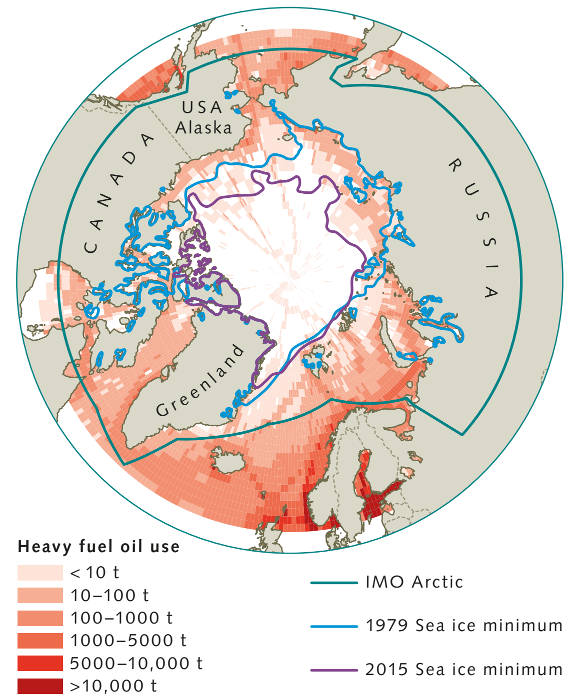
While transit traffic has fallen to a low level, regional and destination-related shipping in the Northern Sea Route is steadily increasing. In 2018, cargo and tanker ships transported 15 million tonnes of goods through this seaway within a period of only eleven months, to destinations in Europe, Asia and South America, among others. This was almost twice as much as in the previous year. Compared to 2014, the amount had increased by a factor of five. The growth can be attributed primarily to the rise in the exports of liquid gas, crude oil and coal from the Russian Arctic sector. The gas-producing company Novatek, for example, shipped more than seven million tonnes of liquid gas from its new Sabetta port in 2018. This is part of the large Yamal Project on the Yamal Peninsula that began operating in 2017.

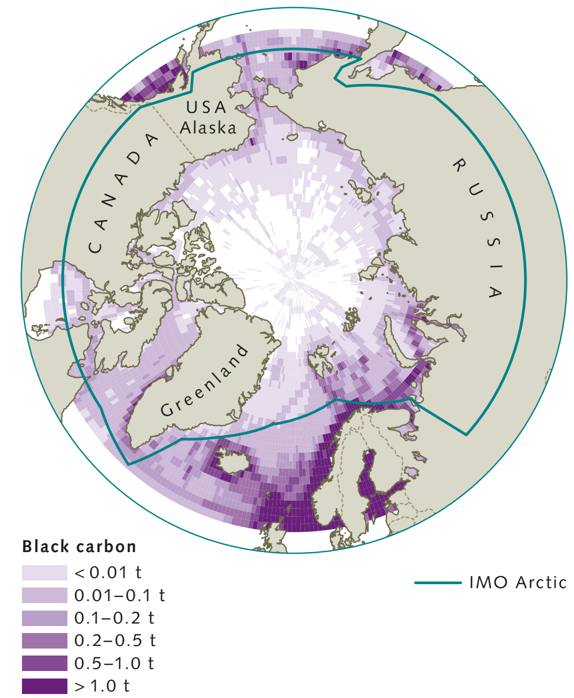
According to predictions, the volume of freight will continue to increase in the Russian Arctic, boosted primarily by the growing coal production in the Taibass Basin on the northern tip of the Taymyr Peninsula. Coal producer VostokCoal is planning to extract up to 30 million tonnes of anthracite coal there annually beginning in 2025. This type of coal is especially carbon-rich. It is needed for metal production in particular, and is only mined in a few countries. The company is aiming to achieve an annual production goal of ten million tonnes by 2019, and all of it will be shipped via two newly built harbours near the port city of Dikson. By the year 2025, every second ship traveling on the Northern Sea Route could be a coal freighter from Dikson.

Like many other extractive companies, VostokCoal will use ice-strengthened freighters for the transport of coal. However, the Russian Ministry of Transport is considering relaxing the very strict conditions and safety requirements for shipping on the Northern Sea Route. Until now, only ships of ice class Arc7 and higher have been allowed to transverse the Northern Sea Route in winter. But since the gas producer Novatek, in particular, has not succeeded in equipping its fleet with the expensive ice-class ships, the ministry announced in November 2018 that it would ease the ice-class regulations. In the future ships with ice class Arc4 and Arc5 will be allowed to travel the coastal waters in winter, but only when accompanied by an icebreaker.

In view of this decision, critics accuse the ministry of placing economic interests above ship safety and environmental considerations, and of taking an unnecessary risk. Less sea ice does not mean less danger. On the contrary, thinner ice is more easily driven by the wind and thus moves faster. This makes ice predictions more difficult. In shallow shelf seas like the East Siberian Sea, just 52 metres deep, there is the added danger of ships running aground when adverse ice and weather conditions make navigation more difficult.

5.20 > In February 2018, on its way from South Korea to France, the liquid-gas tanker ***Eduard Toll*** was the first commercial ship to transit the Northern Sea Route in winter without the aid of icebreakers. It made a short stop in the harbour of Sabetta to load new liquefied gas.





5.21 > According to the International Council on Clean Transportation, around 57 per cent of all ships operating in the Arctic in 2015 were burning heavy fuel oil. About two-thirds of the black carbon emitted by ships can be attributed to this "dirty" fuel.

The environmental impacts of shipping

Like the extraction of resources, Arctic shipping also poses a number of known and possible threats for the sensitive Arctic environment. Should a tanker accident occur or a ship lose oil or fuel for any other reason, the effects of the pollution would last much longer in the cold Arctic than in warmer areas. Clean-up efforts would be very expensive and time-consuming and, according to some experts, certainly not adequate because there are still no known technical solutions that could be effectively applied. Permanent damage to the environment, plants and animals would be inevitable.

Unlike in the Antarctic, ships in the Arctic are still permitted to operate with heavy fuel oil containing sulphur. This fuel is a highly toxic, very viscous waste product from the oil industry that accounted for 57 per cent of marine fuel used in the Arctic region in 2015. If it is released through an accident, a leak or as a result of deliberate discharge and comes into contact with water, it spreads across the sea surface, emulsifies and assumes a multiple of its original volume. The mousse-like mass is then either deposited on the sea ice, where it freezes, or it is washed onto the coasts or sinks to the seabed. Because of its consistency, emulsified heavy oil can contaminate large regions. The Arctic Council has therefore concluded that this fuel poses the greatest risk by ships to the Arctic marine environment.

When heavy oil is burned in the ships' motors, in addition to large volumes of carbon dioxide, air pollutants like sulphur oxides, nitrogen oxides, particulates, and brown and black soot particles are emitted. When these dark particles are deposited on either snow or sea ice, the surface reflectivity is decreased. Both of these materials then absorb more solar radiation and melt faster.

Environmental organizations and the International Maritime Organization (IMO) are therefore advocating a ban on heavy fuel oil in Arctic waters. Negotiations are currently underway. The IMO has set a target to adopt the ban in 2021 and to implement it throughout the Arctic by 2023.

With increasing ship traffic, the danger that non-native animal and plant species traveling with the ships will immigrate to the northern polar region also increases. They may, for example, attach to the ship's hull or stow away in the ballast water. The more ships there are traveling in Arctic waters, the greater also is the danger that they will collide with whales or seals, or that they will disrupt the migrations of the marine mammals or disturb them with motor noise.

Sound waves travel further in cold than in warm water. This means that motor noises or the sound of exploration activity can be heard at greater distances underwater in the Arctic. In addition, with the loss of thick, perennial sea ice, a previously effective acoustic absorber is disappearing that once imbued large portions of the Arctic Ocean with silence.

As early as 1993, researchers reported observations from the waters of the Northwest Passage indicating that beluga whales were able to hear the sounds made by an icebreaker 85 kilometres away. As the ship approached the whales the animals broke out in a panic at a distance of 35 to 50 kilometres. They sounded alarms and fled from the area as a unified herd. Narwhals, on the other hand, fell silent at the noise of the ship and left the region individually.

Biologists from the United States, in a study from 2018, concluded that narwhals, walruses, bowhead whales and belugas are particularly threatened by the increasing ship traffic. The danger for ringed seals and polar bears is somewhat less critical because these animals spend a large amount of time on land in the summer, where the effects of ship traffic are less disruptive. In other studies, scientists are currently studying the impacts of cruise-ship tourism on the animals in the polar regions. Cruises to the Arctic and Antarctic have been a growing market in recent years.

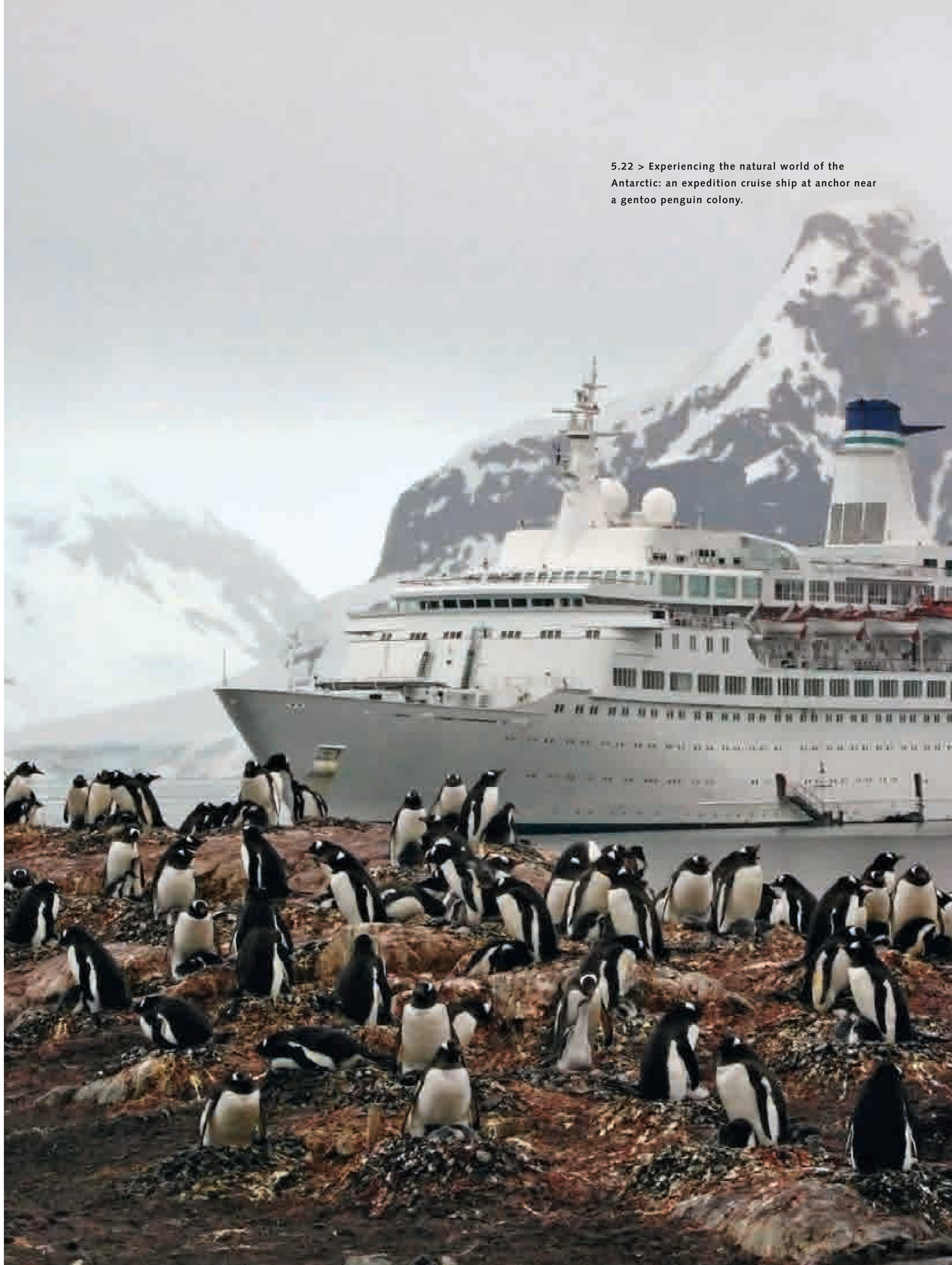
Polar tourism

The polar regions have become more attractive as holiday destinations, for three reasons. Firstly, rising temperatures and the resulting retreat of the sea ice, especially in the Arctic, make it easier to access many regions. Secondly, in view of these dramatic changes, many nature lovers and adventure tourists feel that they have to rush to see the icy landscapes of the Arctic and Antarctic for themselves before they are gone for good. Expert call this "last-chance" tourism. Antarctica – our planet's last wilderness – exerts a particular fascination for travellers who have already visited every other region of the world and now wish to experience what is surely the Earth's most inaccessible continent at the South Pole.

No wonder, then, that tourism in both polar regions has surged in recent decades. The number of cruises visiting Canada's Arctic Archipelago increased from 121 in 2005 to 416 in 2017. And according to experts, the number of tourists visiting Antarctica in the 2019/2020 summer season, mainly on smaller cruise ships carrying fewer than 500 passengers, is likely to exceed 78,000 for the first time – excluding shipboard staff on the total of 63 vessels registered. Figures from the International Association of Antarctica Tour Operators (IAATO) show that 56,168 tourists visited Antarctica in the previous season (2018/2019), compared with just 12,248 in 2000/2001.

Antarctic tourism has experienced just two brief downturns: the first during the global financial crisis, and the second after the International Maritime Organization (IMO) adopted a ban, in August 2011, on the use and carriage of heavy fuel oil on vessels operating in the sea area south of latitude 60° South. Since then, however, tour operators have calculated their fuel consumption so precisely that all the heavy fuel oil is used up before the ships reach Antarctic waters – and visitor numbers are rising again.

In Greenland and on Svalbard, the most popular regions for Arctic cruises, passenger numbers rose steadily until 2007/2008 and since then have levelled off at annual averages of around 24,000 (Greenland) and 40,000 (Svalbard).



5.22 > Experiencing the natural world of the Antarctic: an expedition cruise ship at anchor near a gentoo penguin colony.

