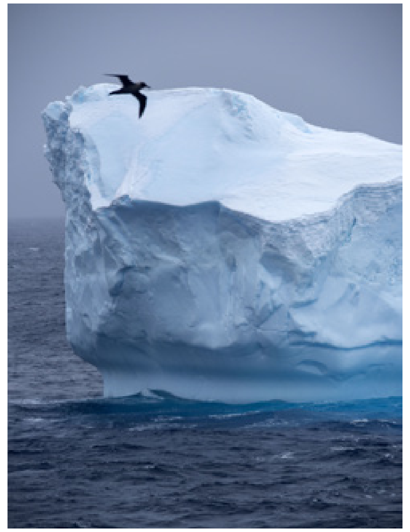
KENICHI MATSUOKA (EDITOR)

Life of the Antarctic ice

From deep inland to the coast



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Life of the Antarctic ice

From deep inland to the coast

Members of the Norwegian-British-Swedish Antarctic Expedition to the coast of Dronning Maud Land in 1949–52 send up a weather balloon. This was the first truly international scientific expedition to Antarctica.

Preface

This book tells the story of the ice in Antarctica – its creation, life and death – starting when snowflakes fall in the interior of the coldest and most remote continent on Earth and ending when the ice joins the Southern Ocean. During this journey of nearly one thousand kilometres, the gigantic Antarctic Ice Sheet has a life of its own but interacts with the Earth System at large and is inextricably linked to climate and sea level change around the globe. The Antarctic ice holds the key to some of the most prominent challenges that global society faces today. For this reason, we think the life of the Antarctic ice is a story worth telling.

Humankind has known and explored Antarctica over only a short span of time, making Antarctica a rather small tag-on to human history. The concept of a Terra Australis Incognita had its roots in the end of the antiquity and the Antarctic Circle was a barrier that remained impermeable until its crossing by Captain James Cook in 1773. The continent itself and the ice that spilled out over its edges were first seen 200 years ago. The first overwintering took place in 1899. It was Captain Carsten Borchgrevink, the Norwegian leader of the British-organised Southern Cross Expedition, who was responsible for this feat.

Many have been drawn towards this mighty landscape, surrounded by unruly oceans. Whalers, explorers, scientists, logistics operators, artists, photographers and tourists – most have returned safely having had the experience of their lives. It is in the interest of us all that Antarctica stays white, cold and pristine. This book gives some insights into why this is important.

This book is written by Antarctic specialists who are part of the huge global team endeavouring to unlock the secrets of the Antarctic ice. These scientists, along with expert supporting personnel, have spent months on the ice studying details that build and refine our understanding of the dynamics of the Antarctic ice, bringing us ever closer to being able to assess the impact of Antarctica on the global climate and the future of humans. This is a mission well worth all those hours working during the Antarctic field season under the glaring summer sun on foot, in vehicles humping over the ice and in airplanes landing on runways of ice. And then, in between fieldwork, there are all those hours devoted to scrutinising satellite data and developing computer models. For the people who get to do this work it feels like a great privilege.

Antarctica is an Eldorado for photographers. Most pictures in this book were taken by scientists and logistics operators while working in the field. They illustrate a story of ice and climate, as well as portraying the challenging conditions to which local animal species are marvellously adapted through evolution and to which humans must strive clumsily to adapt through our technology.

We hope you will enjoy reading and learning about the Antarctic ice and this remote and very important continent. We are sure you will understand why the Antarctic specialists who wrote this book have all fallen in love with this beautiful and fascinating place.

Tromsø, Norway
July 2020

Ole Arve Misund

OLE ARVE MISUND
Director, Norwegian Polar Institute

1

Remote Antarctica in the global picture

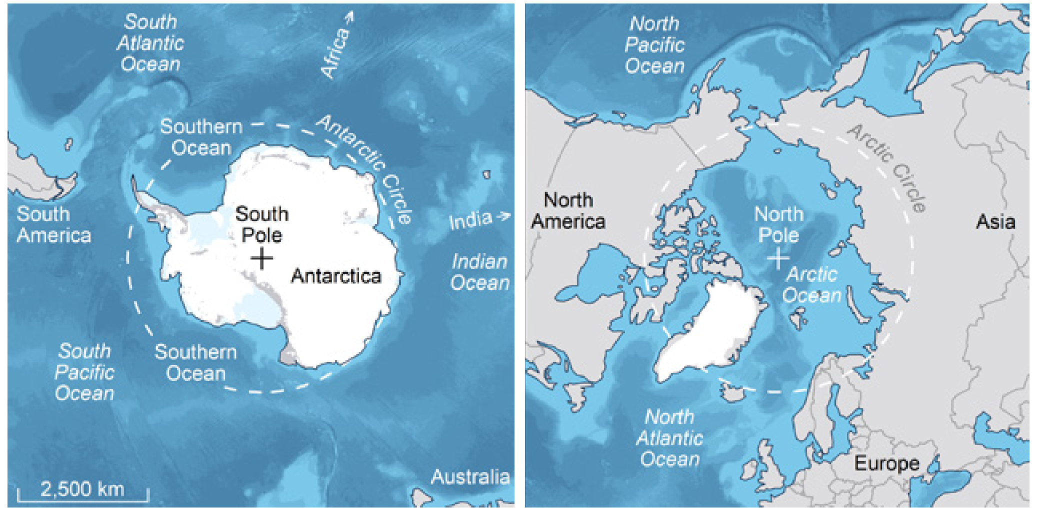
Antarctica is the Earth's coldest, whitest and windiest continent. It is almost totally covered by an ice sheet as thick as 4.5 km in some places. The shoreline is mostly edged by glacier ice hundreds of metres thick – stretching from the continent into the ocean. The changes and instability of these ice masses could impact the whole planet.

Both ends of the world

People often compare the Antarctic and the Arctic, the extreme ends of our planet. Both polar regions experience midnight sun in their summer months, when the sun stays above the horizon day and night, and long polar nights in the winter, when the sun does not even appear in the daytime. The duration of the midnight sun and polar night periods depends on how close you are to the poles; they last half a year at both the North and South poles. When you are near the Arctic Circle at 66.5°N and the Antarctic Circle at 66.5°S, these periods last only a single day.

Apart from these symmetrical features at both poles, the Antarctic and the Arctic are quite different in many ways. The Antarctic is a single continent, whereas the Arctic is composed of the North American and Eurasian continents as well as Greenland, Svalbard and many other small archipelagos. The Antarctic continent is mostly covered by one massive ice sheet – only 0.4% of the continent is ice free. In the Arctic, there are many glaciers and ice caps, but the region's largest ice mass, the Greenland Ice Sheet, makes up only 12% of the area of the Antarctic Ice Sheet.

The Antarctic Ice Sheet is roughly a circle 4,500 km in diameter, covering most of the continent, including the South Pole. This area is roughly half the size



Antarctica is a continent surrounded by ocean, whereas the Arctic can be said to be the opposite: an ocean surrounded by land and dotted with islands and archipelagos.

An autumn evening falls over Lemaire Channel, Antarctic Peninsula.

Antarctica is roughly 1.5 times the size of the USA or China, 5 times India, 20 times France or Chile and 35–40 times Germany, Norway or Japan.

of the African continent and twice as big as the Australian continent.

Antarctica's shoreline is mostly edged by floating glacier ice – hundreds of metres thick – that stretches from the continent into the ocean. Forming what are known as ice shelves, this floating ice around the giant ice sheet accounts for about 12% of Antarctica's icy surface and blankets an ocean area about the size of the Mediterranean Sea and slightly larger than the Greenland Ice Sheet.

Well-known ice top and poorly known ice bottom

Scientists use satellite techniques to determine the height above sea level – the elevation – of the ice surface in Antarctica. These elevations are well known, better than in many other regions of the world. East Antarctica, facing the Atlantic and Indian oceans, is as high as 4 km in its central part. West Antarctica, facing the Pacific, is only half that height.

When you travel in Antarctica on a snow vehicle, the apparent flatness of the surface can cause you to lose your sense of direction. But what seems to be perfectly flat may be a very gently rolling landscape that can hide the vehicle you are trailing behind by a few kilometres. These undulations in the ice surface are often associated with the terrain under the ice – what is known as the bed. Ice surface topography is affected by ice flow and bed topography.