Recorded Seaborne Tourism (based on data provided by companies who submitted Post Visit Report Forms and from other sources where available)					
Year	Number of operators	Number of ships and yachts	Number of voyages	Number of passengers making landings	Number of cruise only passengers
1992/1993	10	12	59	6704	
1993/1994	9	11	65	7957	
1994/1995	9	14	93	8098	
1995/1996	10	15	113	9212	
1996/1997	11	13	104	7322	
1997/1998	12	13*	92	9473	
1998/1999	15	15*	116	9857	
1999/2000	17	21*	154	13,687	936
2000/2001	15*	32*	131	12,109	0
2001/2002	19*	37*	117	11,429	2029
2002/2003	26*	47*	136	13,263	2424
2003/2004	31*	51*	180	19,369	4949
2004/2005	35*	52*	207	22,297	5027
2005/2006	47*	44*	249	25,167	4632
2006/2007	42*	47*	268	28,622	6930
2007/2008	48	55	308	32,637	13,015
2008/2009	44	53	290	26,921	10,652
2009/2010	44	51	239	21,622	15,020
2010/2011	41	47	223	19,065	14,373
2011/2012	36	41	234	21,131	4872
2012/2013	39	45	258	24,892	9070
2013/2014	42	51	283	27,374	9670
2014/2015	37	44	268	26,812	9459
2015/2016	38	48	286	29,960	8109
2016/2017	38	47	298	36,440	7475
2017/2018	44	50	344	42,576	9131
2018/2019	44	56	360	44,600	10,889
2019/2020	46*	63**	432**	59,367**	18,420**

* Includes non-IAATO operated yachts (sailing and motor) where the information was available.
** based on pre-season estimates not actual statistics.

5.23 > Cruise ship tourism in Antarctica is a booming business. According to IAATO, passenger numbers have increased almost twelve-fold since summer 1992/1993.

It is important to note that there are clear differences between the Arctic and the Antarctic where polar tourism is concerned. In the northern polar region, the development of the tourism sector and associated issues such as infrastructure and regulations governing entry and access to Arctic regions are a matter for the individual states. The regions visited most often are those which are easy for holiday-makers to reach, such as Iceland, Alaska and northern Scandinavia.

Norway's Arctic territory, for example, is well-developed and has been a popular holiday destination for decades. The first tourists to visit the Svalbard Archipelago by boat arrived in 1890. Nowadays, most of the archipelago's inhabitants work in tourism. The territory of Nunavut in northeast Canada, by contrast, even lacks a good road network. In this Arctic region, the tourism season is limited to the brief summer, when tourists explore mainly by cruise ship or yacht.

With survey methods varying from country to country and no clear demarcation line between the Arctic and subarctic regions, reliable statistics on visitor numbers and types of tourism for the Arctic as a whole are non-existent. Polar tourism organizations such as the Association of Arctic Expedition Cruise Operators (AECO) collect information on market trends and membership numbers, but focus mainly on the top travel regions, such as Svalbard and Norway, not on the Arctic as a whole.

With regard to cruise ship operations in Arctic waters, however, there will soon be greater clarity. The Arctic Council's Protection of the Arctic Marine Environment Working Group (PAME) launched a new database on shipping activity in the Arctic in February 2019. It collects data on all shipping traffic in the Arctic, including information on ship routes, ship speed, fuel consumption and emissions, the aim being to close existing knowledge gaps on ship traffic in the northern polar region. Representatives of the Arctic states and researchers can now monitor ship traffic trends across the Arctic and draw up appropriate safety and management recommendations on this basis. For all non-Arctic states, however, the database is password-protected and access charges apply.

Antarctica, by contrast, is international territory. Anyone can travel to Antarctica, provided that the tour operator or cruise ship operator has obtained a permit for the visit from an Antarctic Treaty Party. Tourism statistics are collected by IAATO, established in 1991 – in other words, by the tourism industry itself. Critics claim that IAATO often omits tourism industry personnel such as shipboard staff, camp employees and pilots from the statistics, thereby creating the impression that visitor numbers are much lower than they are in reality. Also missing from the IAATO statistics are all the cruise ships, private expedition vessels and yachts whose operators or owners are not IAATO members. For private expeditions to Antarctica, including the various forms of extreme tourism which have become more popular in recent years, there is currently no joint registration centre that would be responsible for data collection.

Instead, IAATO, which currently has 116 members – almost all the Antarctica tour operators – operates a booking system which regulates ship traffic in a way which minimizes the likelihood of encounters between individual cruise ships. The aim, firstly, is to continue to offer passengers a remote wilderness experience. Secondly, the system supports compliance with strict Antarctic Treaty rules, which stipulate that no more than 100 tourists are allowed on shore at one time. Coordination among the tour operators also ensures that there are no waiting times at the main tourist attractions along the Antarctic Peninsula. To maintain this situation despite the increase in ship traffic, IAATO is currently overhauling the booking system: the version previously in use has reached the limits of its capacity.

Unlike the situation in some areas of the Arctic that are both winter and summer holiday destinations, tourism in Antarctica is a highly seasonal business. The expedition ships that carry up to 500 passengers, although most have fewer than 200 on board, operate from the end of October to early March – summer in the Southern Hemisphere – and mainly cruise in the ice-free areas along the Antarctic Peninsula. Regions such as the Ross Sea and East Antarctica are visited only in isolated cases due to the challenging weather and ice conditions.

Expansion of tourism infrastructure

With glaciers, polar bears, the northern lights and so forth proving so attractive to tourists, the Arctic states are hoping that this will open the way for sustainable development of their polar regions. They are therefore promoting further growth in this sector by expanding the tourism infrastructure. In Greenland, for example, there are plans to build three new airports to facilitate tourists' access to the island's icy wastes. The new airports are being constructed in Nuuk, Ilulissat and Qaqortoq and are scheduled to open in 2023. Other drivers of polar tourism development include improvements in equipment and technologies, as well as better geographical knowledge of the Arctic regions based on more detailed nautical charts.

The growth of Antarctic tourism is due to tour operators' expansion of their polar fleets. In summer 2019/2020 alone, nine newly constructed ice-going cruise ships will begin shuttling between the southern tip of Argentina and the Antarctic Peninsula, increasing visitor numbers by 33 per cent. A further 40 or so cruise ships are scheduled for completion by 2023, including a luxury yacht that will carry passengers from Argentina to Antarctica and then – via South America and Europe – to the Arctic; the price per person will range from 51,000 to 146,000 euros.

More fly-in and individual tourism

Until 20 years ago, the Arctic travel industry differed significantly from Antarctic tourism in a number of respects: geographical, infrastructural and legal. In the southern polar region, nature watching, hiking and trips on inflatables were often the only activities available locally, whereas visitors to the Arctic have for many years had a range of options to choose from:

- mass tourism for travellers wishing to see the best-known attractions in maximum comfort;
- sports fishing and hunting tourism for amateurs wishing to pursue these leisure activities in largely unspoilt terrain;

- ecotourism for nature lovers wishing to see unique wildlife and experience the Arctic's natural beauty;
- adventure tourism for holiday-makers wishing to challenge themselves through sport or other physical activity;
- cultural tourism for travellers wishing to meet indigenous communities, learn more about historical events or places of cultural interest, or explore heritage sites in the Arctic.

Antarctica has no indigenous communities and therefore no cultural tourism offer. Nevertheless, the days when tour operators offered visitors to Antarctica nothing but nature watching are long gone. The Antarctica experience now includes helicopter rides, submarine dives, sub aqua, snorkelling, swimming, stand-up paddleboarding, camping, kayak tours, mountaineering, ski tours and snowboarding. Individual and extreme tourism, such as races and marathons, are also available. An increasing number of holiday-makers also book tours into the interior. During the 2015/2016 season, 409 people took up this offer, rising to 679 in 2018/2019 and 733 predicted for 2019/2020.

Six IAATO-affiliated tour operators and logistics services companies now offer tours into the heart of Antarctica as package deals. Depending on the programme and price (which in some cases may amount to more than 90,000 US dollars per person), they can include visits to the South Pole or a penguin colony, excursions in off-road vehicles, or extreme mountaineering and ski tours. However, the personnel and logistical input is immense. Landing strips have to be built and maintained, and camps set up and managed. Such a landing strip and camp, located to the north of the German Antarctic Research Station – Neumayer III, has existed for the past two summers. In the high season, a Basler BT-67 aircraft, modified for flying in polar conditions, now lands here ten to twelve times, bringing in tourists keen to visit the local emperor penguin colony. On its first visit, the plane landed on the sea ice next to the penguins, causing considerable disturbance to parts of the colony and to research activities taking place there.

According to experts, this fly-in and individual tourism in the polar regions seems set to increase, for although tourists have less time to travel nowadays, they are prepared to spend more on their vacations. Argentina's state-owned airline LADE, for example, has announced plans to start commercial flights in 2019 from Ushuaia on the southern tip of Argentina to the Marambio Base, the national research station on Seymour Island in the Weddell Sea. Ten per cent of the accommodation here will then be made available to tourists.

Growth in the number of cruises and short tours to the polar regions is a further emerging trend. Due to high demand, more ships – and larger ships – will be operating in the polar regions and new onshore infrastructure will be required. Some tour operators now carry out their passenger turnarounds in the polar regions – on Svalbard, for example – to spare the cruise ships the long arrival and departure journeys. However, this means that the ships must refuel and replenish their stocks of water and food locally, requiring the establishment of adequate depot and warehouse capacity in port.

The growth in tourism: the environmental risks

For Arctic communities, tourism development creates jobs. However, experts warn that the tourism boom also poses substantial social and environmental risks. They include:

- increased volumes of waste,
- air, soil and water pollution, caused by the increase in air and ship traffic,
- increased risk of accidents, particularly involving cruise ships,
- adverse impacts on local fauna, and
- potential conflicts between tourism and traditional hunting and fishing activities.

In light of these problems, the Arctic Council tasked its PAME Working Group with producing Best Practice Guidelines for sustainable Arctic marine tourism. The Guidelines, published in 2015, define sustainable tourism as "tourism that minimizes negative impacts and maximizes socio-cultural, environmental and economic benefits for residents of the Arctic".

In order to achieve this objective, close collaboration is required among tour operators, communities, government agencies, academia and other stakeholders, according to the document. The Working Group requests the Arctic Council, *inter alia*, to develop a standardized framework for the preparation of site-specific guidelines for conduct in near-shore and coastal areas of the Arctic. A range of topics is to be covered: from mitigating local safety and environmental risks, to educating visitors on ecological, cultural and historical features unique to a particular area, so that tourists arriving via marine vessels are fully informed. Furthermore, according to PAME, an information database on Arctic tourism, which should be publicly available and updated regularly, is required.

PAME also encourages the carriage of Automatic Identification System (AIS) technology on board all vessels engaged in Arctic marine tourism activities. This technology can provide information about a vessel's position, course and speed by satellite communications to maritime administrations, thus providing a more comprehensive picture of vessel traffic and assisting any necessary response or search and rescue (SAR) activity. AIS technology is already mandatory on board cargo and passenger ships above a specific size; smaller passenger ships carrying fewer than 12 passengers are currently exempt.

PAME encourages the Arctic states to streamline governmental marine tourism permitting and oversight processes, advocate publicly for operations to be conducted in a sustainable manner, to share maritime information, and to promote improved communications and regular engagement between vessel operators and the local coastal communities. However, the prerequisite for the latter, in PAME's view, is the designation, within communities, of pre-established onshore contact points for incoming vessels.

Due to a lack of reliable data, it is difficult for experts to make realistic assessments of the environmental impacts of tourism-related activities in Antarctica. The majority of tourists – around 95 per cent – visit the Antarctic Peninsula region. Because they offer cruise ship passengers superlative views of the Antarctic landscape, smaller boats are used for shore landings. There are around 200 landing stages in the region, but 68 per cent of all shore landings are concentrated at just 15 sites. In an extreme case, this means that thousands of tourists visit one and the same site – a penguin colony, say – in a single season.

If these groups of tourists are led by qualified staff who ensure that no one strays off the path or fails to keep the prescribed minimum distance from wildlife, the environmental impacts of these shore landings generally remain within reasonable limits. However, if environmental regulations are ignored, the impacts can be severe. For example, at popular landing sites such as Half Moon Island off the northern tip of the Antarctic Peninsula, it is not uncommon nowadays for large cruise ships with more than 500 passengers on board, which are not permitted to make landings, to come in as close as possible to the local chinstrap penguin colony and to remain at the site for around an hour with their engines running so that holiday-makers can indulge in nature watching. Similar scenarios are reported from well-known seal colonies along the Antarctic Peninsula.

The scale of the disturbance (noise, exhaust fumes, obstruction) becomes even more apparent given that the high season for tourism in Antarctica coincides with the time of year when seals and penguins come onshore in order to breed, suckle their young or moult. Birds in flight are known to avoid shipping areas. Unfortunately, the members of the Antarctic Treaty System have been unable to reach agreement on a joint programme to monitor and assess the impacts of tourism-related activities. A conservation plan for the Antarctic Peninsula is currently being developed by IAATO in collaboration with the Scientific Committee on Antarctic Research (SCAR). At present, however, information about the identified impacts is published solely by the tourism industry itself or by Oceanites, a US-based non-profit organization which, however, maintains close links with IAATO.

Shipping accidents pose a major threat to the polar environment in both hemispheres. In the northern polar

5.24 > In the Arctic, the eight Arctic states share responsibility for air and sea rescue operations. Each country is responsible for a specific sector, with the other countries providing incident support under the Agreement on Cooperation on Aeronautical and Maritime Research and Rescue in the Arctic (now known as the Arctic Search and Rescue Agreement), signed in 2011.

region, especially in the eastern section of the Northern Sea Route and in the Canadian Arctic, but also in the southern polar region, there is a lack of appropriate infrastructure for effective search, sea rescue and clean-up operations.