Did you know …

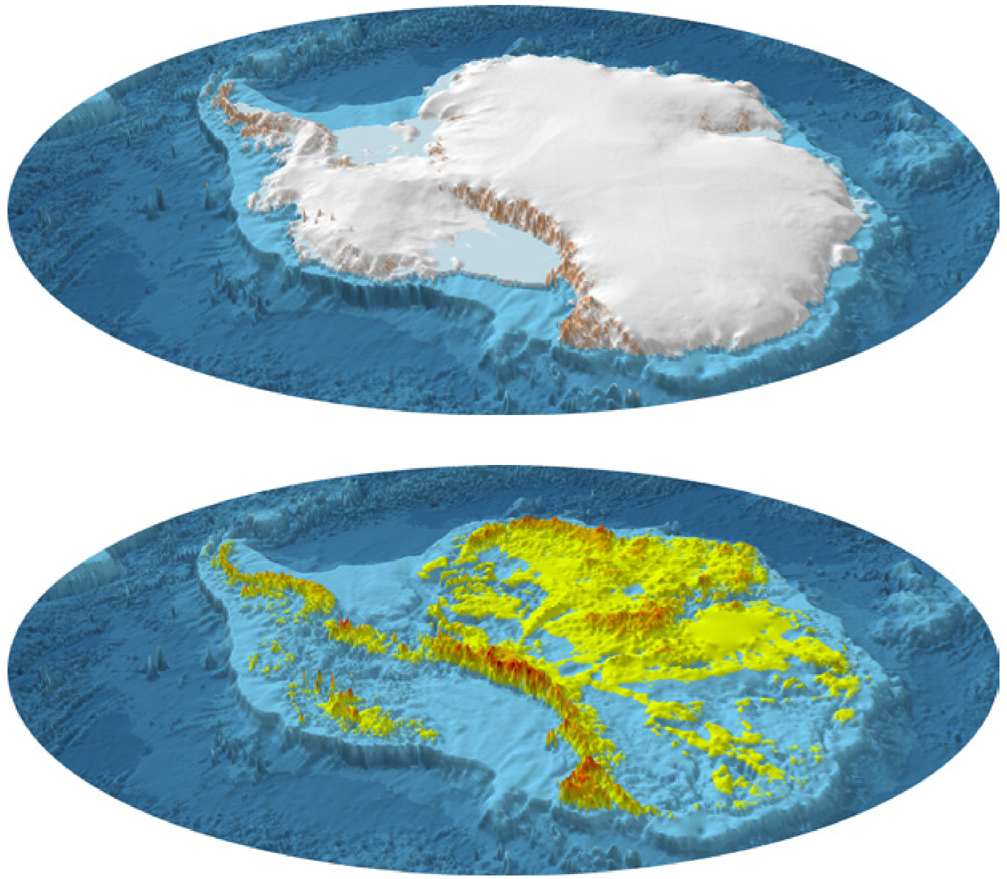
… that the deepest point on land in Antarctica is 3.5 km below sea level?

It is covered by the Antarctic Ice Sheet. A study published in 2020 found the site under the Denman Glacier west of Wilkes Land in East Antarctica. The ice cover is approximately 4.5 km thick.

It is well known that the bed of West Antarctica lies mostly below sea level, but it has only recently been determined that a substantial part of the East Antarctic bed is below sea level too.

The bed topography is much less known than the surface topography because we cannot use satellite techniques to precisely measure the bed under the ice. Instead, we use airborne or ground-based ice-penetrating radar – radio waves that penetrate the ice and reflect from the interface between ice and rock – to determine the bed elevation.

Taking a large view of Antarctica, there is a clear contrast between the elevated East Antarctic bed beneath the ice and the much lower West Antarctic bed. On average, the ice is somewhat thicker in East Antarctica, but it is differences in the bed elevation that make the ice surface higher in the east than in the west.



Most of the Antarctic continent is covered by ice. But imagine that we lift off the ice sheet, exposing the bed beneath it. Much of the bed is below sea level (light blue), and there are also some high mountains (brown/red).

IceGRAV and PolarGAP projects

Flying for geophysics

Antarctica is often a white blotch on world maps – not just because of the snow, but also because of missing data on basic geophysics, such as Earth's gravity and magnetic fields, which would tell us about geological structures under the ice. Magnetic and gravity fields have been measured from space nearly all over the world, but their detailed variations cannot be seen from space, and satellites do not cover the South Pole. Airborne surveys are therefore needed to complement satellite missions such as the European Space Agency's GOCE and SWARM.

The Technical University of Denmark led a team of scientists and engineers from the British Antarctic Survey, the Norwegian Polar Institute, the Argentinean/Chilean polar institutes and the University of Texas that carried out survey flights over unexplored regions including those in Dronning Maud Land and around the South Pole. The projects lasted from 2009 until 2016.

The airfield by the Norwegian Troll Research Station was used as one of the main runways, as well as the US Amundsen–Scott South Pole Station and a few remote camps. The measurements were very successful and filled in the last key geophysical "white spots" on the continent. New discoveries included major kilometre-deep valleys under the ice sheet. The survey also yielded new information about the Recovery subglacial lakes. Such under-ice valleys and lakes control the flow of the ice sheet and are crucial for accurate ice sheet modelling and climate change studies. The data also helped to reveal geological structures under the ice sheet.

Gravity data gaps in Antarctica needed to be filled to precisely determine satellite orbits that are necessary for navigation and geodesy all over the world. This is why the project was partly funded by the US National Geospatial-Intelligence Agency, which publishes global gravity field models for better GPS height measurements and navigation; these models are used by surveyors around the planet and simplified versions are in all modern smartphones.

In a few large regions no ice thickness data have been collected. These regions are shown as flat surfaces on Antarctic bed maps and are called "poles of ignorance".

This contrast between East and West Antarctica is very clear, but it is not all about bed topography.

A closer look reveals a highly variable topography that has been affected by ice flow over the past 34 million years and even some water flow prior to the full glaciation of Antarctica. Deep valleys, mostly gauged out by flowing glaciers, penetrate inland. Some regions have flat beds because ocean sediments accumulated there before Antarctica was iced over.

Secrets under the ice sheet

Unveiling the secrets of the Antarctic bed is time-consuming and even with the use of airplanes and ground vehicles there are still large knowledge gaps. Ice-penetrating radar can reveal the topography under the ice but it cannot deliver geological information. Instead, by measuring gravity and magnetic fields from airplanes and satellites, and observing rocks at little outcrops around Antarctica, we can peer into the outermost part of the Earth's crust, hidden below the thick Antarctic ice.

About 180 million years ago, there was a supercontinent called Gondwana, which broke up into the landmasses that became Antarctica, Australia, New Zealand, India, Africa and South America. Antarctica became stationed around

The few areas in Antarctica where rock is bare of ice are windows into the geology of the continent.

the South Pole about 100 million years ago, while its former neighbours continued drifting toward their current positions. About 34 million years ago the first ice sheet started to grow in central East Antarctica, where the bed was most elevated at the time.

West Antarctica is young, geologically speaking, and includes different areas that developed along the edge of the Pacific Ocean starting about 500 million years ago. The most remarkable geological feature under the ice is the West Antarctic Rift System. A rift is a region where the crust is thin, such as the African Rift System. All of these rifts are geologically young, only tens to hundreds of million years old, but unlike these active systems that are quite elevated, the West Antarctic Rift System is as much as 2 km below sea level and is largely inactive today. It forms a wide and deep cradle of rock for the ice sheet.

So what about East Antarctica? It is much older and its crust is therefore thicker than in West Antarctica, but it is also much less known. For a geologist, East Antarctica is the most important missing piece of the jigsaw puzzle to understand three billion years of the Earth's history.

Antarctica's hidden geology is the key to understanding the origin and evolution of the continent, as well as the fundamental instability of the Antarctic Ice Sheet.

Hotplate under cold ice

Nearly 100 volcanoes have been identified from topographic features under the West Antarctic Ice Sheet. Most of them erupted millions of years ago, but there are two active volcanoes in Antarctica. One is Mount Erebus, in the Ross Embayment near the US McMurdo Station and New Zealand's Scott Base, which last erupted in 2005 and still is seismologically active. The other is on Deception Island, a small island covered with little glaciers located at the northern tip of the Antarctic Peninsula.

Active volcanoes are extreme cases and are rare in Antarctica, but their presence shows that the West Antarctic Ice Sheet lies on a hotplate. Geothermal heat is a combination of heat coming up from deep down in the Earth's mantle, heat production by radioactive elements within the crust, and tectonic and volcanic history. The thin crust of the West Antarctic Rift System means that the warm mantle lies relatively close to the surface. This part of West Antarctica has one and a half times more geothermal heat than old East Antarctica.

The geology of Antarctica is not uniform. The continent is composed of two distinct geological regions, East Antarctica and West Antarctica, divided by the Transantarctic Mountains.

The Norwegian research vessel *Kronprins Haakon* is purpose-built for the challenging conditions of the Southern Ocean.

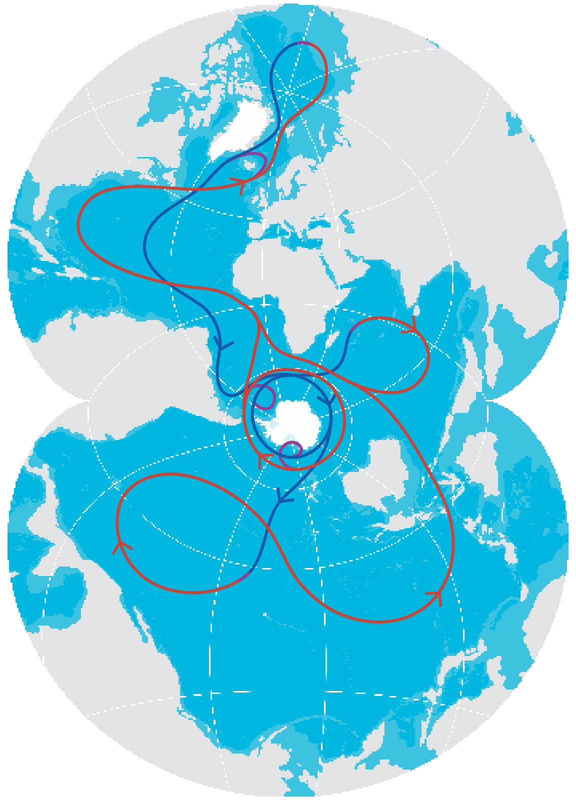
Shallow ocean around the ice sheet

Ocean bathymetry – the topography of the seafloor – plays a crucial role in determining interactions between the ocean and the ice sheet. But the geology and topography under the Southern Ocean are poorly known.