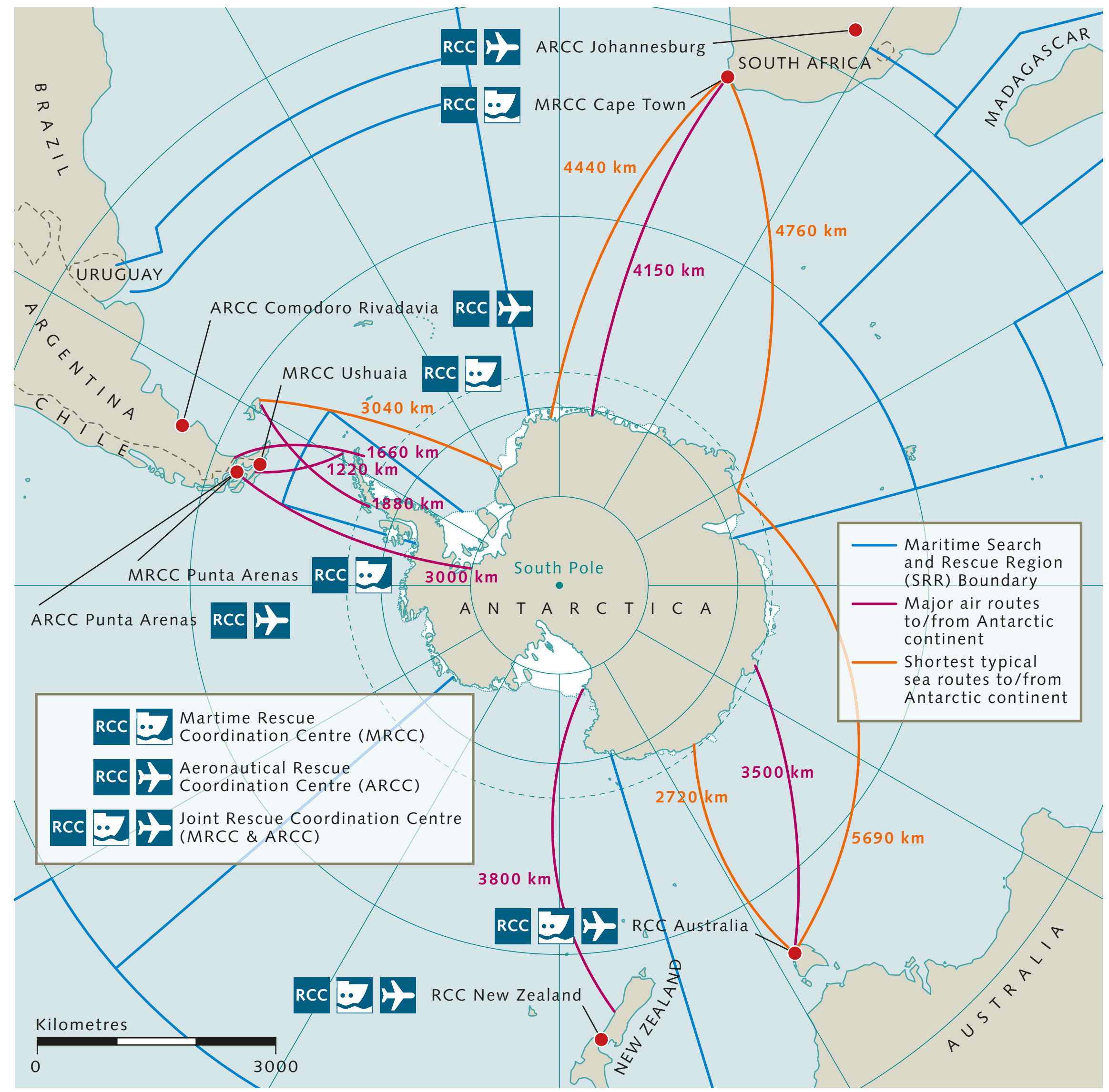
Furthermore, the Arctic regions of both Canada and Russia have only rudimentary satellite cover, making emergency communication much more difficult. Effective management of the impacts of an accident is therefore almost impossible.

The potential consequences of a shipping accident in the Antarctic were illustrated by the *Bahía Paraíso* disaster in 1989. This 131-metre vessel ran aground off the Antarctic Peninsula, spilling 645,000 litres of diesel across 30 square kilometres of sea. Although there were no human fatalities, the marine environment was badly damaged. The entire annual broods of birds such as skuas and blue-eyed shags were wiped out by oil pollution, and populations of Adélie penguins in the region collapsed.

Assistance in an emergency

In order to improve maritime safety in the Atlantic region of the Arctic, a consortium of maritime search and rescue centres, research institutes and public authorities from 13 countries formed the new Arctic and North Atlantic Security and Emergency Preparedness Network (ARCSAR) in September 2018. Their joint objective is to close gaps in the existing emergency response network and develop measures enabling the Arctic's search and rescue services to adjust to the increase in vessel traffic and passenger numbers. As air and sea rescue in the Arctic is often a coast guard responsibility, border guard units from the eight Arctic countries undertake joint incident preparedness training within the Arctic Coast Guard Forum and are involved in discussions to identify options for improving their collaboration.

The urgent need to expand emergency response capacities was demonstrated by the *Viking Sky* cruise ship incident off the west coast of Norway in March 2019. The



5.25 > Air and sea rescue in the Antarctic is managed by five maritime rescue coordination centres (MRCCs) located in Australia, New Zealand, Chile, Argentina and South Africa. However, local emergency assistance is often provided by other ships which interrupt their activities to respond to a vessel in distress.

A regulatory framework for greater safety in polar waters

In view of the increasing shipping traffic in the polar regions, the International Maritime Organization (IMO) has adopted new safety regulations. They are intended to minimize the risk of accidents and protect the environment and people in the Arctic and Antarctic regions from the adverse effects of shipping. The provisions of the International Code for Ships Operating in Polar Waters, also known as the Polar Code, have been in force since 1 January 2017 for all ships operating in the Arctic and Southern Oceans.

The code sets mandatory standards for (1) the construction of a ship, (2) its safety equipment, (3) its field of operations, (4) the qualification of the crew and (5) possible search and rescue operations, as well as establishing environmental protection precautions. It applies in addition to the International Convention for the Safety of Life at Sea, 1974 (SOLAS), which has previously regulated the safety standards for worldwide marine shipping.

To comply with the Polar Code, all ships operating in the Arctic and Antarctic seas must, for example, be equipped with technical equipment that enables them to access current weather and ice data at any time. Additional communication channels that can be used in case the satellite connection breaks down are also required, as are heated windows for good visibility on the ship's bridge, deck equipment that the crew can use to remove snow and ice (hammers, brooms, etc.), and enclosed-type lifeboats. All ships operating in the Arctic and Antarctic regions must also have enough warm survival suits on hand for every passenger, and fire-fighting equipment stored in locations that are protected from the cold and are ready for use at all times.

With regard to environmental protection, the Polar Code tightens the rules of the International Convention for the Prevention of Marine Pollution from Ships (MARPOL), which applies to all ships. The discharge of oil or liquids containing oil is strictly prohibited in the polar regions. All oil tankers must be equipped with a double hull to prevent oil leakage in the case of an accident. In addition, stricter guidelines regulate the handling of food waste, animal remains and other waste. In the polar regions, food waste may only be disposed of in the sea under certain conditions. All other waste material has to be collected and incinerated or disposed of on land at the next port call.

The regulations require ship crews to undergo special polar training. Masters, chief mates and deck officers, for example, must be trained in ship management and behaviour in marine areas with ice before they can work in the polar regions. Furthermore, the ship's command is required to always have an operation manual on hand describing exactly how the particular ship must and may be operated in polar waters. It includes, among other things, a notation of the designated polar class of the ship. The code distinguishes between three categories: A Class A certificate is issued to ships whose design permits use in areas with at least medium first-year ice, plus older ice inclusions (Polar ice classes 1 to 5). B-class ships are capable of independently breaking thin first-year ice without risk of damage (Polar ice classes 6 and 7). Class C ships can operate in polar waters where there is no ice or very little ice (with Baltic ice class or no ice reinforcement at all).

The initiators of the Polar Code touted the implementation of the new security requirements as a great success. After all, the new regulations had been in development and negotiation for almost 20 years. But the requirements do not go far enough for environmental organizations. The Polar Code does recommend using fuel in the Arctic region that is less toxic than heavy oil, but it does not yet prohibit its use. An acceptable regulation is currently being negotiated. In addition, recommendations for action regarding the handling of ballast water and organisms attached to the ship's hull are not legally binding. These are intended to prevent the ships from introducing invasive species into the Arctic.

Issues such as underwater noise, exhaust emissions and the handling of grey water have not been addressed in the new regulations. Grey water is waste water from the showers and bathrooms on board a ship. This water generally contains large amounts of chemicals (shampoo, soap), bacteria, microplastic particles (toothpaste, peeling products) and other pollutants. Cruise ships, for example, discharge a large proportion of their waste water into the sea. Environmental agencies in the USA estimate that an average ship passenger produces between 135 and 450 litres of grey water daily. In most areas of the Arctic Ocean this water may be directly discharged into the sea.

Conservationists further criticize that the rules of the Polar Code do not apply to fishing boats, private yachts with fewer than twelve passengers, and smaller cargo ships of less than 500 gross registered tonnes. Their potential damage to the environment may not be as great as if a large oil tanker were to crash. However, fishing boats make up a large proportion of the ships operating in the Arctic waters, and the number of private yachts is constantly increasing, at least in the area of the Northwest Passage.

5.26 > Although the Polar Code does not yet apply to fishing boats, it is hoped that its regulations regarding the handling of waste and garbage on ships will contribute to protecting the polar seas from increasing pollution.

ship, with 1373 people on board, found itself in distress after suffering engine problems during a storm and, as the bad weather continued, began drifting very close to the shore. The rescue service were able to evacuate around 470 people over a 19-hour period using six helicopters. The other passengers had no option but to remain on board while shipboard staff repaired the fault.

Luckily, this incident occurred close to the Norwegian coast in a region where helicopters could be scrambled and enough rescue personnel mobilized without delay. Further north – along the east coast of Svalbard, for example – it would have been almost impossible to mount this type of rescue operation as there are only two rescue helicopters stationed in the archipelago. According to media reports, however, more than 26 smaller expedition cruise ships and several large cruise ships carrying up to 1000 passengers will be operating around Svalbard in summer 2020 alone. Some of them will visit regions for which no detailed bathymetric charts exist. There is therefore a high risk of accidents.

In Antarctica, international cooperation on aeronautical and maritime search and rescue (SAR) is a more urgent necessity than anywhere else in the world. Rescue missions here, in the world's most remote region, are highly complex and therefore expensive. As there are no local rescue units, emergency assistance is generally provided by other vessels, such as station supply ships, fishing boats, cruise ships or research vessels, which then interrupt their activities in order to respond to a vessel in distress.

The five southernmost states – Australia, New Zealand, Chile, Argentina and South Africa – are responsible for coordinating aeronautical and maritime rescue in the five search and rescue areas in the Southern Ocean. They operate maritime rescue coordination centres (MRCCs) which manage any SAR operation that may be required; they also issue regular weather reports and provide other vital navigational aids for their respective SAR areas. The centres are located in Canberra (Australia), Wellington (New Zealand), Punta Arenas (Chile), Ushuaia (Argentina) and Cape Town (South Africa). Chile and Argentina also operate a joint coastal patrol (Patrulla Antártica Naval Combinada, PANC), set up in 1998. From November to March, coast guard vessels from the two countries patrol the Drake Passage and the congested waters along the Antarctic Peninsula and respond swiftly to distress calls and alerts. Their teams are trained to carry out search and rescue operations and should also take steps to protect the environment in emergencies. PANC units provided assistance, for example, during the firefighting and rescue mission when Brazil's Antarctic research station, Estação Antártica Comandante Ferraz, on King George Island burned down in February 2012.

In order to facilitate the work of the maritime rescue coordination centres, the Council of Managers of National Antarctic Programs (COMNAP) and IAATO share up-to-date shipping data with the centres. The Antarctic Treaty Parties also set up an SAR working group in 2012 and agreed to hold regular international SAR workshops, which are attended by maritime rescue coordination centre representatives, delegates from the national research programmes, spokespersons from IAATO, CCAMLR and the IMO, and commercial suppliers and service providers. Together, they discuss how aeronautical and maritime rescue can be improved and which lessons should be learned from previous operations.

Fishing in the Arctic

The Barents Sea is one of the Arctic regions in which fishing accounts for most of the ship traffic. According to the Arctic Council, up to 1600 different fishing vessels operate in the region annually. Deep-sea fishing is a key economic sector in both Norway and Russia, and a substantial proportion of the catch is exported. Obtaining precise figures on catch volumes in Arctic waters is difficult, however, as the Arctic Ocean lacks a clearly defined boundary.

The Food and Agriculture Organization of the United Nations (FAO) divides the world's seas into 19 major fishing areas, five of which cover Arctic waters. They are:

- Major Fishing Area 18 – Arctic Sea, excluding the Arctic marine waters between 40° West and 68° 30' East longitude;

5.27 > Fishing in the cold Arctic waters has always involved hard physical labour in arduous conditions. Nowadays, however, many vessels use state-of-the-art fishing gear, making the industry much less labour-intensive.

- Major Fishing Area 21 – Northwest Atlantic, including the Davis Strait and Baffin Bay;
- Major Fishing Area 27 – Northeast Atlantic, including the Norwegian Sea, the Barents Sea and the waters of the central Arctic Ocean between 40° West longitude and the north island of Novaya Zemlya (to a point at 68° 30' East longitude);
- Major Fishing Area 67 – Northeast Pacific, including the eastern Bering Sea, and
- Major Fishing Area 61 – Northwest Pacific, including the western Bering Sea.

The Northwest Pacific is one of the world's most productive maritime regions; it is also the Earth's most important fishing area, yielding a catch volume of more than 22 million tonnes of fish and shellfish annually. In the Northeast Pacific, the catch is just one-seventh of this amount (2016: 3.1 million tonnes). However, the Alaska fishing industry is an important economic sector in the North American Arctic, bringing in approximately 1.7 billion US dollars in revenues. The main species caught in the North Pacific are Alaska pollock *(Gadus chalcogrammus)*, Pacific cod *(Gadus macrocephalus)*, Pacific halibut *(Hippoglossus stenolepis)*, shrimp and Pacific salmon species such as red salmon *(Oncorhynchus nerka)*.

In Major Fishing Areas 21 and 27 in the North Atlantic, a total of 10.1 million tonnes of fish were caught in 2016, with Arctic fishing operations concentrated mainly in the ice-free coastal waters. In other words, fishing mainly took place in the exclusive economic zones (EEZs). The most important fishing grounds in the Atlantic region of the Arctic are located in the Barents Sea, the Norwegian Sea and around Greenland and Iceland. Species caught in these areas are Atlantic cod *(Gadus morhua)*, haddock *(Melanogrammus aeglefinus)*, Atlantic herring *(Clupea harengus)* and Arctic species such as capelin *(Mallotus*

The fishing ban in the central Arctic Ocean

The central Arctic Ocean is one of the few regions of the world without a commercial fishing industry. This situation will remain unchanged for the next 15 years, for in October 2018, the five nations with Arctic coastlines reached an agreement with Iceland, China, Japan, South Korea and the European Union to ban high seas fisheries in the international waters of the central Arctic.

The Agreement to Prevent Unregulated High Seas Fisheries in the Central Arctic Ocean (CAOF Agreement) protects an area roughly the size of the Mediterranean Sea from commercial fishing for an initial period of 16 years and includes the option of automatic extension every five years.

The signatory states thus aim to give the international scientific community sufficient time to study the region, covering 2.8 million square kilometres, to assess its fish stocks and to develop sustainable management strategies. Until recently, permanent ice cover on the high seas portion of the central Arctic Ocean made fishing in those waters impossible, and very little fisheries research was conducted. For that reason, little is known about the local fish populations: their size, their migration routes, habitats and predator-prey relationships. The same applies to the polar cod, which has already been heavily fished along the southern margins of its natural range.

The agreement on a fishing ban in the central Arctic Ocean was motivated primarily by the retreat of the sea ice, caused by climate change, which has led to an increase in human activity in the Arctic Ocean. Today, as much as 40 per cent of the central Arctic Ocean is ice-free in summer. This has opened up the area to shipping, and interest in fishing in the Arctic has increased.

villosus), Greenland halibut or Greenland turbot *(Reinhardtius hippoglossoides)*, northern prawn *(Pandalus borealis)* and polar cod *(Boreogadus saida)*.