The continental shelf mostly extends for 100–300 km beyond the ice sheet, but the Ross and Weddell embayments, facing the Pacific and Atlantic oceans, are exceptions. Here, the continental shelf extends nearly 1000 km. Across the shelf, the seafloor is no more than about 1 km below sea level. At the edge of the continental shelf, the seafloor drops off steeply to 4–5 km below sea level.

Furious Fifties and Screaming Sixties

Antarctica and the Arctic are similar in many ways, but the ocean–land distribution is completely different in the two regions. While the Arctic is an ocean surrounded by landmasses, Antarctica is a continent surrounded by ocean. Antarctica is far less accessible than the Arctic; getting there by ship means crossing the roughest waters on the planet. Storms encircle Antarctica and whip up waves as tall as high buildings. This has earned these latitudes in the Southern Ocean the nicknames Furious Fifties and Screaming Sixties. This notoriously rough sea is the key to understanding the connections between Antarctica and the rest of the planet.



Warm, buoyant seawater (red) carries heat from the tropics to the poles, and cold, dense water (blue) sinks to the deep ocean basins in the polar regions. This "conveyor belt" connects the world's oceans.

Ocean "rivers" connect the world

With no landmasses to block ocean currents between Chile's Cape Horn and the Antarctic Peninsula and forced by ferocious westerly winds, the Antarctic Circumpolar Ocean Current spins clockwise around Antarctica. Its flow accounts for more than 500 times the volume transport of the Amazon River. It is by far the largest ocean current on Earth, connecting waters from the Indian, Pacific and Atlantic oceans and linking the global circulation with the southern polar climate. In the south, the Antarctic Circumpolar Current branches off into gyre circulations in the large basins of the Ross and Weddell seas.

Carrying with them warmer northern waters, these currents mix at their southern rim with the colder Antarctic Coastal Current, which circulates anticlockwise along the Antarctic continental margin. Such oceanic fronts separate the different water masses of the Southern Ocean.

A freezing ocean

While the thick floating ice shelves that extend from the ice sheet can work as icy lids insulating the ocean from the atmosphere and keeping it warm, the ocean further north is exposed to an extremely cold climate. Vast areas of the Southern

Pancake ice forms on the Southern Ocean at the beginning of winter.

The strong winds blowing against this snowmobile driver also push sea ice further offshore and open up patches of open water known as polynyas.

Ocean freeze during the polar night each winter, making it virtually inaccessible to ships. With stunning growth rates of about a 100,000 km^2 a day, the maximum sea ice extent in September – the austral spring – effectively doubles the size of the continent. Solar heating and a northward drift into warmer waters melt most of this ice in summer.

In addition to the rapid sea ice growth at the margins, "sea ice factories" are found near the glaciated coast. Here, strong winds push the pack ice further north and expose open-ocean waters to air temperatures as low as -40°C. Such openings in the ice cover are called polynyas. Whereas pure water freezes at 0°C, salty seawater freezes at -2°C. When seawater freezes to ice at the surface, the sea ice can retain only a fraction of its salt, meaning that the sea ice factories in the polynyas also produce much saltier and colder water than normal seawater. This extra-salty cold water, called brine, is denser than ordinary seawater and sinks.

As this heavy seawater sinks, currents from the north are forced up to the surface at the fronts of the Antarctic Circumpolar Current. In this way, the dense water on the Southern Ocean contributes to a circulation that revolves through all the world's ocean basins on time scales of centuries. The waters off Antarctica help distribute ocean heat, carbon and nutrients between the continents, shaping the planet's climate and its eco-regions.

The floating ice shelves protect the ocean from the cold air above. In winter, the sea ice can grow 100,000 km^2 – the size of Iceland or South Korea – in one day, and make the ice on the ocean bigger than the ice sheet itself.

Travelling to Antarctica

There are several gateways to Antarctica: Cape Town (South Africa), Hobart (Australia), Christchurch (New Zealand), Punta Arenas (Chile) and Ushuaia (Argentina). When transporting scientists, support personnel and equipment, a national Antarctic programme uses the gateway closest to its research station. A few voyages are made to serve each station over the summer months by icebreakers, ice-class vessels or ordinary vessels escorted by an icebreaker. Many of these also serve as research ships. They go across the Furious Fifties and Screaming Sixties and navigate through seasonal and multi-year sea ice zones. Equipment is unloaded and loaded at the cliff of the ice shelf or on the sea ice.

For many years, ships were the only means of transportation to Antarctica and it took weeks to reach the continent. Today most personnel go by airplane. Except for a few airfields – such as the one at the British Rothera Station on the Antarctic Peninsula – most runways are on ice or snow. To construct these, soft snow is removed and heavy vehicles harden the remaining snow. Typical flight time from a gateway to the continent is about 6 hours by jet airplane. Flights within the continent are carried out with smaller propeller planes. They can land on unprepared surfaces, the captain having first carefully inspected the area from the air.

Antarctic flight operations are challenging because of the harsh weather and limited infrastructure. Planned flights are undertaken during the summer, from November to March. In case of emergency, evacuation flights can be made during the dark winter, but weather conditions may prevent immediate action. Even with such limitations, aviation increases the safety of personnel overwintering in Antarctica.

Near this glaciated landscape, in the vicinity of Cape Adare by the Ross Sea, the Norwegian explorer Carsten Borchgrevink overwintered with his British Southern Cross Expedition team in 1898–1900. Borchgrevink was among the first to set foot on the Antarctic continent.

The coldest and windiest continent

The Furious Fifties and Screaming Sixties can be seen from space. Satellite imagery shows “trains” of storms moving all around the Antarctic continent. In contrast, the Antarctic continent itself appears cloudless and calm because the elevated ice sheet blocks the weather system so storms do not usually penetrate far inland.

Travellers heading south through a tangle of sea ice and polynyas gradually see more blue sky than dark clouds as they approach the continent. But the newly arrived traveller is confronted with a harsh reality under the clear sky: Antarctica is the coldest and windiest continent on Earth.

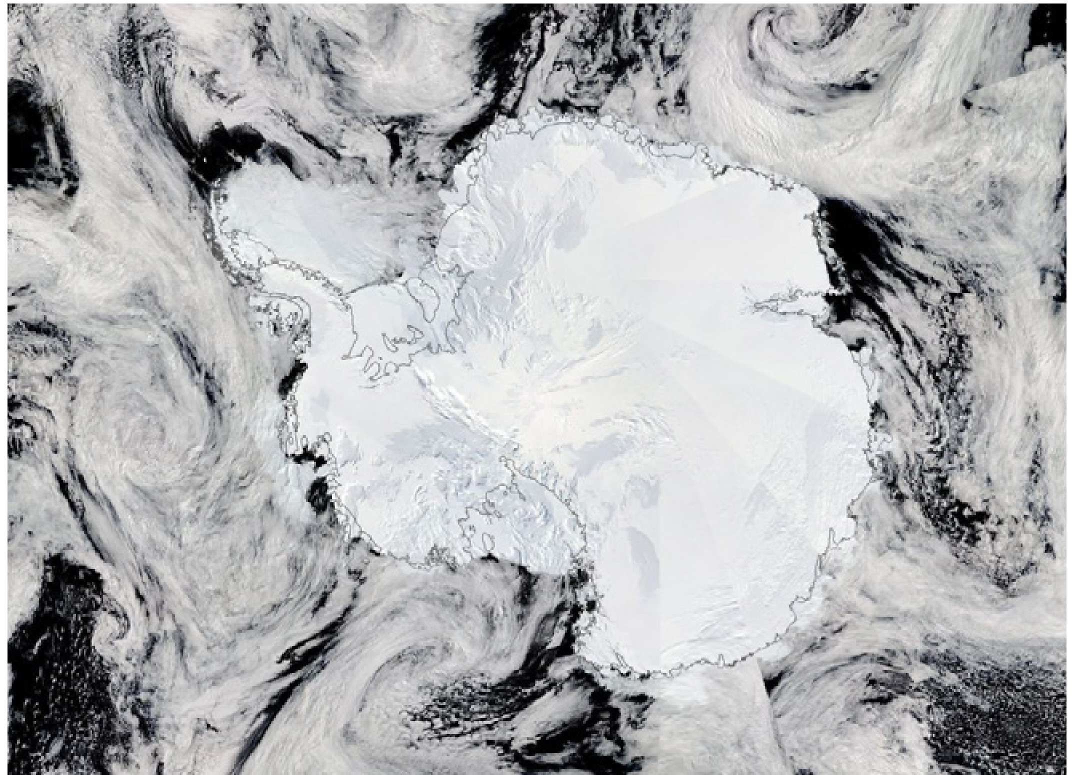
The reason for this is the snow on the ice sheet. The top of the ice layer consists of fresh, fine-grained and ultraclean snow. This snow is so bright that less than one-fifth of the sun’s radiation is absorbed by the surface. The other four-fifths are reflected back to space. A person standing on the Antarctic Ice Sheet is thus exposed to a double dose of the sun’s radiation: one directly from above and one that is only slightly weaker from below. To avoid sunburn and snow blindness, scientists working in Antarctica always wear highly protective sunscreen and dark sunglasses, and bring a backup pair.