In the subarctic regions of the Barents Sea and the Norwegian Sea, up to 20 species are caught, including northern krill and copepods. Fishing is of crucial economic importance for Iceland, Greenland and the Faroe Islands in particular. In the latter two cases, income from the sale of fishery products accounts for 20 per cent of gross domestic product (GDP) and almost 90 per cent of total export revenue. Arctic fishing is governed by a number of conventions and regulations, including:

- domestic legislation and regulations applicable to fishing within the various exclusive economic zones (EEZs),
- European Union fishing regulations (in the North Atlantic),
- bilateral or multilateral agreements between two or more countries with straddling fish stocks. The main fish stocks in the Barents Sea, for example, have been monitored by the Joint Norwegian-Russian Fisheries Commission since 1976. Catch quotas and fish sizes are agreed on a bilateral basis.
- measures adopted by the regional fisheries management organizations (RFMOs). In the North Atlantic, for example, the North East Atlantic Fisheries Commission (NEAFC) controls the high seas fishery and, in response to requests from Contracting Parties (Denmark, the EU, Iceland, Norway and the Russian Federation), makes recommendations on the management of stocks in the exclusive economic zones. The other RFMOs of relevance to areas of the Arctic Ocean are the Northwest Atlantic Fisheries Organization (NAFO) and the International Commission for the Conservation of Atlantic Tuna (ICCAT).
- international conventions such as the UN Fish Stocks Agreement, which entered into force in 2001 and complements the United Nations Convention on the Law of the Sea (UNCLOS). The UN Fish Stocks Agreement aims to ensure the long-term conservation and sustainable use of straddling and highly migratory fish stocks, based on a cooperative approach.

In all areas of the Arctic, catch limits and fishing periods are established and fishing licences are allocated on the basis of scientific recommendations made, for example, by the International Council for the Exploration of the Sea (ICES), specifically its Arctic Fisheries Working Group (AFWG). Every year, this Working Group performs assessments of the status of stocks of key importance for fisheries in the Barents Sea and Norwegian Sea and provides advice to the relevant management bodies, such as the Joint Norwegian-Russian Fisheries Commission.

Both national and transregional fisheries authorities with jurisdiction over Arctic waters comply with precautionary and sustainability principles. This means that the catch that can be taken from a species' stock within a specific period is such that the fish population is maintained with no decrease in productivity and no cause for concern about negative impacts on the ecosystem. There is also stringent monitoring of fish stocks; as a result, experts take the view that most fish stocks in Arctic waters are in a healthy state.

West Greenland cod is an exception, however. This stock was so heavily fished between 1950 and 1980 that the population became depleted in the 1980s and stocks have not recovered. Furthermore, over the past decade and more, Canadian and West Greenland snow crab fishers have observed a decline in catch figures. However, these decreases may be due to migration of snow crab further north as a consequence of climate change.

Also due to climate change, the habitats of many edible fish species are shifting northward towards the pole. In the Barents Sea, some Arctic fish stocks have already migrated out of reach of coastal fishers, who in consequence are now focusing on other species or merging to form deep-sea fishing consortia. In the Barents Sea region, scientists observed a good ten years ago that fewer fishers were putting to sea than previously, but the ships in operation were larger and using more up-to-date fishing gear.

Fish species composition in the Barents Sea changed during the period 2004 to 2012. Previously, it was mainly the Arctic species that ended up in the nets, such as bigeye sculpin *(Triclops nybelini)*, Greenland halibut or Greenland turbot *(Reinhardtius hippoglossoides)* and snailfish *(Liparis spp.)*. Today, the catch mainly consists of North Atlantic species that prefer somewhat warmer conditions, including the Atlantic cod, haddock and American plaice *(Hippoglossoides platessoides)*. Furthermore, non-native species such as Kamchatka crab (also known as the red king crab) *(Paralithodes camtschaticus)* and snow crab *(Chionoecetes opilio)* have spread in the Barents Sea and have proliferated to such an extent that crab fishing is now a profitable business.

Climate-related species migration is also filling the nets of fishers in Greenland, Newfoundland and Labrador with high-value edible fish from the Atlantic. Off the east coast of Greenland, mackerel fishers are now catching Atlantic bluefin tuna *(Thunnus thynnus)* as well. There has also been a substantial increase in the cod catch. In 2013, Greenland's deep-sea fishers caught 10,700 tonnes of cod, rising to 17,800 tonnes in 2017. This trend confirms scientific forecasts from 2014 that fishing revenues generated by Arctic states along the Atlantic seaboard will increase by 39 per cent from 2000 to 2050.

Spurred on by the prospect of a profitable cod and halibut fishery in future, government authorities and indigenous representatives in Canada's Nunavut territory are investing seven million Canadian dollars in fisheries research projects off the east coast of Baffin Island. Until now, the indigenous communities on Baffin Island engaged solely in small-scale subsistence fishing. A commercial fishing fleet, however, has the potential to create much-needed employment in the region. Fishing vessels from Newfoundland and Labrador are now achieving such high catch volumes off the Nunavut coast that their revenue soared from 38 million Canadian dollars in 2006 to 86 million in 2014.

While the southern Bering Sea is home to the world's most important fishing grounds, commercial fishing in the northern Bering Sea operates on a much smaller scale. Indeed, in 2009, the North Pacific Fishery Management Council, which is responsible for the US areas of the Chukchi and Beaufort Seas, imposed a ban on commercial fishing here in order to protect the fragile marine biotic communities from potentially adverse effects. Likewise, no commercial fishing is known to be taking place in the far north of Canada. In both these regions, communities are engaged in fishing solely for subsistence purposes, with fish being one of the main food sources for indigenous populations in Alaska and Canada's northern territories. Along the north coast of Canada, the main species caught are Arctic char *(Salvelinus alpinus)*, Atlantic salmon *(Salmo salar)* and broad whitefish *(Coregonus nasus)*. The total annual landed catch has amounted to approximately 800 to 900 tonnes since the mid-1990s.

Marine biologists are currently working intensively on new fisheries monitoring and management strategies as a basis for documenting species migration and climate-related population decline and for setting catch limits, including across fishing area boundaries. This reflects the fact that climate change is making sustainable management of fish stocks in Arctic and subarctic waters increasingly difficult.

Fishing in the Antarctic

Conserving and managing marine life, such as krill and fish, in the Southern Ocean is the responsibility of the Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR). The sea area under its jurisdiction is bounded by the Antarctic Polar Front – the zone where the cold water of the Antarctic encounters the warmer sub-Antarctic waters – and in some places extends beyond the Antarctic Circle. It covers a total area of 35.7 million square kilometres, representing approximately ten per cent of the Earth's oceans.

The primary objective of the CAMLR Convention is the conservation of all marine living resources and ecosystems in the Southern Ocean. However, the Convention also states that the term "conservation" includes rational use of these resources. Fishing in the Southern Ocean is strictly regulated, and nature conservation should always take precedence over fishing interests. As one of the core pillars of the CAMLR Convention, the Commission establishes catch limits on the basis of scientific knowledge and applies a precautionary approach in this context. All CCAMLR members must act in accordance with the Convention and prevent the fragile marine species and ecosystems in the Southern Ocean from being damaged by fishing operations.

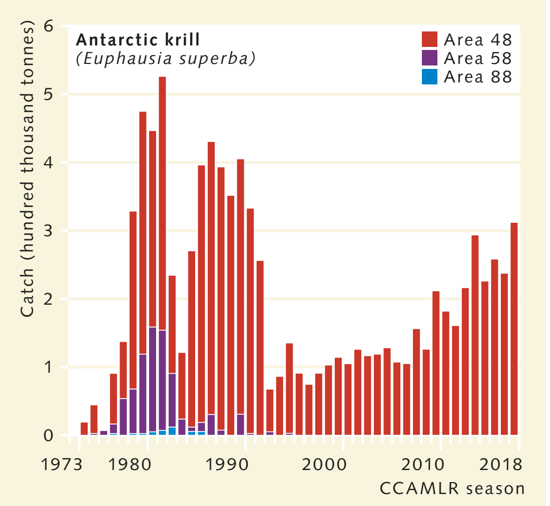
Within the CCAMLR region, there are neither fishing ports nor any indigenous populations that engage in subsistence fishing. The entire catch from Antarctic waters is landed outside the Convention Area. Fishing in Antarctica is currently limited to a small number of species, including Antarctic krill *(Euphausia superba)*, mackerel icefish *(Champsocephalus gunnari)*, Patagonian toothfish *(Dissostichus eleginoides)* and Antarctic toothfish *(Dissostichus mawsoni)*, also known as Antarctic cod. In addition, over the past year, Russia has been fishing for Antarctic king crabs *(Neolithodes yaldwini* and *Paralomis birsteini)* on a trial basis.

At present, Antarctic krill is caught almost entirely in the Atlantic sector of the Southern Ocean, more specifically in the waters west of the Antarctic Peninsula, around the South Orkney Islands and around South Georgia. The annual catch volume amounts to 200,000 to 300,000 tonnes, with Norwegian trawlers bringing in roughly 60 per cent, Chinese fishers accounting for 20 per cent and South Korean vessels landing 10 per cent. In 2017, eleven vessels were engaged in krill fishing. This decreased to nine vessels in 2018, but together, they increased the krill catch compared with the previous year. This year, the Norwegian company Aker BioMarine put a new ship into service. Custom-built for krill fishing, *Antarctic Endurance* is 130 metres in length and cost more than 140 million US dollars. It is equipped with state-of-the-art technologies that make the vessel's operation more environmentally sound and increase the efficiency of its krill harvesting.

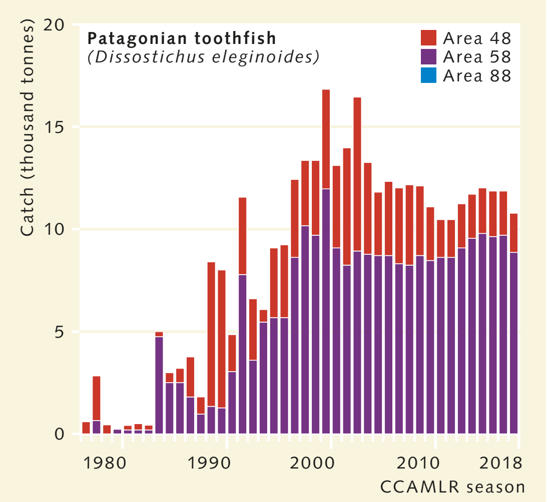
The total volume of the krill catch has been increasing for more than 20 years. In 2019, 312,989 tonnes of krill were caught – but this amount is still much lower than the catch limits set by by CCAMLR, i.e. 620,000 tonnes for the krill fishery in the Atlantic sector and 892,000 tonnes for the East Antarctic sector. At present, very little krill fishing is conducted in this latter sector. CCAMLR has been attempting for some years to revise these catch limits on the basis of new scientific data, also to take into account the potential impacts of climate change on Antarctic krill stocks.

Like krill, mackerel icefish is caught with nets. This is a target species for fishers on the shelf waters of South Georgia and Heard Island, whose annual catches of this

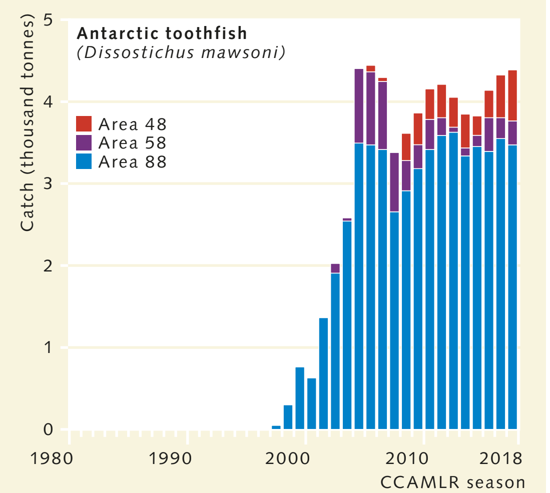
5.28 > Economic development in the Arctic regions is changing the lives of indigenous communities. Snowmobiles, cars and air travel are now just as much a part of their daily lives as traditional seal and snow goose hunting, as this wall hanging in the museum in Iqaluit, Canada, shows.



5.29 > Antarctic krill is mainly caught in the Atlantic sector of the Southern Ocean. Catch volumes have been rising continuously for some years, partly because the omega-3 fatty acids extracted from krill are used as a food supplement.



5.30 > Patagonian toothfish *(Dissostichus eleginoides)* are caught using bottom-set longlines in depths of 1200–1800 m. The fishery is strictly regulated and monitored by CCAMLR. The catch limit set for this species for 2018 was 2600 tonnes.



5.31 > The Antarctic toothfish *(Dissostichus mawsoni)* is a close relative of the Patagonian toothfish and is caught in exploratory fisheries in some regions. This means that catch limits are reviewed annually by CCAMLR's Scientific Committee and Working Group on Fish Stock Assessment.

species amount to 400 to 500 tonnes. The fishing vessels mainly come from Great Britain (57 per cent) and Australia (25 per cent).

Patagonian toothfish, on the other hand, is generally caught using longlines in depths of 1200 to 1800 metres. Longlines vary in length from three to ten kilometres and have thousands of baited hooks attached at intervals. French, British and Australian vessels set longlines around South Georgia and in several areas in the Indian sector. The total catch amounts to 11,000 to 12,000 tonnes per year. By contrast, the Antarctic toothfish catch is around a quarter of this figure. Antarctic toothfish is caught using longlines by fishers from Korea, New Zealand, Britain, Russia, Spain and Ukraine. The fishing grounds are located in the Atlantic and Indian sectors of the Southern Ocean and in the Ross Sea.

Both species of toothfish grow to up to two metres in length and reach 60 to 80 kilograms in weight. They are slow-growing species, only reaching sexual maturity at eight to ten years of age, and have a potential lifespan of 45 to 50 years. These characteristics make both species highly vulnerable to overfishing. With a temperature tolerance limit of just two degrees Celsius, the Antarctic toothfish is also endangered by climate-related warming of the Southern Ocean.

Russia is currently the only country to fish for king crabs *(Neolithodes yaldwini* and *Paralomis birsteini)* in the Pacific sector of the Antarctic. Although this takes the form of a small-scale trial, the damage to the environment is considerable. Like lobster, individuals are caught in pots, each measuring 1.5 metre in diameter. Some 120 of these pots are attached to a weighted line. To make it easier to pull in the line, buoys are attached at one end and drift on the water surface. These marker buoys can easily become snagged on icebergs or ice floes, which then drag the entire line, with the weights and pots attached, for many miles across the ocean floor, destroying the fragile biotic communities on the seabed. For this reason, Germany and other CCAMLR states are currently lobbying for CCAMLR to ban this fishery.

It is the Commission (CCAMLR), at its annual meetings in Hobart, Tasmania, that determines where and to what extent fishing operations are permitted in Antarctica. Decisions are adopted by consensus, which means that any CCAMLR member is in a position to veto measures, such as the establishment of marine protected areas (MPAs), that do not accord with its interests. Nevertheless, the Commission has introduced far more stringent controls on fishing in the Antarctic in recent years to monitor compliance with agreed catch limits and closures and reduce illegal fishing.

Closures include a seasonal restriction on longline fishing, which may only take place in winter (in certain fishing grounds), and special measures to reduce bycatch of seabirds such as albatrosses and petrels. The birds often follow the longline ships, swallow the baited hooks when the lines are being set and are then dragged under water, where they drown.

In the early days of Antarctic longline fishing in the 1980s and 1990s, so many seabirds died on the longlines that some populations declined by as much as 40 per cent. As a result, some species of albatross are now critically endangered.

The conservation measures agreed by CCAMLR are proving effective, however. Weighting the lines to propel them to greater depths more quickly, attaching fluttering ribbons to scare the birds away and requiring longlines to be set at night have resulted in a sharp drop in seabird bycatch. Compared with the early 1990s, when longline fishing in the Convention Area caused more than 6000 seabird deaths each year, the figure is now less than ten birds annually, even though the number of longlines and hooks in use in the Southern Ocean has increased in recent years.

In the 1990s, illegal fishing for Patagonian and Antarctic toothfish also increased. Illegal fishing generally involves the use of extremely damaging deep-sea gillnets, which are banned throughout the Convention Area. The market for Patagonian and Antarctic toothfish is highly lucrative: depending on supply and demand, prices can range from ten to 20 US dollars per kilogram, sometimes much more. Toothfish is marketed as Chilean sea bass, mainly in North and South America but also in some Asian and European countries.

The CAMLR Commission has introduced a rigorous reporting and monitoring system in order to curb illegal fishing – with some success. In 1996, an estimated 30,000 tonnes of toothfish were landed illegally, but this fell to less than 1500 tonnes in 2014. There are now only isolated signs of illegal fishing activity. However, researchers report that as a result of overfishing in the 1990s, some toothfish stocks became depleted and have not yet recovered. They mention the stocks around Prince Edward Islands, on the Kerguelen Plateau and on the Banzare Bank in the Indian sector of the Southern Ocean (58° 50' South and 77° East) as examples.

New tensions in the Arctic?

Economic development in the Arctic offers new opportunities for international cooperation, but according to some observers, it may also raise security concerns – for example, because some Arctic states are expanding their military presence here due to NATO members' growing scepticism towards Russia since its annexation of Crimea, or because the renewed trade dispute between the US and China makes negotiations on Arctic issues more difficult. Global politics, observers say, directly influences – and in some cases hinders – cooperation among the Arctic states.

Other researchers emphasize that there is no empirical evidence for this spillover effect. They point out that far fewer troops are stationed in the Arctic today than during the Cold War, and that the deployment of military units in the Arctic is not generally a response to a perceived threat to the coastal states' national security. The Arctic states, they say, are more concerned with guarding the length of the newly exposed border – previously well-protected by ice – especially since the number of Arctic actors and vessel operations have increased. They also point out that military personnel are involved in aeronautical and maritime search and rescue (SAR) missions and that for Russia, the deployment of military units is a way of supporting development of infrastructure in remote Arctic regions.

In recent years, the Russian government has invested substantial sums in constructing and expanding its military bases along its Arctic coastline. A new army base has been established in Franz Josef Land, for example. According to a statement by the Russian government, the military is needed in the Arctic in order to protect shipping on the Northern Sea Route and other economic activities. However, the US government under President Donald Trump believes that US security interests are under threat from the presence of the Russian military in the Arctic and from the close economic cooperation between Russia and China. The US armed forces have announced plans to increase their naval patrols in Arctic waters. In 2020, the US also intends to modernize a military air base in Iceland, from which the US military withdrew in 2006 and which it now uses solely for occasional reconnaissance flights.

Despite these developments, German observers do not consider political cooperation in the Arctic to be at risk. In their view, Arctic cooperation is well-institutionalized and based on international rules that are recognized by all parties, and has proved to be extremely efficient and effective thus far. They consider that calls for new Arctic security institutions – voiced at the Roundtable on Arctic Security at the Munich Security Conference, for example, focus too much attention on the topic. As a result, the issue of security could ultimately overshadow existing cooperation formats, potentially giving impetus to the very factors of insecurity that should be resolved. In light of the dramatic changes taking place in the Arctic, international partnership and cooperation in the northern polar region are now more important than ever, observers say.

An example of what cross-border inter-alliance cooperation in the Arctic can look like was provided by Russia and Norway in May 2019, when coast guards and search and rescue units from these two neighbouring countries teamed up for a day of joint SAR training in the Barents Sea. The units practised finding people in distress at sea and conducted an oil-spill clean-up exercise.

5.32 > The Arctic states conduct joint air and sea search and rescue (SAR) exercises on a regular basis to ensure effective cross-border cooperation and optimal protection of human lives and the environment in emergencies.

Conclusion

Growing interest in the polar regions

Perceptions of the polar regions have changed fundamentally in recent decades. Once, these largely inaccessible regions mainly attracted seal hunters and whalers. Now, however, in the wake of climate change, there is growing international interest in exploring the Arctic and Antarctic and in tapping the potential of both polar regions for various forms of commercial exploitation. Consequently, membership of policy-making organizations is growing, along with the need for more regulation and consensus. Some traditional polar nations are adopting a more protectionist stance, making the process of reaching compromises more difficult in the Arctic and Antarctic alike.

In Antarctica, which is under the joint administration of the Consultative Parties, the principle guiding all activity is to preserve and protect the only region of the world dedicated to peaceful cooperation and research. The Antarctic Treaty and related environmental agreements restrict the use of Antarctica to research, sustainable and now strictly controlled fishing, and tourism.

The Arctic territories, by contrast, fall within the jurisdiction of the individual Arctic states. These states have a legitimate interest in promoting the economic development of the hitherto sparsely populated regions. Most Arctic nations, especially Russia, are now giving greater attention to resource extraction and shipping, for the Arctic is resource-rich: according to one study, the region north of the Arctic Circle holds approximately 22 per cent of the world's undiscovered oil and natural gas. Large deposits of coal, iron ore, rare earths and other minerals are also to be found here. The extraction of these resources will become more lucrative in future as demand for them increases and the retreat of the ice opens up access to the northern regions.

However, the very substantial resource wealth has also led to territorial disputes among the Arctic coastal states. These disputes have smouldered for decades in some instances and are still only partially resolved. The bounty of the polar regions is also attracting interest from distant non-Arctic countries, notably China. Such countries are attempting to secure access rights and to have a say over the future of the Arctic by entering into bilateral agreements with Arctic states. Their strategies further involve investing in resource extraction and greatly increasing their engagement in the Arctic Council.

Resource extraction is accompanied by an increase in shipping in Arctic coastal waters. In the tourism sector, the cruise industry is also experiencing growth, with the number of ships and trips rising steadily. In order to minimise the attendant risk of maritime accidents, all vessels operating in polar waters must comply with the Polar Code, which prioritises prevention. Shipping in both polar regions is, as ever, a high-risk business due to the low temperatures and rapidly changing ice and weather conditions. If a vessel gets into difficulty, it can take a very long time for help to arrive, especially in the Antarctic.

A precautionary approach, combined with sustainability principles, must be the benchmark for these and all other areas of human activity in the polar regions. The Arctic and, indeed, some areas of Antarctica are radically changing due to climate change, and this puts great stress on local biotic communities and natural processes. Humankind must therefore do all it can to minimize its footprint in these highly fragile regions, not increase it through the reckless pursuit of profits.

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Living with the oceans. 2019

6

The Arctic and Antarctic – Extreme, Climatically Crucial and In Crisis

As this sixth *World Ocean Review* is being written, meteorologists are reporting record high temperatures across much of the Arctic. Right now, in July 2019, some 6000 square kilometres of tundra and taiga in Alaska are burning in conditions of extreme aridity and summer temperatures above 30 degrees Celsius. Even larger areas are affected in Siberia, where massive wildfires have led the Russian authorities to declare a state of emergency in five regions. The water masses in the Bering Sea and Chukchi Sea are up to four degrees Celsius warmer than the average for the years 1981 to 2010. Summer sea-ice cover in the Arctic looks set to shrink to a new minimum, and in June 2019 scientists observed the earliest start to the summer melt of Greenland's ice sheet since records began. During a prolonged period of warm weather in the following month – July – the ice cap lost 197 billion tonnes of ice, 160 billion of them as a result of surface melt. The snow is starting to melt even at the ice sheet's highest point, 3200 metres above sea level. At the same time, strikingly little winter sea ice is forming on the Southern Ocean, even though air temperatures over East Antarctica are somewhat lower than usual. In the western part of Antarctica, on the other hand, temperatures are too warm – as they have often been in recent years. In the face of this flurry of bad tidings from the Arctic and Antarctic, it no longer seems justified to talk about the "eternal ice" of the polar regions.

Satellites and an ever-growing network of meteorological measuring stations and instruments now keep us constantly updated on general weather conditions in the Arctic and Antarctic. These two regions are the cold poles of the Earth: because of their geographical position, the tilt of the Earth's axis and the Earth's movement around the sun, sunlight and warmth do not reach them continuously – and the solar radiation that does arrive is weaker than in regions closer to the equator. In consequence, the polar regions have for thousands of years cooled so much during the polar night that vast areas of new sea ice form each year and snow falls wherever the air contains sufficient moisture. When the sun returns in spring, the pure white expanses of ice and snow reflect up to 90 per cent of the solar radiation that reaches them (albedo effect). If dust, meltwater or other dark surfaces are present on the ice, or if the sea is free of ice, a far smaller proportion of the solar energy is reflected back. The ice and snow cover thus slows the temperature rise in the region and enables glaciers and ice sheets to form. Due to the albedo effect, the Earth as a whole warms far more slowly than it would if the polar regions were devoid of snow and ice. For this reason, the northern and southern polar regions play a key part in the Earth's climate system. Their importance is amplified by the fact that the temperature differences between the cold polar regions and the warm tropics drive the winds and ocean currents that circle the Earth and thus contribute significantly to the global dispersal of the warmth stored in the seas and in the atmosphere.

Despite the extreme climate in both polar regions, the fact is that the Arctic and Antarctic differ fundamentally in many respects – not just in terms of their evolution and settlement history but also with regard to their flora and fauna, the impacts of climate change and their present use by human communities. To understand these differences, it is essential to consider the location and geography of the two polar regions. Antarctica is a continent almost entirely covered by ice masses and completely surrounded by water. Vast atmospheric wind flows and ocean currents have formed around this southern continent, increasing its isolation. In the northern polar region, by contrast, continental land masses surround a small ocean, located in their midst. In some places these land masses merge or are connected by now-submerged land bridges. When global sea levels were low, animals, plants and humans were thus able to colonise the northern territories. The most notable example of a land link was the Bering Land Bridge, a broad strip of land that joined eastern Siberia and Alaska at the height of the last ice age and enabled the primeval hunters of Siberia to migrate to North America.

The central position of the Arctic Ocean at the pole means that it is covered by sea ice, which increases its extent in winter and shrinks in summer. Because it has not yet melted completely in summer, the ice cover is often described as permanent. By contrast, the sea ice in the Southern Ocean melts so extensively in summer that experts regard it as seasonal ice cover.

The land-ice masses of Antarctica are impressive. They cover 98 per cent of the continent and contain so much fresh water that global sea levels would rise by 58.3 metres if they were to melt completely. In the far north, only the Greenland ice sheet is a comparable mass of land ice. It contains enough ice to raise the water level around the world's coasts by about 7.3 metres if it were to melt.

The simultaneous existence of large ice masses in both polar regions is something of an anomaly in the Earth's long history. Since the Earth was formed, its shifting continents have seldom positioned themselves in a way that enables polar climate conditions to arise in both north and south, with both regions icing up. While scientists have now reconstructed the climate history of the Antarctic fairly precisely, many questions about the glacial history of the Arctic still remain unanswered. There is an urgent need for historical climate data to improve forecasting of the possible impacts of climate change on the polar regions.

Rising air and water temperatures in the wake of climate change are inducing fundamental changes in the polar regions, albeit with marked differences between north and south. Climate-induced change commenced much earlier in the Arctic than in the Antarctic and is still more noticeable in the far north than at the southern pole. In Antarctica, the temperature rise is affecting only the Antarctic Peninsula, whereas the Arctic has become a hotspot of climate change in recent decades. It is warming more than twice as fast as the rest of the world (by 2.7 degrees Celsius between 1971 and 2017), with winter temperatures rising faster than summer temperatures. The years 2014, 2015, 2016, 2017 and 2018 were all warmer on average than the preceding 113 years.

This dramatic warming has been triggered by complex interactions between the atmosphere, land, sea and shrinking ice – a process that scientists term Arctic amplification. There is considerable debate in scientific circles about the extent to which particular effects contribute to

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amplification. Some researchers argue that the drastic warming is primarily due to the shrinking snow and ice cover in the Arctic. The fewer light-coloured areas are present, the lower the reflective power of the Arctic and the greater the quantity of solar energy that remains in the northern polar region, triggering changes in the oceans and atmosphere. New findings indicate that total loss of the remaining Arctic sea ice would have an effect on global warming equivalent to releasing an additional trillion tonnes of carbon dioxide into the atmosphere – the quantity currently emitted by humans over the course of about 25 years. This would greatly accelerate climate change.

Other scientists point out that the warming air over the Arctic absorbs more water vapour and that clouds therefore form more frequently, further impeding the radiation of heat energy into space. However, at certain times of year and with some types of cloud, this effect can be reversed and the cloud cover then has a cooling effect. Each argument has its merits and can be backed up by statistics. The actual explanation for amplification doubtless lies in the interplay of multiple factors, whose scope and effects vary not only seasonally but also from region to region.

Given the extent of the climatic changes in the Arctic, scientists are now concluding that the northern polar region has entered a new stage. Significantly less snow is falling in many areas and the sea-ice cover on the Arctic Ocean is steadily shrinking. The pack ice is noticeably younger, thinner, more fragile and hence more mobile than when satellite measurements began in 1979. At the end of the summer, the ice-free areas of the sea are now so extensive that the sun is able to warm the Arctic Ocean on a large scale. This warmth in turn causes fundamental changes in the ocean itself and in the atmosphere above it.

Scientists now know that the retreat of the sea ice in the Barents Sea and Kara Sea is distorting the strength and flow pattern of the jet stream over the northern hemisphere and hence indirectly affecting the weather in the mid-latitudes. Because the temperature contrasts between the tropics and the polar region are decreasing, the band of strong winds that determines the weather in the mid-latitudes is weakening and changing course. In summer, this increases the likelihood of extreme weather such as heat waves and droughts in Europe. In winter, on the other hand, a weakening jet stream leads to periods of exceptional cold in Central Europe and the American Midwest, while over Svalbard and the Bering Sea warm air masses penetrate far into the Arctic.

The retreat of the sea ice brings with it changes in the stratification of the water masses in the Arctic's marginal seas, such as the Barents Sea, with stratification becoming similar to that in the North Atlantic. Scientists call this the "Atlantification" of the Arctic Ocean. Furthermore, the melting of the sea and land ice is discharging more fresh water into the Arctic Ocean. The consequences of this are still unclear, but scientists believe that it could slow the turnover of the water masses in the North Atlantic, thereby weakening the Gulf Stream that is so important to Europe.