Did you know ...

... why Antarctica is colder than the Arctic?

It is because it is highly elevated and isolated from other continents. Except for a few areas, the Antarctic surface snow stays frozen all year. The snow reflects most of the heat from the sun.

Trains of storms encircle Antarctica while the interior is cloud-free, as seen from space.



Even in the middle of summer, most of the Antarctic snow surface remains solidly frozen, with the exception of some low-lying, northward protruding land masses and ice shelves, mainly on the Antarctic Peninsula. In the inland plateau the temperatures rarely rise above -20˚C even in midsummer. This is because the snow efficiently reflects the sun's heat and is barely warmed by it.

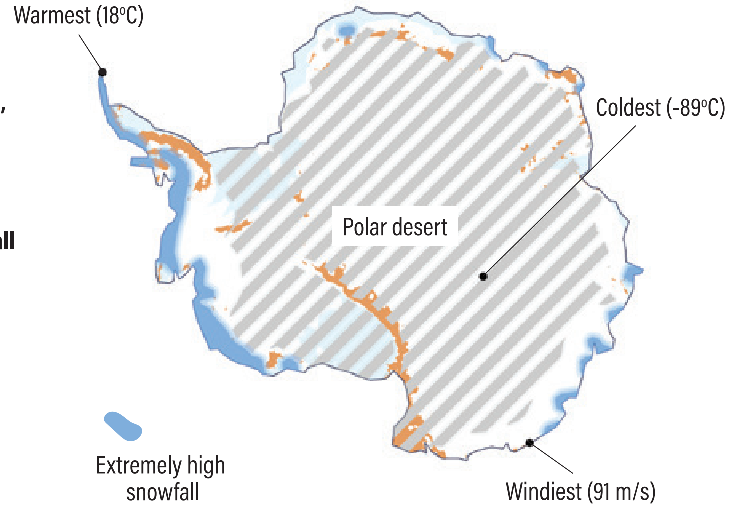
This bright Antarctic surface is only half of the story of the austral summer. The other is that the sun is above the horizon most of the season. Midnight sun – 24-hour daylight – happens almost all over Antarctica, its length varying by latitude.

Deadly cold and dry

When the sun sets at the end of the summer and the polar night begins, temperatures drop rapidly. This is aided by the expanding band of sea ice that insulates the atmosphere from the relatively warm ocean.

Not surprisingly, Antarctica holds the official record for the lowest temperature ever measured: -89.2˚C. This was observed in the middle of the austral winter on 21 July 1983 at the Russian Vostok Station, situated on the East Antarctic Ice Sheet at 3,500 m above sea level. Here, in the deep interior of the continent, conditions are perfect for low temperatures: the overlying atmosphere is thin, cold, cloudless and dry.

The lowest temperature ever recorded on Earth is -89.2˚C. It was measured in the interior of East Antarctica on 21 July 1983.



Antarctica is mostly a polar desert, but the fringe of the continent receives a lot of snow by Antarctic standards (0.5 to 1 m/year). This amount of precipitation is still small compared to the tropics.

Working in Antarctica demands warm clothing and protection from the wind and the sun's rays, which bombard through the thin ozone layer overhead and from the reflective snow underfoot.

The few meteorological stations in Antarctica are extremely thinly spread, and lower values could easily have been missed. Indeed, satellites reveal that in interior East Antarctica the temperature of the snow surface can drop to nearly -100˚C. This happens in small depressions in the almost flat ice sheet inland, where cold air pools, similar to alpine valleys that become cold spots on winter mornings.

Another effect of the extremely cold air in interior Antarctica is that the atmosphere contains very little moisture. As a result, the interior ice sheet has less than 250 mm of snowfall per year, which officially qualifies as desert – a polar desert. Most of this snow falls as diamond dust, tiny ice particles that form in clear sky conditions. The diamond dust often makes sundogs, sun pillars and sun haloes when the sky is clear. These fantastical atmospheric phenomena break up the monotony of the Antarctic interior.

The home of the blizzard

Cold, heavy air flows down to lower elevations. This happens everywhere on Earth, including the Antarctic interior, which seems so flat. Indeed, the Antarctic Ice Sheet is so large and the polar night lasts so long that small creeks of cold air deep inland become powerful rivers of wind flowing down to the coast over

Taking advantage of Antarctica's strong winds, members of the Norwegian South Pole Expedition 2011 used snow-kites to speed up their long journey in polar explorer Roald Amundsen's tracks, 100 years after he reached the South Pole.

On the planet's windiest continent, a person is no match for winds that can blow 5-tonne containers a distance of several kilometres, as has happened here at Troll Research Station in Dronning Maud Land.

Antarctic katabatic winds are the strongest on Earth.

thousands of kilometres. These form what is perhaps the most conspicuous feature of Antarctica's near-surface climate: katabatic winds, from the Greek word for "descending".

The Antarctic katabatic winds are the strongest and most persistent winds on Earth. Commonwealth Bay, east of Wilkes Land in coastal East Antarctica, experiences katabatic winds that are especially violent. The Australian explorer and scientist, Sir Douglas Mawson, who unintentionally set up camp there in the summer of 1911–12 during a period of relative calm, dubbed this "the home of the blizzard".

It turned out to be one of the windiest places on Earth, with an annual average wind speed of 80 km per hour and gusts in excess of 250 km per hour. With winds this strong, drifting snow reduces visibility to virtually zero and the human body cools rapidly, making outside activities dangerous.

2

Inland Antarctica

Day by day, year by year and century by century, small quantities of snow fall on the Antarctic continent. Some snow is assimilated into the strong dry wind, but most stays frozen on the surface. Inland Antarctica is the coldest place in the world, but the base of the ice is warm enough to host lakes and rivers.

The Norwegian-US Scientific Traverse photographed from the Plateau Station Tower, midway on the expedition's crossing from Troll Research Station to the South Pole.

Did you know …

…how the Pole of Inaccessibility got its name?

It was because it is the spot on the continent which is furthest away from the sea in all directions. This area is very seldom visited.

Snow becomes ice

As the snow falling on the Antarctic continent accumulates in layers, it turns into firn. As new snow is added at the top, the firn gets more compact, eventually becoming glacier ice. This process happens in the top 100–150 m of the ice sheet. Whereas frozen water is a single giant crystal, glacier ice is composed of billions of ice crystals that have been transformed from snow crystals into something called polycrystal. Single ice crystals seem perfectly stiff, but polycrystal glacier ice is not. If the glacier ice were rigid like single crystals, snowfall would slowly make Antarctica grow upward into an enormous tower of ice as new snow is added every year and Antarctica is too cold for it to melt. The Antarctic Ice Sheet is not growing like this because polycrystalline glacier ice deforms with time: it creeps.

Members of the Norwegian-US Scientific Traverse check out the bust of Soviet leader Lenin at the Pole of Inaccessibility. Soviet scientists put up a station here in 1958 and placed a bust of Lenin on top of the chimney – now listed as an Antarctic historic monument. When this picture was taken 50 years later, the building and the base of the bust were covered by snow. This tells us that only about 10 cm of snow fell per year since 1958 in this polar desert.

Scientists encamp for weeks or months on end in harsh conditions.

Ice is like ketchup

Scientists often say that glaciers "flow", but they do so in a way quite different from air or water.

To better understand this phenomenon, let's consider cooking oil. It moves, though slowly, when you pour it in a pan. Cooking oil (like water) flows even if the pan is flat on the stove because its own weight is enough to make it move. As the pan warms up, the oil moves more smoothly. If you tilt the pan steeply, the oil moves faster. In other words, the oil moves faster when more stress is applied.

Next, consider thick ketchup. When you spread ketchup on a hamburger bun with a knife, you don't really need any force to do it. But ketchup poured on the bun from a bottle does not spread out widely under its own weight. Ketchup has higher internal friction than cooking oil and water. When only a small force – such as its own gravitational force – is applied to ketchup, the friction is high: it is highly viscous and does not readily flow outward. But when a larger force is exerted, such as spreading with a knife, ketchup deforms very easily, so then it is not really viscous after all.

Did you know ...

... that there is a glaciological difference between ice and snow?

It is snow if air can go through it, whereas it is ice if air cannot go through. This transition happens when the snow density reaches about 90% of the density of pure ice. Beyond this, air mixed with snow becomes air bubbles trapped in the ice.

Norwegian–US Scientific Traverse

Science during the International Polar Year

The first International Polar Year (IPY) in 1882–83 was a landmark of coordinated international efforts to enrich our knowledge of the Arctic and Antarctic. It took place well before humans made it to the South Pole for the first time in 1911. The spirit of that first IPY has been carried over more than a century, leading into the fourth IPY in 2007-08.