The sad reality, even now, is that the retreat of the sea ice in the Arctic is accompanied by increasing erosion of the Arctic permafrost coasts. Where there is no sea-ice cover, the wind is able to whip up waves which then hit the fragile coasts. The water also warms faster and thaws the coasts a little more with each incoming wave. On land, the rising temperatures thaw the permafrost to great depths and reduce the stability and load-bearing capacity of the once-frozen substrate. In addition, microorganisms start to break down organic material that was previously bound up in the permafrost; this process produces large quantities of carbon dioxide and methane, which are naturally released into the atmosphere, further accelerating climate change.

The warmth is also melting land-ice masses in the Arctic. In July 2019, scientists reported that Alaskan glaciers that flow into the sea are actually melting up to one hundred times faster than previously assumed. With Greenland's ice sheet at the forefront, the shrinking glaciers of the northern polar region are currently contributing more to rising global sea levels than the melting of the mountain glaciers or the ice masses of the Antarctic. In summer 2019, the warmth caused the first of Iceland's 400 glaciers to melt to such an extent that it has lost its status as a glacier. Scientists have affixed a memorial plaque to the fragmentary remains of the Okjökull glacier. The text, in English and Icelandic, contains a stark warning: "In the next 200 years all our glaciers are expected to follow the same path."

Climate change is also affecting the polar flora. Trees and shrubs are now moving into the tundra, replacing low-growing, cold-adapted lichens, mosses and plants in a process known as Arctic greening. Elsewhere, warmth and increasing aridity are causing Arctic browning as plant life withers; wildfires are becoming more frequent, releasing further quantities of greenhouse gases. In Alaska alone, forest and tundra fires in July 2019 released a quantity of carbon dioxide equivalent to the entire annual emissions of a country such as Sweden. The fires are thus amplifying global climate change.

Forecasts of what the future holds for the polar regions' marine biotic communities are also extremely worrying. With the melting of the sea ice, the habitat of the ice algae is shrinking. They are the most important primary producers in the Arctic Ocean, so wherever they disappear, fish, zooplankton and bottom-dwellers must seek new sources of food. This is having a devastating effect on marine food webs beyond the boundaries of the Arctic, as studies in the North Pacific show. Large-scale shrinkage of the ice was followed first by a decline in fish stocks and then by the death of large numbers of seabirds and grey whales. The viability of cold-adapted Arctic marine life is also affected by the rising water temperatures and the increasing acidification of the oceans. Acidification is particularly detrimental to organisms that form skeletons, cases or shells from calcium carbonate.

Those that can, adapt to the new environmental conditions. However, cold-adapted polar species such as the polar cod and the Antarctic toothfish are unable to do this: the temperature range that suits them is too narrow for them to be able to adjust quickly to the rapid warming of the oceans. The young of some species are particularly sensitive to excessively warm temperatures. These inhabitants of the polar seas have no choice but to migrate to the last remaining cold regions. However, a glance at the long-term temperature forecasts for the Arctic Ocean shows that even this option will not exist for long. Within 30 years – and possibly much sooner – the Arctic Ocean is likely to be free of ice in summer. By then it will be inhabited by refugee species that have migrated from the warm mid-latitudes to the northern polar region.

Further victims of the retreating ice include polar bears, walruses, penguins and other seabirds and mammals that depend on sea ice. Because the absence of ice deprives them of their hunting grounds, starving polar bears are already to be found hanging around rubbish dumps in Arctic communities and settlements. Using computer models, biologists have calculated the mortality of adult polar bears in the western Hudson Bay. They found that between three and six per cent of all adult males die if the summer fasting period lasts 120 days. If this starvation period lasts an additional 60 days – i.e. for 180 days in all – between 28 and 48 per cent of the bears are at risk of dying from hunger. In view of the continuing retreat of the sea ice, the researchers therefore believe that in the long term the imposing white giants will become extinct.

Svalbard's reindeer have turned to eating seaweed that has been washed up on the beach when rain falls on the snow cover in winter and forms a thick layer of ice that prevents them scraping their way through to the lichens that are their preferred food. They appeared to be surviving on this alternative diet, but when researchers from the Norwegian Polar Institute conducted their annual survey on Svalbard in spring 2019, they found that around 200 reindeer had starved to death in the rainy winter of 2018/2019. Such a high winter mortality rate had been observed only once before.

While global warming is driving rapid and widespread change in the Arctic, change in the Antarctic is proceeding more slowly and its extent varies from region to region. In addition, the formation of the hole in the ozone layer over the Antarctic led to climatic changes that are still having a significant impact on the region today. This means that scientists cannot with certainty attribute new developments to the global rise in the concentration of greenhouse gases.

What is clear, however, is that the face of the Antarctic is changing in many places. This is particularly evident in the Antarctic Peninsula, the western Antarctic and around the Totten Glacier in East Antarctica, but there are also initial signs of change in areas that were thought to be

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stable, such as the Weddell Sea. The greatest warming that has been documented is taking place in the Antarctic Peninsula. In recent decades, this has led to a decline in sea-ice cover in the Bellingshausen Sea, the collapse of several ice shelves on the eastern and western coasts of the peninsula – including the main portion of the Larsen B Ice Shelf, spanning 3250 square kilometres – the rapid retreat of many smaller glaciers and major changes in the marine food web. In most regions of Antarctica, however – and especially in the centre of the continent – the air temperature has risen little or not at all. Scientists attribute this partly to the cooling effect of the hole in the ozone layer. Ozone is a greenhouse gas: where the ozone layer thins, the gas is depleted. This means that the lower stratosphere and the troposphere cool more quickly and the air temperature falls.

The warmth comes instead from the sea. In West Antarctica, warm water masses from the Circumpolar Current travel up the continental slope to the shelf sea and then through trenches to places far below the floating ice shelves and glacier tongues. There they melt large areas of the ice masses from below. This increases the rate of ice calving and reduces the adhesion of ice flows to their bed – for example, where they rest on islands or submarine mountains that have until now acted like chocks and prevented the ice masses slipping. Without these brakes, the ice masses start to move faster. This means that the ice shelves and glacier tongues are not only retreating at record speed (iceberg calving) but are also transporting more ice from the interior to the sea (higher flow rate), causing the sea level to rise. In West Antarctica this vicious circle is likely to continue until the West Antarctic Ice Sheet has collapsed completely. Much of its ice mass rests on the sea floor and is therefore fully exposed to the warm water masses.

The flow rate of the vast Totten Glacier in East Antarctica is increasing in the same way. If its ice losses are added to those in West Antarctica and the Antarctic Peninsula, it becomes clear that total ice losses in Antarctica have trebled since 2010. Their contribution to global sea-level rise has also increased. Sea levels are now rising at 3.3 millimetres per year – twice the rate recorded in 1990. Almost two-thirds of the rise is attributed to the discharge of meltwater, while the remaining third is due to the expansion of seawater as it warms.

Antarctica has no permanent settlements and therefore only a few hundred researchers are witnesses to the retreat of the glaciers. In the Arctic, by contrast, some four million people are directly affected by climate change. These contrasting population figures are also explained by the geography of the polar regions. Humans have been able to access most Arctic regions on foot. Our ancestors left North Africa and settled Siberia around 45,000 years ago, later migrating over the Bering Land Bridge to North America. However, humans were unable to make a home for themselves in Greenland and the far north of Europe until the great ice sheets of the last ice age had melted and opened up the route to the Arctic.

The exploration of the Arctic by Europeans began in the late 15th century when seafaring traders were looking for a northern sea route to India and China. The freezing temperatures and thick Arctic pack ice defeated many – including the Italian John Cabot who did, however, discover Labrador as he travelled west. Almost six decades later, the same conditions also halted the first Arctic expedition that attempted to sail through what is now the Northeast Passage. It would be another 175 years before Vitus Bering, an envoy of the Russian Tsar, set out from Kamchatka and became the first European to sail through the strait between Asia and North America that now bears his name. The first voyage through the Northeast Passage was accomplished by the Swede Adolf Erik Nordenskiöld on the steamship *Vega* in 1878/1879. A complete transit of the Northwest Passage, by contrast, was not achieved until 1906, when it was traversed by the Norwegian Roald Amundsen. This daring voyage took Amundsen three years.

While explorers such as Fridtjof Nansen were already surveying the Arctic Ocean in the late 19th century, Antarctica remained a white spot on the map for a very long time. It was the travel reports by the Baltic German naval officer Fabian Gottlieb von Bellingshausen, who circumnavigated Antarctica between 1819 and 1821 and spotted large herds of walruses and seals, that inspired whalers and seal hunters to press ever further south in their search for new fishing grounds and thus discover large parts of the Antarctic Peninsula and the Weddell Sea.

The hunters were followed by explorers and scientists from Britain and Germany. They divided Antarctica into quadrants and explored it in a number of expeditions between 1901 and 1905. However, the findings of the first German Antarctic expedition, led by Erich von Drygalski, received little public recognition. This expedition took place at the start of the era of colonial imperialism: polar research was becoming a sporting contest that was more about being the first nation to advance into unknown territory or reach the pole than about scientific discovery. Members of these expeditions faced deadly dangers every step of the way. Among the best-known of those who lost their lives to Antarctica are the British captain Robert Falcon Scott and his companions. In 1911 they lost the race to the South Pole to the Norwegian Roald Amundsen and died on the inland Antarctic ice on their journey back.

After the First World War, as technology improved and expeditions became increasingly professionalized, the key role of the Arctic and Antarctic in the Earth's climate also came to be recognized. The standing of polar research increased considerably as a result. International scientific cooperation paved the way for the Antarctic Treaty. The Treaty, which entered into force in 1961, still requires Antarctica to be protected and to be preserved for peace and science. It also places the power to make decisions on all matters relating to Antarctica in the hands of its active member states (Consultative States). Antarctica is therefore governed by the club of Antarctic nations.

However, research is far from being the only human activity in the region. While commercial whaling is now prohibited, fishing is still permitted in some parts of the Southern Ocean. Catch quotas are limited and compliance is strictly monitored by the Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR). Environmentalists nevertheless criticize the fishing activity as a major intervention in the sensitive polar ecosystems. In addition, tens of thousands of cruise-ship passengers visit Antarctica each year, and the number is rising. The passage of ships cruising by the tourist highlights on the Antarctic Peninsula has now increased to such an extent that experts believe it is causing widespread damage to the native flora and fauna. Another problem is that an accident at sea requires search and rescue units to rush to the area from some distance away, and ice conditions – which are hard to forecast – can make rescue efforts very difficult.

Shipping along the Arctic coasts, too, is increasing, driven partly by the growing number of cruise ships but to a large extent by the increased resource mining activity in northern Russia, Scandinavia and North America. The Arctic is rich in minerals: one study estimates that 22 per cent of the world's undiscovered oil and gas reserves lie north of the Arctic Circle. Coal, iron ore, rare earths and other minerals are also found in the region. Mining these resources could well become an attractive economic prospect for the Arctic nations, because global demand is increasing and the retreat of the ice is facilitating access to the northern regions. Russia alone plans to spend more than 160 billion US dollars in the coming years on developing the economies of its Arctic territories and expanding the Northern Sea Route. Financially powerful partner countries such as China and Saudi Arabia are supporting these plans in the hope that bilateral cooperation or participation in projects will secure them rights of access to Arctic resources.

Their economic strategies may be legitimate, but genuine farsightedness on climate issues is in short supply. Furthermore, growing ambitions in the Arctic seem to be leading to new political power struggles. The zone of peace, as the Arctic was termed for a short time after the Cold War, has once again become a geopolitical arena of hard-won compromises and wrangling over common interests. The same applies to the Antarctic. At the same time, joint solutions are urgently needed to protect the climate and the polar regions. As long as humankind carries on extracting and burning fossil fuels on a large scale, the heat spiral and the melting of the ice in the polar regions will continue – with catastrophic consequences for the whole world. Climate change has now become a climate crisis. A resolute approach is therefore required from all states to mitigate its impacts so that the Earth can continue to provide a suitable habitat for present and future generations.

Glossary

The Glossary explains the meaning of specialist terms which are particularly important for an understanding of the text but which cannot be defined in the individual chapters due to space constraints. Glossary terms are printed in bold in the body of the review, making them easy to identify.

Antarctic Polar Front: This term is sometimes used as a synonym for the Antarctic Convergence, and it designates the northern boundary of the Southern Ocean. In this 30- to 50-kilometre-wide zone, cold, northward-flowing surface water from the Antarctic region meets warmer, southward-flowing surface water from the temperate latitudes of the Atlantic, Pacific or Indian Oceans. Because the cold Antarctic water, at around two degrees Celsius, is more dense and heavier than the warmer eight-degree water from the north, it sinks in the convergence zone and flows northward at a depth of 800 metres. The specific location of the Antarctic Convergence depends on the longitude, weather and season. Its position may shift to the north or south by up to 150 kilometres, but as a rule the Antarctic Convergence is at about 50 degrees south latitude. The sharp increase in surface-water temperature within the Antarctic Convergence forms a barrier to the northward dispersal of many polar marine organisms. These are practically non-existent north of the Antarctic Polar Front because the water is too warm for them there.

North Atlantic Current: warm surface current that is a continuation of the Gulf Stream extending from Newfoundland to Europe, and that transports its heat to north-western Europe. The Gulf Stream and its extension, the North Atlantic Current, are driven by winds and thermohaline circulation, i.e. by differences in salinity and temperature of the sea water. On its northward path, the waters of the North Atlantic Current release large quantities of heat into the atmosphere, thus contributing to the mild climate in north-western Europe.

Condense: A substance condenses when it transforms from a gaseous to a liquid state. The process of condensation is therefore the reverse of evaporation. The phase transition from water vapour to liquid water is one of the basic physical processes in the Earth's water cycle. Without it the water vapour contained in the air would not form fog, clouds or raindrops. The condensation of water vapour, however, is dependent on to two conditions. For one, the air has to be at least slightly oversaturated with water vapour. For the other, it is necessary to have particles suspended in the air that act as condensation nuclei.

Geostrophic: This term is commonly used in the fields of meteorology and oceanography, where it is used in the context of geostrophic equilibrium, a state of equilibrium that occurs in the atmosphere or in the ocean if only the Coriolis force and the horizontal pressure gradient force are taken into account and the two forces cancel each other out. As a result, a geostrophic wind or a geostrophic current is generated that is directed perpendicular to the pressure gradient force.

Ilulissat Declaration: a legally non-binding declaration signed by the five Arctic coastal states Canada, Denmark, Norway, Russia and the USA on 28 May 2008 in Ilulissat, Greenland. The countries promised to resolve intra-Arctic conflicts peacefully, to protect the Arctic environment, particularly from oil spills, to promote stricter environmental guidelines within the International Maritime Organization (IMO), to expand air and sea rescue along their Arctic coasts, and to cooperate more closely in research. Additionally, the five states emphasize in this declaration that there is no need for a new UN agreement to resolve intra-Arctic territorial disputes, but that the five Arctic coastal states will resolve all conflicts on the basis of the international law of the sea.

Ottawa Declaration: a document signed by the eight Arctic countries Canada, Denmark, Finland, Iceland, Norway, Russia, Sweden and the USA that established the Arctic Council as an intergovernmental forum for dialogue and defined its basic functions and procedures. The Declaration was signed by the Foreign Ministers of the participating states on 19 September 1996 in Ottawa, the capital city of Canada.

Plate-tectonic processes: the movements of the various continental plates that make up the Earth's outer shell (lithosphere). These plates drift apart, collide with one another, or slide past each other, causing earthquakes and volcanism. Where two plates spread apart – like on the mid-ocean ridges – large quantities of magma rise up out of the Earth's interior and form new basaltic crust, a new, solid rock shell. In regions where two plates move toward each other, long collision zones are created in which various processes take place depending on the composition and age of the two plates.

Abbreviations

ACGF Arctic Coast Guard Forum

AECO Association of Arctic Expedition Cruise Operators

AEPS Arctic Environmental Protection Strategy

AMAP Arctic Monitoring and Assessment Programme

AMOC Atlantic Meridional Overturning Circulation

ARCSAR Arctic and North Atlantic Security and Emergency Preparedness Network

ARGO Array for Realtime Geostrophic Oceanograph

ASFR Arctic Security Forces Roundtable

ASOC Antarctic and Southern Ocean Coalition

ATCM Antarctic Treaty Consultative Meeting

ATS Antarctic Treaty System

AWIPEV: German-French Arctic research station operated by the Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research (AWI) and the Polar Institute Paul-Émile Victor (IPEV) in Ny-Ålesund on Spitsbergen, Svalbard

CAFF Conservation of Arctic Flora and Fauna

CAMLR Convention on the Conservation of Antarctic Marine Living Resources

CARA Circum-Arctic Resource Appraisal

CBD Convention on Biological Diversity

CCAMLR Commission for the Conservation of Antarctic Marine Living Resources

CCAS Convention for the Conservation of Antarctic Seals

CLCS Commission on the Limits of the Continental Shelf

CNPC China National Petroleum Corporation

COMNAP Council of Managers of National Antarctic Programs

CRAMRA Convention on the Regulation of Antarctic Mineral Resource Activities

EEZ Exclusive economic zone

EPPR Emergency Prevention, Preparedness and Response

FAO Food and Agriculture Organization of the United Nations

GRACE Gravity Recovery and Climate Experiment

IAATO International Association of Antarctica Tour Operators

ICCAT International Commission for the Conservation of Atlantic Tuna

ICES International Council for the Exploration of the Sea

IMO International Maritime Organization

IPCC Intergovernmental Panel on Climate Change

ISA International Seabed Authority

LNG Liquefied Natural Gas

MARPOL International Convention for the Prevention of Marine Pollution from Ships

MSC Munich Security Conference

NAFO Northwest Atlantic Fisheries Organization

NATO North Atlantic Treaty Organization

NEAFC North East Atlantic Fisheries Commission

NEGIS North East Greenland Ice Stream

NSR Northern Sea Route

PAME Protection of the Arctic Marine Environment

PANC Patrulla Antártica Naval Combinada

ppm parts per million

RFMO Regional Fisheries Management Organisation

RuBisCO Ribulose-1,5-bisphosphat-carboxylase/-oxygenase

SAR Search and Rescue

SCAR Scientific Committee on Antarctic Research

SCR Suez Canal Route

SOLAS International Convention for the Safety of Life at Sea

UNCCD United Nations Convention to Combat Desertification in those Countries Experiencing Serious Drought and/or Desertification, particularly in Africa

UNCLOS United Nations Convention on the Law of the Sea

UNFCCC United Nations Framework Convention on Climate Change

USGS United States Geological Survey

UV ultraviolet

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Contributors

Many experts have contributed their specialized knowledge to the compilation of the *World Ocean Review* in 2019. These included, in particular, scientists working in one of the member institutions of the German Marine Research Consortium (KDM).

Prof. Dr. Peter Braesicke is an atmospheric research scientist at the Institute of Meteorology and Climate Research – Atmospheric Trace Gases and Remote Sensing (IMK-ASF) which is part of the Karlsruhe Institute of Technology (KIT). He heads the modelling group at IMK-ASF and in his numerous studies addresses the detailed interactions between atmospheric composition and the climate. He is a member of the lead author team of the current Scientific Assessment of Ozone Depletion: 2018 and heads the Helmholtz-Climate-Initiative Regional Climate Change (REKLIM) as its scientific coordinator. REKLIM is a consortium of nine research centres within the Helmholtz Association that engage in joint transdisciplinary research on the regional impacts of climate change.

Dr. Harald Elsner is a research geologist and expert on mineral raw materials at the Federal Institute for Geosciences and Natural Resources (BGR) in Hannover. He observes the global markets for raw materials and in his studies regularly addresses the questions as to which raw materials are in demand, the size of their existing reserves, and the degree to which these deposits could in future be exploited, if at all. In particular, he focuses on rare earths, i.e. "high-tech" metals that will be needed for future technologies, on heavy minerals, and also on the mass raw material sand.

Dr. Klaus Grosfeld is a research geophysicist at the Climate Sciences Division of the Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research (AWI) in Bremerhaven. His research focus is on mass balances of the polar ice sheets and their contribution to global sea-level rise. Moreover, he is Managing Director of the Helmholtz-Climate-Initiative Regional Climate Change (REKLIM) and heads the Knowledge Transfer Research Unit at the Alfred Wegener Institute. At this research unit, Klaus Grosfeld and his colleagues develop ideas for new formats, products and measures designed to inform the wider public as well as decision-makers in the business world, the policy sphere and society at large on important developments in the polar regions and to provide advice.

Prof. Dr. Julian Gutt is a marine ecologist at the Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research (AWI) in Bremerhaven. He studies benthic communities of the Southern Ocean in terms of their diversity, ecosystem functions and vulnerability to environmental change. To this end, he primarily uses imaging methods as they spare the ecosystem from damage and depict the benthic communities in their natural state. He has conducted these investigations in the course of numerous expeditions to the Arctic and Antarctic, twice as chief scientist on board of the German research icebreaker *Polarstern*. Julian Gutt contributes his polar expertise and many years of experience to numerous international organizations, such as the Scientific Committee on Antarctic Research and the policy-advising Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES).

Dr. Stefan Hain heads the Environmental Policy Staff Unit at the Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research (AWI) in Bremerhaven. Among other roles as part of this function, he is the institute's contact person for the Federal Environment Agency (UBA), Germany's regulatory body for all activities within the remit of the Antarctic Treaty. The marine biologist completed his doctorate at the AWI and then worked at the interface of science and policy for more than 25 years. One of his positions was as Head of the Coral Reef Unit of the United Nations Environment Programme in Cambridge, UK. In 2009 he returned to the AWI and since then he has been working as the institute's environmental policy spokesperson, coordinating AWI's contributions to a variety of international processes which could potentially impact on the institute's research activities, especially those in the Antarctic. He invests a particularly great amount of time and energy in the German-European project to establish a Marine Protected Area in the Weddell Sea. The application for the designation was prepared by the AWI. However, the relevant negotiations at the Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR) are difficult and protracted.

Dr. Hartmut H. Hellmer works as a physical oceanographer at the Physical Oceanography of Polar Seas Section of the Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research (AWI) in Bremerhaven. His focus is on the interactions between the polar marginal seas and the ice shelves, i.e. the floating extensions of the Antarctic ice sheet. His investigations resulted in the mathematical formulation and numerical implementation of thermohaline exchange processes at the ocean/ice-shelf interface, as well as BRIOS, the first coupled ice-ocean model for the southern hemisphere. The simulations using this model have shown that the expected warming in the Antarctic may result in changes in the southern Weddell Sea circulation, which transports warm water masses into the cavities of adjacent ice shelves. The associated increase in basal melting can reduce the buttressing effect of an ice shelf and result in the accelerated loss of inland ice which in turn would contribute to sea-level rise.

Dr. Heike Herata has been Head of the Protection of the Arctic and Antarctic Section at the German Federal Environment Agency (UBA) since 2006. Prior to taking this position, the hydrologist had studied and completed her doctorate at the Technical University of Dresden and was a research associate at the Institute of Water Management (Institut für Wasserwirtschaft) in Berlin. In 1991 she became a research associate at the Federal Environment Agency, working first on marine protection and later in the Discharges and Inputs to Surface Waters Section. As part of her current position she is in charge of enforcing the German Act implementing the Protocol on Environmental Protection to the Antarctic Treaty (AUG), which makes her the Head of the national regulatory body for the Antarctic. Additionally, at the international level she contributes to the work of the ATCM, CCAMLR and IAATO. In 2014 her role was expanded to include the protection of the Arctic. As part of this role, Heike Herata is involved in negotiations conducted in the Arctic Council and in the IMO.

Dr. Thomas Hollands is an expert on remote sensing data and on observations of sea-ice movement from space. From 2009 to 2019 he was a research associate of the Earth Observations Systems working group of the Polar Meteorology Section at the Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research (AWI) in Bremerhaven. During this time the geoscientist completed his doctorate on motion tracking of sea ice with satellite data. His subsequent work included the development of methods allowing for the observation and classification of polynya events by combining a number of different satellite sensors. Based on these data it is possible, for example, to estimate the amount of sea ice produced in the polynya.

Prof. Dr. Angelika Humbert is a glaciologist at the Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research (AWI) in Bremerhaven where she leads the working group on ice-sheet modelling. The aim of this working group is to develop an understanding of the physical processes underlying the flow of ice in ice sheets, ice streams and glaciers that is sufficiently precise to allow for their expression as mathematical formulas in computer-based ice models, which will help to predict the dynamics of ice masses, their future development and their contribution to sea-level rise. To this end, the ice modelling team conducts both process and systems studies. In process studies the scientists model, for example, the effects of subglacial water, warming of the ice, or the migration of the grounding lines of glaciers or ice shelves. Systems studies include investigations of the behaviour of entire ice sheets or of individual ice-stream/ice-shelf systems, such as the Recovery Glacier or the Filchner Ice Shelf.

Dr. Ralf Jaiser is a physicist working as a climate modeler in the Atmospheric Physics Section of the Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research (AWI) in Potsdam. He specializes in the large-scale circulation of air masses up into the stratosphere and its change over time. Instead of measuring the circulation patterns himself, Dr. Jaiser analyses the many datasets available from climate models. Among other outcomes, his research contributes to understanding how sea-ice decline in the Arctic Barents Sea and Kara Sea weakens the jet stream and thus also impacts mid-latitude weather.

Dr. Sebastian Knecht is a research associate at the Sociology Faculty of the University of Bielefeld. His research mainly focuses on international relations, geopolitical narratives, institutional change and the transfer of scientific knowledge with regard to polar and maritime governance. He is coeditor of the book *Governing Arctic Change: Global Perspectives* (Palgrave Macmillan) and co-author of the German language introductory textbook on international policy and governance in the Arctic entitled *Internationale Politik und Governance in der Arktis: Eine Einleitung* (Springer).

Dr. Gert König-Langlo studied meteorology at the University of Hamburg and, following his graduation, overwintered at the German Georg von Neumayer Antarctic research station. He has been fascinated by the Antarctic ever since. In 1989 he became a research associate at the Alfred Wegener Institute for Polar and Marine Research (AWI) where he became scientific leader of the meteorological observatories at the Neumayer Antarctic research station and on the German research icebreaker *Polarstern*. Both of these observatories collect long-term meteorological data for climate research. For several years up until his retirement in 2017, Gert König-Langlo was also Director of the World Radiation Monitoring Center (WRMC), which as the central archive of the Baseline Surface Radiation Network (BSRN) makes available to climate scientists the best possible surface radiation measurements.

Dr. Thomas Krumpen is a sea-ice physicist conducting research at the Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research (AWI) in Bremerhaven. The focus of his work is on the impact of climate change on Arctic and Antarctic sea ice. In particular he is interested in determining which atmospheric and oceanographic processes govern changes in the polar regions and in determining the implications for sea-ice-associated ecosystems and biogeochemical cycles resulting from the changing ice cover. To these ends, he draws on satellite data that provide information on changes in sea-ice thickness and spatial extent over the past 35 years. The satellite data are supplemented with measurements taken as part of expeditions of the research vessel *Polarstern* or by the *Polar 5* and *Polar 6* polar research aircraft. The focus of these measurements is on recording ice thickness in key Arctic regions by means of a sensor called the "EM-Bird".

Dr. Stefan Kruse works as an ecologist and vegetation modeller in the Polar Terrestrial Environmental Systems research group at the Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research (AWI) in Potsdam. Changes in polar vegetation in the wake of current climate change are his specialty area, and in particular changes of the treeline. To this end, he studies areas of tundra and forest with varying species composition and vegetation density, and records tree growth using dendroecological methods. Moreover, the scientist uses the genetic information of individual trees in order to draw conclusions on their short-distance and long-distance distribution. He processes the data collected in an individuals-based forest computer model that he himself has programmed. The model makes it possible to apply climate scenarios in order to test the impacts of warming on the vegetation. For example, Stefan Kruse was able to show that the treeline is moving northward at a much slower pace than warming currently allows.

Dr. Andreas Läufer has been Head of the Polar Geology Unit at the German Federal Institute for Geosciences and Natural Resources (BGR) in Hannover and is a specialist on Antarctic geology and geodynamic processes. In order to understand these processes, the structural geologist has undertaken regular research expeditions to the Antarctic over the past 30 years. One of his target areas is Victoria Land with the adjacent Ross Sea region, where he uses geological and geophysical methods to study rocks not covered by ice in order to identify indicators that allow for a reconstruction of the formation and breakup of the southern supercontinent Gondwana.

Prof. Dr. Cornelia Lüdecke teaches the history of natural science at the University of Hamburg and has been a corresponding member of the International Academy of the History of Science in Paris since 2012. For almost 30 years now she has been leading the History of Polar Research working group of the German Society of Polar Research and since 2004 she has chaired the History of Antarctic Research Expert Group of the Scientific Committee on Antarctic Research (SCAR). She has authored 18 monographs and more than 180 papers on the history of meteorology, geography, oceanography and polar research. Since 2012 she has also been Vice President of the International Commission of the History of Oceanography.

Dr. Stefanie Lutz is a microbiologist and expert on the diversity and ecology of microorganisms in cold environments, and especially in the Arctic. For her PhD thesis at the University of Leeds she investigated pigmented snow and ice algae and their contribution to the darkening of glacial surfaces in the Arctic and Antarctic. She thus contributed to an understanding of the degree to which snow and ice algae increase the rate of glacial surface melting. As a postdoctoral research assistant at Helmholtz Centre Potsdam – German Research Centre for Geosciences (GFZ) she continued this research at the interface of microbiology, microbial ecology and bioinformatics and was involved, for example, in the Black & Bloom interdisciplinary research project in Greenland. She currently works as a research associate at Agroscope in Switzerland.