The Norwegian Polar Institute and US National Science Foundation worked together to carry out a traverse starting from Troll Research Station to Amundsen–Scott South Pole Station, and back to Troll Research Station through inland Dronning Maud Land. This region had major data gaps where even basic conditions such as topography and snowfall rates were largely unknown. The traverse is so far the largest Norwegian scientific expedition to the interior of Antarctica. It went through the Pole of Inaccessibility, the site in Antarctica furthest away from the Southern Ocean.

The traverse encountered numerous challenges on the deadly cold East Antarctic plateau. Although the plan was to reach the South Pole by the end of the first season, mechanical problems with the vehicles made this impossible. Instead, a winter camp was set up about 400 km from the Amundsen–Scott South Pole Station. The originally planned route to the South Pole and then back to Troll Research Station was completed in the following field season.

A major achievement of this expedition was the first radar assessment of the Recovery subglacial lakes, which were assumed to exist on the basis of the flat ice surface that had been observed from satellites. Other important achievements included mapping the ultra-dry areas in the polar desert and quantifying changes in snowfall rates and other climate parameters in the past millennia through extensive ice coring and radar profiling along the route.

Glacier ice behaves like ketchup but in a more extreme way. Suppose a perfectly cube-shaped glacier is cold enough, say -20°C, so that the ice does not melt nor slip. When this glacier is placed on completely horizontal bedrock, the gravitational force works only vertically and there is no horizontal stress. When the bedrock is slightly tilted, the glacier does not move.

However, when the tilt of the bedrock is increased and the gravitational force applied to the glacier goes beyond a certain amount, the ice starts to deform. The glacier ice behaves like a solid when the applied stress is small, but when subjected to more stress it behaves like a viscous fluid. That is why glacier ice and ketchup are called visco-plastic materials.

A slab of Antarctic ice lying on a perfectly flat bed will flow when its top is sufficiently tilted and the ice is thick enough to make it deform under its own weight. Therefore, a tilted bed is not necessary to make the ice flow.

If glacier ice behaved like frozen water, Antarctica would be a colossal ice tower. But glacier ice deforms with time and creeps towards the ocean.

Rock outcrops often serve as stationary reference points when ice motion is measured using high-precision GPS techniques.

The ice near the bed is warmed by geothermal heat making nearly half of the ice sheet base wet. Bed temperatures in Antarctica are rarely below -10°C.

The first commandment

When ice thickness and tilt exceed a certain combined value, glacier ice starts to flow. Even though surface slope and the thickness of the ice each can vary, they usually add up to about the same combined value in most parts of the Antarctic Ice Sheet as well as in mountain glaciers in other parts of the world.

This relationship is often called the "first commandment" in glaciology. It explains why alpine glaciers on a steep slope are thinner than the Antarctic Ice Sheet on a relatively flat bed.

Cold top and warm bottom

Ice deformation is also highly temperature dependent. When the ice temperature is -10°C it deforms faster than ice at -30°C. Actually, ice at 0°C deforms 100 times faster than the ice at a temperature of -30°C. When the temperature is even lower, the deformation is less temperature dependent, and such ultra-cold ice deforms much slower than warmer ice.

Antarctica's ice surface is very cold. Inland, the record low temperature is nearly -90°C, and the yearly mean temperature can be below -50°C. This cold surface draws heat from the ice interior. Also, as new snow is added to the top, cold ice moves downward from the surface, which further cools down the ice interior. Because of this, the shallower ice stays cold, say -30 – -50°C. If more snowfall occurs, this cold ice layer tends to be thicker and the top two-thirds of the ice sheet are nearly as cold as its surface. This is the case in West Antarctica, where there is more snowfall than in East Antarctica.

The Antarctic Ice Sheet lies on a warm bed – a hotplate of geothermal heat. Geothermal heat in Antarctica is not particularly high compared to the other continents, but it is enough to make the deep ice close to the bed much warmer than the ice near the surface. It is hard to find locations where the bed temperature is below -10°C in Antarctica.

Antarctica's wet bed

How can we peer into the base of the Antarctic Ice Sheet? Drilling through several kilometres of ice is a major endeavour that has been carried out at only

The Norwegian South Pole Expedition 2011 ascended the Axel Heiberg Glacier in the Transantarctic Mountains to reach the interior plateau.

a handful of sites. These few direct observations of the basal ice have revealed that in most cases it is not very cold and the bed is wet.

Airborne and ground-based radar have been used to learn about bed conditions in large areas. In radar surveys, radio-wave pulses are sent down into the ice. Ice is reasonably "transparent" for radio waves, which go through the thick ice and bounce back from the bed at the bottom of the ice sheet. The ice thickness can be estimated on the basis of the travel time of this two-way trip. The electromagnetic energy associated with this bed echo depends on what is under the ice. A thick water layer makes a strong echo. When the bed is frozen, the echo is very weak.

Another powerful way to examine the bed conditions is computer models. They can calculate ice motion and heat transfer and can predict where the bed under the Antarctic Ice Sheet is frozen or wet. The computer models need to be fed with information about snowfall, bed topography, geothermal heat and other conditions, including their histories. Because many of these conditions are not

Did you know …

… that ice melts below 0°C?

Usually ice – the solid form of water – becomes liquid at 0°C. But the melting point of ice is lower when ice is under pressure. In the Antarctic interior, the ice sheet is nearly 3 km thick and the ice near its base can melt even at -2.6°C.

The Antarctic winds create striking snow sculptures.

well known, radar surveys and computer models are used together to produce the best possible diagnosis of the Antarctic bed. As a result, we now know that nearly half of the Antarctic Ice Sheet has a wet bed.

Lakes and rivers under cold ice

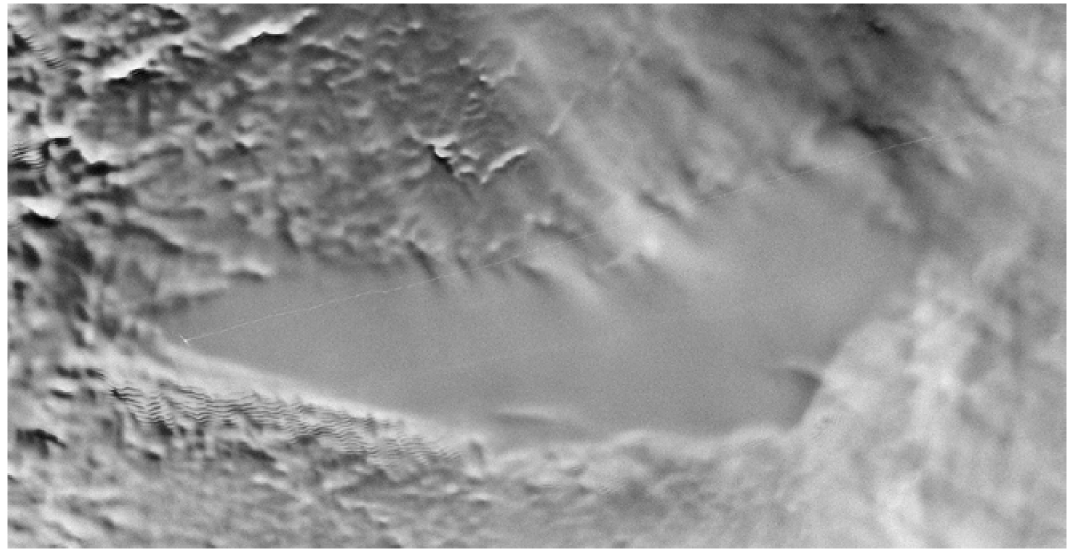
When the ice sheet is thick enough to insulate the ice sheet's bed from the cold atmosphere, and there is sufficient geothermal heat, the bed becomes wet. Any extra geothermal heat melts the ice at the bottom of the ice sheet – a few millimetres per year at most. This sounds insignificant compared to the thickness of the Antarctic Ice Sheet, which is 2.2 km on average. But a little bit of melting continuing for many thousands of years over vast areas will produce large amounts of subglacial water – lakes and rivers – under the ice sheet.

Under pressure from the overlying ice sheet, subglacial water flows towards where the ice is thinner and the bed elevation lower. Radar surveys find wet environments such as rivers, ponds and lakes, and they are often at locations predicted by scientists studying the ice and the bed topography. Basal meltwater makes up small streams that flow into large rivers and continue their journey to large lakes or even to the ocean.

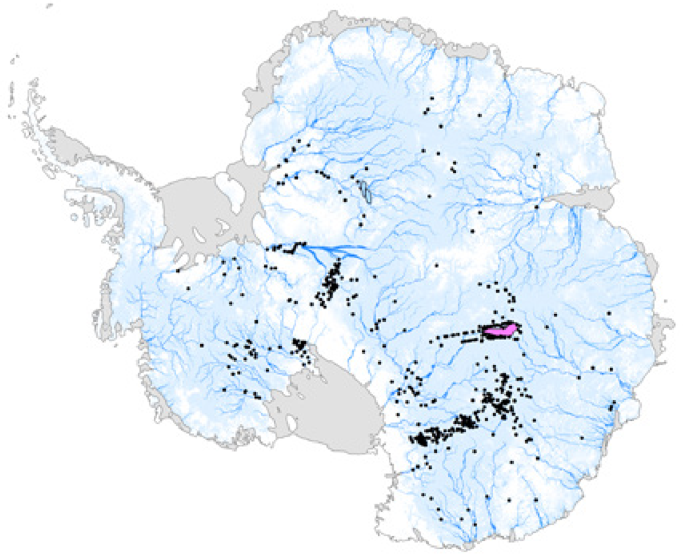
Did you know …

… that the lowest temperature record in the world was thanks to a sublacial lake?

The Russian Vostok Station, where the record was made, lies on a huge subglacial lake surrounded by sloping ice sheet surfaces. This topography pools cold air over the area.



Satellite image of the smooth ice overlying Lake Vostok. The lake is 280 km long and 50 km wide.



The bed under more than half of the Antarctic Ice Sheet is wet (light blue). Subglacial meltwater makes up rivers that flow into subglacial lakes (black dots) and even into the ocean. The largest subglacial lake, Lake Vostok, is marked in pink. The bed is colder in some areas (white) than others, but it is seldom below -10°C, except near some outcrops where the ice is very thin.

There are lakes and rivers underneath the thick ice sheet covering the Antarctic continent. These formed over thousands of years by the slow melting of the ice from below.

The largest lake by far under the Antarctic Ice Sheet is Lake Vostok. It is the 16th largest lake in the world – about half the size of Lake Baikal. Vostok's water is estimated to be 700 m deep at its centre.

The ice sheet over such huge lakes is afloat. With no underlying bumps to disturb it, the smooth surface of this floating ice sheet is visible from space.

Lakes drain and refill

Radar surveys have revealed 250 subglacial lakes under the Antarctic Ice Sheet. Lake water reflects radio waves very strongly, so the lake surface appears as a brighter and flatter reflector compared to the surrounding bed in the radar image.

The number of known subglacial lakes increased dramatically in the late 2000s as new observational techniques were implemented to monitor "active" subglacial lakes that drain and refill over months or years.

Basal melt occurs continuously, producing meltwater that flows into a lake. As the lake fills, it can jack up the ice cover, resulting in a locally elevated ice sheet surface.

A few satellites, such as NASA's ICESat and ICESat-2 and ESA's CryoSat-2, carry instruments to continuously measure very precisely the distance between the satellite and the Earth's surface, yielding detailed information about the

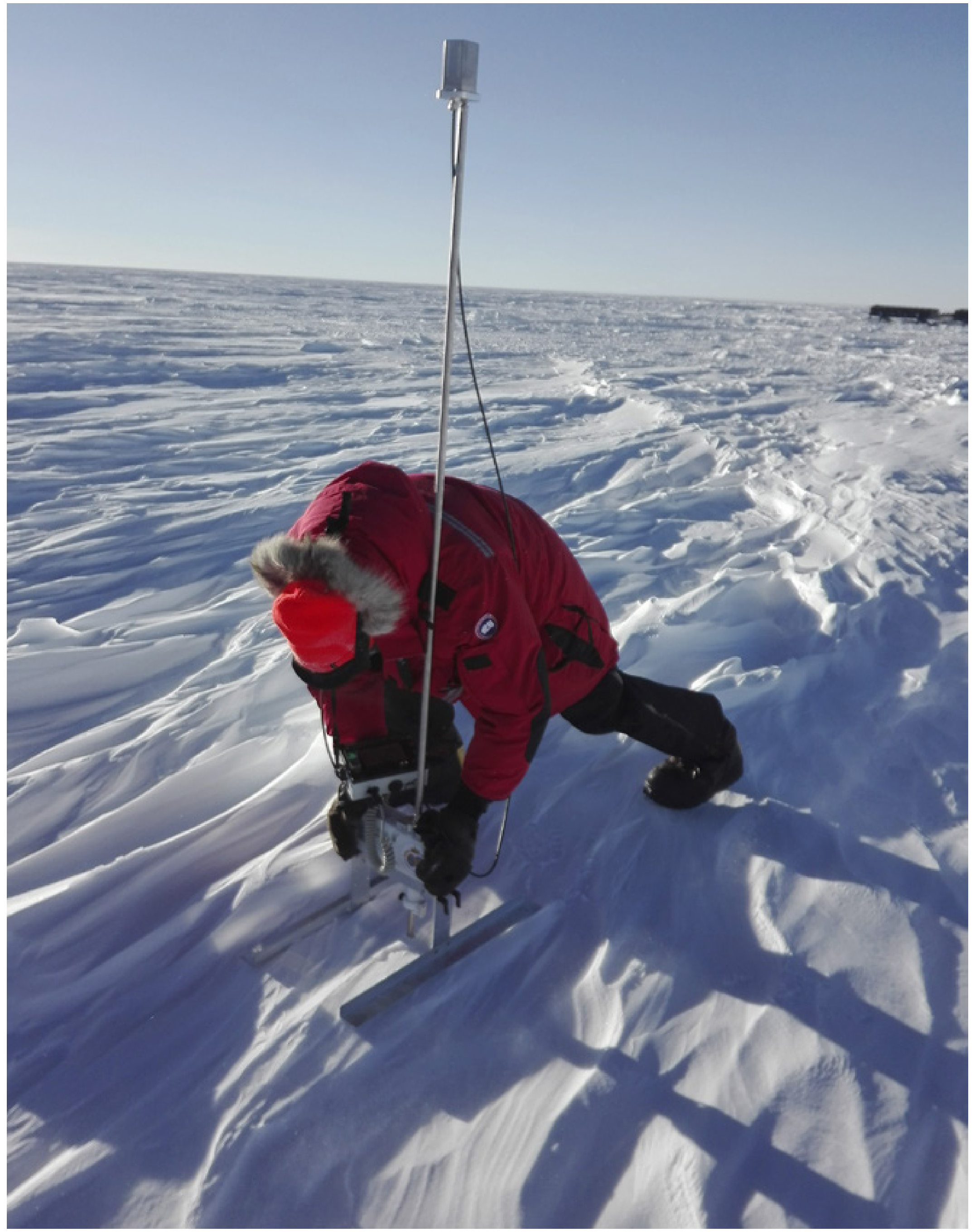
A tracked vehicle hauls a heavily loaded sledge en route to a fieldwork site.

surface topography. This instrument using pulsed radio waves or visible laser lights is called an altimeter and is often used to monitor dynamic features, such as evolving volcanoes and landslides. Applied to the Antarctic Ice Sheet, it repeatedly measures local elevation changes that can reflect subglacial water movement.

Ice sheet surface elevations can change for several reasons. For example, the surface can be elevated after a huge snow storm. Similarly, strong winds that blast away soft snow on the surface can lower surface elevation. In the case of draining and refilling subglacial lakes, surface elevation changes occur in smaller areas and often in tandem: a rise in one area happens at about the same time as a fall in another place. Observations of dropping and rising surfaces recurring at the same locations suggest that subglacial rivers fill up lakes, which eventually drain, sending water to lakes further downstream, and get refilled again from the subglacial rivers upstream.

Conventional radar methods have found about 250 lakes and satellite altimetry has added more than 130. Scientists think that many more subglacial lakes will be discovered as further research fills in missing information about what lies under Antarctica's ice.

The Antarctic Ice Sheet is so thick that scientists have directly observed the bed at very few sites. Radar surveys and computer models have helped reveal Antarctica's wet bed.



A scientist checks the characteristics of near-surface snow, which are key to interpreting satellite data.

Slip-sliding away

Deformation of ice is nearly always what causes the ice sheet to flow when the bed is frozen. However, when the bed is wet, subglacial water affects ice flow not only over subglacial lakes but also over areas under the ice with little water.

As basal ice over a wet bed is warmer than ice over a frozen bed, the ice deforms faster, causing more frictional heating and more subglacial melt. Subglacial water lubricates the bed, causing the ice sheet to slide, particularly when the ice sheet surface is sufficiently sloped. The movement of glacial ice over a wet bed is affected by the presence of sediments between the ice and the hard bedrock. This is especially a factor in West Antarctica.

Ice deforms like ketchup, and wet sediments under the ice sheet also behave like ketchup – but when sediments contain a lot of water, they are much softer than ice. Both water and sediments reduce the friction of the bed against the overlying ice, allowing it to slide forward in addition to the slow creep of the ice's deformation.

Ice deformation, sediment deformation and basal sliding of ice on sediment all contribute to the motion of the Antarctic Ice Sheet. The concept is simple but difficult to observe and model.

The ice sheet covers almost 400 lakes. The lakes are at the base of the ice, on the bedrock.

Where did the sediments come from?

About 45% of the Antarctic bed is below sea level. As the majority of the West Antarctic Ice Sheet lies on the bed below today's sea level, it is often called a marine ice sheet.

Millions of years ago, when there was less ice locked up in Antarctica, there was more water in the ocean, so the sea level was higher than it is today. The bed was also higher than today – though still below sea level – over the majority of West Antarctica and parts of East Antarctica. These regions may have marine sediments originating from before Antarctica was glaciated.

Not all sediments under the current Antarctic Ice Sheet are marine sediments. For the past few tens of million years since the initiation of the Antarctic Ice Sheet, it has been grinding away at the underlying rock and carrying the bits of broken rock to the coast, depositing them there as glacial sediments.