Dr. Felix Mark is a marine biologist and research scientist at the Integrative Ecophysiology Section of the Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research (AWI) in Bremerhaven. He has specialized in physiological adaptation mechanisms of marine ectotherms and investigates the organisms' responses to marine warming, ocean acidification and oxygen depletion, from the organism as a whole down to the molecular level, and with a particular focus on polar fish. Felix Mark undertakes regular expeditions to the polar seas and was the consortium leader of "Theme 3: Ocean Acidification and Warming Impacts Across Natural Systems and Society: From Mechanisms to Sensitivities and Societal Adaptation" as part of the major German research programme on Biological Impacts of Ocean Acidification (BIOACID).

Dr. Marion Maturilli is an atmospheric physicist at the Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research (AWI) in Potsdam and is responsible for the Meteorological Observatory of the German-French AWIPEV research base in Ny-Ålesund, Svalbard. Using the long-term meteorological data collected at the observatory, she investigates climatic changes in Svalbard and in the European part of the Arctic, with a focus on the occurrence of low-pressure areas and on the changing atmospheric heat and moisture transport into the Arctic. In a number of different studies, the atmospheric researcher has also combined observational data from terrestrial surfaces, oceans and sea ice in order to improve the understanding of the complex interactive processes at play in the Arctic and their contributions to "Arctic amplification".

Dr. Michaela Mayer has been working as a marine biologist and ornithologist in the polar regions since 1994. The sites of her research work have included on board the German research icebreaker Polarstern, at the German-French AWIPEV research base in Ny-Ålesund, Svalbard, and at the Argentinian Antarctic research station Carlini on King George Island. When she is not on a research expedition, the scientist manages a private institute for sustainable activities at sea (Institut für Nachhaltige Aktivitäten auf See, INASEA), which she established in Bremen, and where she carries out studies on environmental impacts of tourism, shipping, offshore projects and other human activities at sea, develops strategies for reconciling environmental protection and cost-effective project implementation, and advises companies on environmental management issues.

Prof. Dr. Bettina Meyer is Head of the working group on "Ecophysiology of pelagic key species" at the Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research (AWI). The aim of her working group is to identify physiological bottlenecks in the life cycles of pelagic key species such as krill, calanoid copepods and salps, to investigate their productive and adaptive capacity with regard to (anthropogenic) environmental change, and to understand the impact of these species in biogeochemical cycles. The data obtained are taken into account in individuals-based modelling and in ecosystem models that allow for predictions of population changes in key organisms and for an understanding of the ecosystem-level impacts of these changes.

Dr. Katja Mintenbeck is a research marine biologist at the Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research (AWI) in Bremerhaven. Her work focuses on the ecology of Antarctic marine biocoenoses and the sensitivity of Antarctic fish to disturbances and environmental change. Since 2017 she has also worked as the Scientific Director of the IPCC Working Group II Technical Support Unit. As part of this role she was responsible for the IPCC Special Report *Ocean and Cryosphere in a Changing Climate*, published in September 2019.

Dr. Juliane Müller is a geoscientist at the Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research (AWI) in Bremerhaven, where she heads PALICE, the Helmholtz Young Investigator Group. The aim of PALICE is to investigate changes in polar sea-ice cover and associated shifts in oceanic and atmospheric circulation patterns during past climate fluctuations. To this end, the team analyses marine sediment cores, searching for fossil organic molecules, i.e. biomarkers, preserved in the sediment. These allow the scientists to determine if and when the region in which the core was taken was covered with sea ice. The resultant data are an important basis for the development and testing of climate models.

Dr. Ilka Peeken is a research sea-ice ecologist at the Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research (AWI) in Bremerhaven where she studies the ecology, biogeochemistry and pollution of sea ice. She primarily focuses on the interconnections between sea ice and the various organisms living in or underneath the ice with a view to determining the extent to which climate change is altering sea-ice habitats and what these changes mean for the marine environment. To this end she takes sea-ice samples in the course of numerous expeditions, analyses the species diversity of the marine organisms living in the sea ice, studies the role of these species in the global carbon cycle, and looks at the impacts of the shift from multi-year ice to one-year ice on the ecosystem's biodiversity and carbon production. As a parallel endeavour, she measures sea-ice pollution by microplastic particles and investigates the impact of this pollution on sea-ice organisms.

Dr. Karsten Piepjohn is a polar geologist at the German Federal Institute for Geosciences and Natural Resources (BGR) in Hannover where he investigates the geodynamics of continental margins around the Arctic Ocean. His focus is on the initial opening of the Arctic Ocean and related magmatism, the development of sedimentary basins, and the formation of a deformation belt extending from Svalbard across northern Greenland to far into the Canadian Arctic, which is connected to the opening of the Eurasian Basin of the Arctic Ocean.

Prof. Dr. Alexander Proelß is a legal scholar and lecturer on international maritime and environmental law, international law and public law at the Law Faculty of the University of Hamburg. In addition to aspects of general international and European law, his areas of research primarily include international environmental law and the law of the sea, foreign constitutional law and selected areas of national environmental law. He is involved in numerous national and international research projects and also contributes his expertise to major projects such as the Priority Programme on Climate Engineering of the German Research Foundation (DFG).

Dr. Benjamin Rabe is a research oceanographer at the Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research (AWI) in Bremerhaven where he investigates the composition and circulation of Arctic Ocean water masses. Together with a Swedish colleague he is coordinating the oceanographic research to be undertaken during the year-long drift in the Arctic by the German research icebreaker *Polarstern* (MOSAiC expedition). In the autumn of 2019, the ship will let itself get trapped in the sea ice north of Siberia and will then drift in the pack ice for an entire year across the North Pole and toward the Fram Strait. During this time, scientists from seventeen nations will study the sea ice, as well as the ocean beneath and the atmosphere above it, in order to determine how these components of the polar climate system interact and which of the interactions give rise to the rapid decline of the Arctic sea ice.

Dr. Volker Rachold is Head of the German Arctic Office at the Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research (AWI). In this role, the former permafrost researcher and long-term Director of the International Arctic Science Committee (IASC) advises the German federal government on questions related to the Arctic. For example, he substantively prepared the 2nd Arctic Science Ministerial Conference on behalf of the German Federal Ministry of Education and Research. On behalf of the Federal Foreign Office he supported the German representatives in the Arctic Council's Arctic Monitoring and Assessment Programme (AMAP) working group. His own scientific career began as a geochemist, a scientific discipline in which he completed his doctorate and postdoctoral habilitation.

Dr. Thomas Rackow studied technomathematics and completed his studies with a thesis on iceberg drift. He subsequently completed his doctorate in physics at the University of Bremen. Since 2015 he has been working as a climate modeller at the Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research (AWI) in Bremerhaven where he studies mechanisms that give rise to climate variability. His aim is to integrate processes currently missing from contemporary climate simulations, such as minor eddies or iceberg drift, and to thereby improve the resultant climate predictions. Thomas Rackow is also involved in science communication. For example, as part of the MOSAiC Summer School on board the Russian icebreaker *Akademik Fedorov* he taught 20 international Masters and PhD students how to mathematically predict the motions of sea ice and drifting objects such as icebergs.

Dr. Christoph Ritter is an atmospheric research physicist at the Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research (AWI) and he spends an average of seven weeks every year at the Meteorological Observatory of the German-French AWIPEV Arctic research base in Ny-Ålesund, Svalbard. At AWIPEV he uses the LIDAR system – an instrument consisting of a laser, a telescope and a counting unit – to shoot laser pulses several kilometres up into the sky and measure their reflection in order to study atmospheric aerosols. His aim is to determine as precisely as possible the distribution of different aerosol types present in the atmosphere with a view to improving the simulations by climate models of the aerosols' impact on the climate.

Dr. Ingo Sasgen is a geoscientist at the Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research (AWI) in Bremerhaven. He uses satellites to study the growth and shrinkage of the polar ice sheets. Among other things, this allows the remote sensing expert to draw conclusions on the meltwater contributions to global sea-level rise made by Greenland and the Antarctic. He also combines satellite data on the gravitational field of the ice masses with radar data on changes in the elevation of the ice surface. This makes it possible for him to show in high resolution the regions in which the ice sheets are shrinking at a particularly fast rate and how the ice-loss zones are expanding over time. Together with a colleague at the AWI he is currently developing a new statistical forecasting method for predicting mass flux of the Greenland Ice Sheet.

Prof. Dr. Ursula Schauer is an oceanographer at the Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research (AWI) in Bremerhaven. In the course of her science career she has led several expeditions of the German research icebreaker *Polarstern* to the Arctic. She is a distinguished expert on the Arctic Ocean circulation. Her research work includes investigations of deep-water formation in the far north, long-term changes in the temperature and salinity of the Arctic Ocean, and interactions between the ocean and extensions of the Greenland Ice Sheet. The knowledge that between 1980 and 2010 Greenland Sea deep-water warming has been about ten times higher than average warming rates estimated for the global ocean is one of the products of her studies and measurements.

Dr. Stephan Schiffels is Leader of the Population Genetics group at the Max Planck Institute for the Science of Human History in Jena. His research aims at reconstructing global relationships among population groups as well as prehistoric population movements. To this end he analyses and compares genetic data obtained from archaeological sites (DNA from skeletal remains) with those of people currently alive. As a parallel endeavour, the scientist – who holds a doctorate in physics – developed new statistical and bioinformatics methods that allow for the ever more sizeable sets of genetic data to be processed and investigated. Among other activities, he led an international study in 2019 on the genetic origins of the North American First Peoples, especially of those in the American Arctic. The results of the study were published in the journal *Nature*.

Dr. Volker Strass is a seafaring oceanographer at the Physical Oceanography of Polar Seas Section of the Climate Sciences Division at the Alfred Wegener Institute (AWI) in Bremerhaven. His scientific research covers a broad range of topics, ranging from the large-scale meridional ocean circulation to the mesoscale dynamics of fronts and eddies, and down to small-scale turbulent fluxes between the ocean's surface mixed layer and the atmosphere. In this context he is particularly interested in those climate-relevant processes that govern oceanic heat and carbon uptake. With regard to carbon uptake, he also concerns himself with biogeochemical cycles and engages in interdisciplinary research on the impact of physical processes on photosynthesis, and – using acoustic techniques – on interactions between phytoplankton and zooplankton and the resultant sinking of organic matter. Most of his research expeditions take Volker Strass to the Southern Ocean, primarily to the Antarctic Circumpolar Current region and into the Weddell Sea.

Dr. Jens Strauss is a geoecologist who heads the working group on Permafrost Biogeochemistry of the Permafrost Research Section at the Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research (AWI) in Potsdam. He has specialized in deep ice-rich permafrost (Yedoma) and his research strives to determine the size of the organic carbon pool frozen in Yedoma, the quality of this carbon, and the speed at which it may be broken down by microorganisms and released in the form of greenhouse gases if it thaws. His field research serves as a basis for models that calculate the quantities of carbon dioxide and methane naturally emitted in the event of large-scale permafrost thawing. Jens Strauss is currently the lead scientist on a project addressing this issue. The project entitled Changing Arctic Carbon Cycle in the Coastal Ocean Nearshore (CACOON) is co-financed by the German Federal Ministry of Education and Research.

Dr. Johannes Sutter is an ice modeller at the Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research (AWI) in Bremerhaven and at the Climate and Environmental Physics division of the University of Bern. His research focuses on the question of how Antarctic ice masses reacted to past warm periods, and he develops scenarios with regard to the contribution to sea-level rise by the Antarctic Ice Sheet as a result of future climate change. His ice-sheet modelling has helped in the search for ideal drill sites for the "Beyond EPICA – Oldest Ice" international research project in the course of which glaciologists endeavour to retrieve ice cores from the oldest ice in Antarctica.

Prof. Dr. Jörn Thiede is a geologist and palaeontologist. Since 2011 he has been the Director of the Köppen Laboratory of the Institute of Earth Sciences at Saint Petersburg State University/RF. Earlier in his career, the Professor of Palaeo-Oceanography in Kiel had worked as the foundational Director of the Research Centre for Marine Geosciences, a precursor to the current GEOMAR Helmholtz Centre for Ocean Research Kiel. He subsequently became the Director of the Alfred Wegener Institute for Polar and Marine Research (AWI) in Bremerhaven, a position he held for ten years. He has travelled all the world's oceans as part of national and international expeditions on research vessels with a view to understanding the history of the oceans' physiography, their water masses, and the organisms that inhabit them. Jörn Thiede has received numerous prestigious research awards for his scientific achievements and been inducted into science academies at home and abroad.

Dr. Renate Treffeisen is the Head of the Climate Office for Polar Regions and Sea Level Rise at the Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research (AWI) in Bremerhaven. As part of this role, the former atmospheric research scientist develops innovative formats for conveying research results from the polar regions that allow them to be utilized by decision-makers in the policy sphere, the business world and society at large. In her additional role as science editor, she also administers the meereisportal.de online portal in which sea-ice researchers at the AWI and the University of Bremen make available sea-ice data and regularly publish analyses on the development of the Arctic and Antarctic ice sheets.

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Partners

Future Ocean: The Kiel-based research network harnesses the collective knowledge of marine scientists, economists, medical scientists, mathematicians, legal scholars and social scientists in pursuit of the study of oceanic and climate change. A total of more than 250 scientists working at Kiel University (CAU), GEOMAR Helmholtz Centre for Ocean Research Kiel, Kiel Institute for the World Economy (IfW) and the Muthesius University of Fine Arts and Design join forces to develop options for sustainable marine protection and exploitation.

IOI: The International Ocean Institute is a non-profit organization founded by Professor Elisabeth Mann Borgese in 1972. It consists of a network of operational centres located all over the world. Its headquarters are in Malta. The IOI advocates the peaceful and sustainable use of the oceans.

KDM: The German Marine Research Consortium combines the broad expertise of German marine research. Its membership comprises all of the research institutes that are active in marine, polar and coastal research. A primary objective of the KDM is to collectively represent the interests of marine researchers to national policy-makers and the EU as well as to the general public.

mare: The bimonthly German-language magazine *mare*, which focuses on the topic of the sea, was founded by Nikolaus Gelpke in Hamburg in 1997. *mare's* mission is to raise the public's awareness of the importance of the sea as a living, economic and cultural space. Besides the magazine, which has received numerous awards for its high-quality reporting and photographs, its publisher mareverlag also produces a number of fiction and non-fiction titles twice a year.

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Producing a publication like the *World Ocean Review* is a collective effort which relies on the dedication and commitment of a large number of people. I would therefore like to first express my thanks to all the participating scientists for their contributions to this review. I am also most grateful to the organizational team of the German Marine Research Consortium and the The Future Ocean Network in Kiel for ensuring a smooth and uninterrupted communication process and for working so hard behind the scenes.

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Nikolaus Gelpke
Managing Director of maribus gGmbH

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