Troll Research Station

There are 40 year-round Antarctic stations registered by the Council of Managers of National Antarctic Programs (COMNAP). Most of them are on the Antarctic Peninsula or close to the coast. The US Amundsen-Scott South Pole Station, Russian Vostok and Italian/French Concordia stations are on the inland plateau.

The Norwegian Troll Research Station in Dronning Maud Land is surrounded by mountains and situated on solid rock 200 km from the coast, at 1290 m above sea level. Established in 1989–90 as a summer station, the station was upgraded to a year-round facility in 2005. It is run by the Norwegian Polar Institute and manned by an overwintering staff of six. It can accommodate up to 80 people in summer. Jet airplanes land at a long runway nearby. Cargo is transported to the station from ships berthing at the ice-shelf front.

Troll is the only year-around staffed station in a steeply sloped region (by Antarctic standards) from the plateau to the coast, where coastal and inland weather systems meet. The location allows for unique observations of processes over the Antarctic slope in a region that is otherwise an "observation vacuum".

Data collected at the station are important for regional studies in Dronning Maud Land and for research on global questions. Long-term monitoring includes meteorology, atmospheric radiation, environmental toxins, seismic activity, greenhouse gases and the upper atmosphere, led by the Norwegian Institute for Air Research, NORSAR, the University of Oslo and the Norwegian Polar Institute.

Troll also functions as a logistical hub for glaciological, biological and geological field expeditions for Norwegian and international projects. The work of scientists from institutions based in countries other than Norway constitutes almost 40% of the time spent by scientists at the station.

Large hoarfrost crystals – made from water vapour in the air – materialise on objects when it is very cold, the sky is clear and there is no wind.

The birth of glaciers

Ice travels from inland to the coast in a few different ways. Near the central Antarctic Ice Sheet, where the ice is virtually flat, it hardly moves. Nonetheless, the ice follows the direction of the ice slopes. Further from the inland ice domes, the surface of the ice becomes more sloped. The ice picks up speed as it moves downstream and eventually forms fast-flowing glaciers.

Glaciers make their own cradles on a geological timescale as they carve out increasingly deep channels that suck in more ice. As the ice thickens, the gravitational stress on the base increases, causing more ice deformation. This warms up and softens the ice, which again enhances ice flow and erosion, in a self-reinforcing loop.

You may imagine glaciers as white ice bodies filling the bottoms of deep valleys between high mountains. Many Antarctic glaciers look like this, particularly in the Transantarctic Mountains near the Ross Sea and on the Antarctic Peninsula. However, the majority of Antarctic glaciers do not have rock outcrops at their sides. These glaciers completely fill the deep valleys and ice spills over lateral mountains. These mountains are also cradles for glaciers, though they are underneath the glacier ice. In some cases, where subglacial water runs into

Some sediments found under the Antarctic Ice Sheet formed when Antarctica was under the ocean and not yet covered by ice. Other sediments came from the inland bed, eroded by the ice over millions of years.

A glacier flows between the Transantarctic Mountains towards the Ross Ice Shelf.

Expert crew manoeuvre a snow vehicle across a snow bridge spanning a deep crevasse.

sediment basins, forming wet basal sediments, parts of the ice flow much faster than the surrounding ice. These glaciers are often called ice streams and are typical along the Siple Coast, where they flow into the Ross Ice Shelf.

Large flow speed differences between ice streams and neighbouring slower-moving ice create a shear zone in which the ice is torn apart in places. The resulting crevasses hinder ground-based research using snow vehicles but provide excellent landmarks when the ice motion is measured from space.

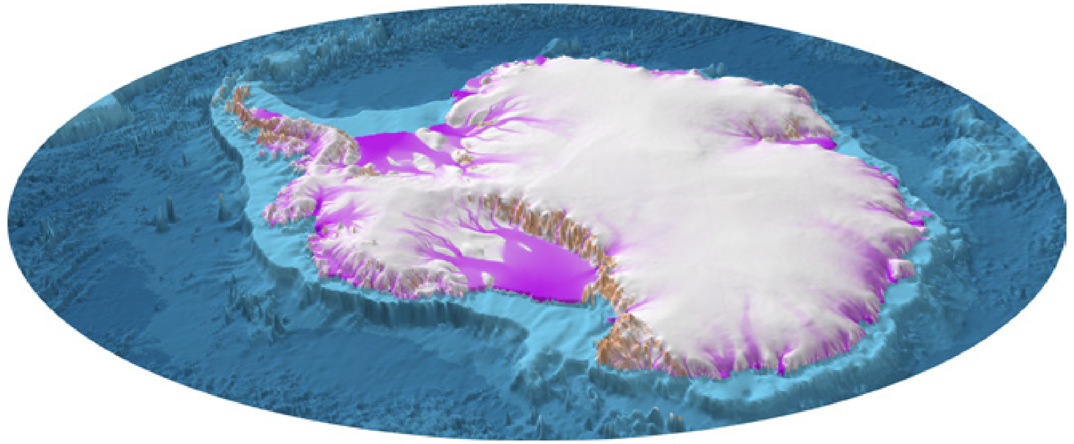
Science has come far using modern technology. Yet what causes a glacier to form or to change from slow-moving to fast-moving ice is not fully understood.

How do we measure ice flow?

Scientists install markers on the ice and track the motions using GPS receivers just like the ones in mobile phones, but with much greater precision. These give precise data, although only at limited locations over limited periods. To measure the speed and direction of the entire ice sheet, satellite images taken over weeks to months are assembled as a sort of time-lapse photography.

An engineer on board a survey airplane monitors real-time data.

Major ice streams and glaciers have numerous tributaries that originate from deep inland.



Stretching and compression of moving ice over rough terrain make the ice crack up into crevasses. On ice shelves, stretching of the floating ice makes rifts. The movement of crevasses, rifts and other surface features can be tracked from satelitte image to satellite image over time. This is often the only way to see that an ice sheet is active because the movement itself is too slow to be seen by the eye in real time. Covering the continent piece by piece, thousands of repeat satellite images reveal ice sheets in motion all over Antarctica.

Satellite data show that ice sheet speed in Antarctica varies from a few metres per year over much of the vast inland to several metres per day for glaciers and ice streams. These highly precise measurements reveal that the major glaciers have long tributaries originating deep inland. The mechanisms of glacier formation and the transition from slowly moving ice to fast-moving ice remain largely unknown, however.

Adélie penguins – near this towering iceberg – represent the most widely distributed of penguin species.

3

Coastal Antarctica

A snowflake has travelled through the atmosphere before it falls onto the surface in Antarctica's interior. Here it changes shape, transforms into glacial ice and contributes to the build-up of the kilometre-thick ice cover of the Antarctic continent. This is the beginning of a new journey towards the coast, where it eventually ends up in the vast ocean.

Discharged ice from Antarctica becomes ice shelves floating on the ocean.

Here, at the edge of the ice shelf, the calving front discharges huge icebergs into the ocean.

Heading towards the sea

Unlike glaciers in Svalbard and Alaska, Antarctic glaciers and ice streams do not abruptly end when they meet the ocean. There is often so much ice being discharged from Antarctica that it forms ice shelves that float on top of the seawater and fills inlets and bays.

The flotation level is controlled by the density contrast between ice and water. Pure ice is about 90% as dense as seawater, so about 90% of a block of pure ice is found below sea level. This ratio is somewhat lower for ice shelves, which are topped by a layer of snow and firn that is not as dense as pure ice, but even so, what we see above the water is just a small part of the ice mass.

The grounding line is where the ice lifts from the bed and becomes afloat, adding to the sea level. Parts of the ice sheet grounding line are easily visible in satellite imagery as a transition from sloping grounded ice to flatter floating ice shelves. However, many of the major ice streams are already so vast and flat inland that it is impossible to see where they become afloat.

The moon and sun are of service here. Tides make the floating parts of the ice shelves bob up and down all the way to the grounding line, where the transition between the fully grounded side and the free-floating side is a flexure, or “hinge”, zone. These boundaries of tidal impact can be determined from space by satellites that take precise elevation measurements. This has recently made it possible to map the ice sheet grounding line around the entire continent.

Floating ice shelves

Ice shelves scattered all around coastal Antarctica make up 12% of the total ice-covered area in Antarctica. More than half of this area is confined to the giant Ross and Ronne-Filchner ice shelves in the Ross and Weddell seas at either side of the continent. Since most of the ice shelf is located below sea level, the sea level is not raised when this ice melts, just like ice cubes in a glass of water.

Almost all of Antarctica’s ice shelves are confined to the continental shelf, where the ocean is relatively shallow. The topography of the seafloor under the ice shelves is largely unknown. Radio waves used to measure the bed topography under grounded ice do not penetrate through seawater. Airborne gravity data offer a picture of large-scale seafloor topography: the different densities of ice, seawater and the Earth's crust affect overall gravity differently. Finer topography measurements need time-consuming, ground-based seismic surveys on ice shelves, which have been carried out for very limited areas. Seafloor topography further out to sea from the edge of the ice shelves is also poorly known because heavily packed sea ice often keeps away research vessels with sonars.

Antarctica's continental shelf lies about 1 km below sea level, and the ice shelves thin to a few hundred metres near the front. Since almost 90% of this floating ice is below sea level, the seawater cavity under the ice shelves typically varies between a few hundred to 500 metres from top to bottom.

About three-quarters of Antarctica's coastline is fringed with ice shelves, the floating extensions of the ice sheet. Nearly nine-tenths of an iceberg are below the waterline, hence the expression "tip of the iceberg", which refers to a small part of a serious problem.

Icebergs

Icebergs are large chunks of ice that have broken off from the ice shelves around the continent, about half a kilometre tall. Most huge icebergs have a tabular shape; icebergs larger than 19 km along at least one side are tracked using satellites and named. The biggest iceberg ever recorded was known as Iceberg B15. This gigantic berg measured 295 x 37 km – bigger than Jamaica. It broke off the Ross Ice Shelf in the year 2000. B15 separated into smaller pieces, two of which were still drifting and being tracked early in 2020.

An iceberg's base melts away because the ocean is warmer than the iceberg and ocean waves tend to break large bergs into smaller pieces. In June 2020, only 45 tabular icebergs south of 60°S were large enough to be tracked, but there are a tremendous number of smaller icebergs around Antarctica. These bergs move to the western Weddell Sea, east of the Antarctic Peninsula, where many bergs stay a long time as they slowly melt away. While the bottoms of icebergs melt, snow on the top adds to their volume. So the overall thickness of icebergs does not change rapidly and some large bergs survive and are carried northward by currents.

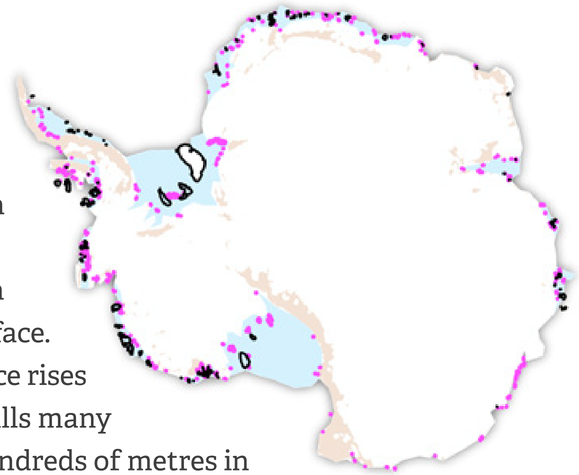
Ice rises – guardians of the ice shelves

The ice particle that started its journey in the atmosphere has arrived a stone's throw from the towering ice cliffs at the ice shelf edge, after a long trip through the atmosphere and inland Antarctica. Here, large icebergs calve off, and a new

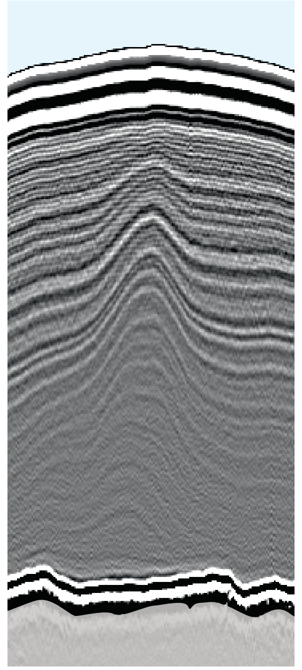
Tabular icebergs break off from the ice shelf and are carried by ocean currents.

journey in the Southern Ocean will begin. However, the ice encounters a sudden slowdown caused by the guardians of Antarctic ice shelves: ice rises.

The seafloor under ice shelves is not completely smooth and flat. As with continental shelves elsewhere in the world, there are many shallow banks. Some of these are high enough to collide with the base of ice shelves, causing hills on the surface. With the help of local snowfall on ice pinned to a bank, these ice rises have developed over thousands of years into dome-shaped hills many tens or even hundreds of kilometres in diameter and up to hundreds of metres in height. Measured against the vast scale of Antarctica, they are small in size, yet they significantly slow down the flow of the upstream ice shelf. These ice rises defend the ice shelves from external forcing that can potentially destabilise the ice shelves. Ice rises can be said to be guardians of the ice shelves.



The map shows ice rises (black) and rumples (purple) all around Antarctica.



Radar imagery of an ice rise shows Raymond Arches beneath the summit. The stratigraphy curves even though the half kilometre of ice is resting on a flat bank.

Mini ice sheets

As the ice rises' summits are many hundred metres above the surrounding ice shelves, they are tall enough to have a local ice flow regime from the summit to the surrounding ice shelf. In these "mini ice sheets" most of the various ice flow regimes working on the gigantic ice sheets are happening on a small scale, making them more convenient places to study how ice deforms than in an ice sheet.

The mini ice sheets are ideal laboratories for investigating how ketchup-like glacier ice deforms under various forces. Since ice is like thick ketchup, which spreads only when significant stress is applied, the ice is super stiff near the mini ice sheet summit, where the surface is virtually flat.

Many ice rises are guardians stabilising the ice shelves. There are almost 100 ice rises distributed in nearly all ice shelves around Antarctica.

A camp on an ice rise summit makes a remote field base. The top of the ice rise is virtually flat, like inland ice domes.

In a study in 1983, Charles F. Raymond predicted that less stiff ice drapes over the stiffer ice much like honey poured over a piece of hard candy. The effect of draping can be seen in the ice stratigraphy where ice layers of a given age occur much deeper in the ice rise flanks than beneath the ice dome. This age asymmetry is revealed by ice penetrating radars. Raymond's study is one of the rare cases where a theoretical prediction based solely on mathematical assumptions was spectacularly confirmed by observations more than 10 years later, when the first arching was observed on Siple Dome in the Ross Sea by Raymond himself and his colleagues.

Ice rises are great climate archives

Ice rises contain a rich climate archive that researchers exploit using ice cores. Air bubbles sealed in the ice column are samples of past atmospheres that can be analysed for chemical and gas composition. This has greatly contributed to our understanding of past climates and their link to greenhouse gases. Ice cores are usually drilled on ice domes where the ice flow is so minimal that the stratigraphy is well intact. The domes of ice rises are no exception to this.

Ice cores can teach us about the climate of earlier times. Air bubbles trapped inside the ice thousands of years ago reveal the chemical composition of the atmosphere at the time.

A MADICE core from the Leningradkollen Ice Rise revealed many layers melted by summer warmth.

MADICE

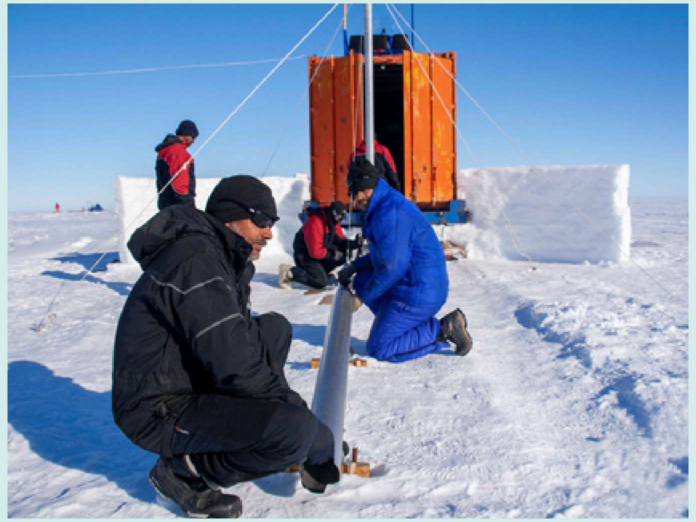
An India–Norway collaboration

Except for a few Antarctic "metropolitan" areas that have multiple research stations belonging to different countries, popping over to visit the closest neighbour means boarding an airplane. The remoteness fosters a strong will to cooperate in Antarctica, especially when it comes to logistics.

India and Norway are among the closest neighbours in Dronning Maud Land. Their Maitri and Troll stations are located 360 km apart – about 1 hour by propeller airplane. Nivlisen Ice Shelf, in front of India's Maitri Station, was chosen for the MADICE project 2016-21 as it is quite different from Dronning Maud Land's Fimbulisen and Roi Baudouin ice shelves, which had already been studied. Nivlisen had the potential to be another gold mine that would yield new insights into the highly variable climate along the coast and the dynamics of the interconnected system of an ice shelf and ice rises along the Antarctic coast. It was therefore an ideal site for the project, which studied mass balance, dynamics and climate of the central Dronning Maud Land coast.

In the two field seasons, the science team set out from the Maitri Station toward the ice shelf. The India–Norway joint team crossed wide crevasses by filling them with snow from the unlimited local supply. Based at camps set up on ice rises and on the ice shelf, the researchers conducted radar and GPS surveys and extracted ice cores at the ice rise summits.

The typically windy and stormy conditions of ice rises – a result of their elevation above the flat expanse of the ice shelf – did not make the scientific work easier. Calm weather posed other challenges: strong sunshine can make ice drills so warm they stop working. To get around this, the ice coring team did most of their drilling at night; they had breakfast while the glaciology team were enjoying their dinner. The team collected much data and are still working on analysing it. Two key findings so far are that the ice shelf front facing the ocean may melt more from the base in the future as the sea ice cover diminishes, and that snowfall rates have significantly reduced since the 1980s, with implications for sea level changes.



Blåskimen Island Ice Rise in Dronning Maud Land, seen from space, is located at the calving front and is about 30 km x 30 km. The black area is open ocean with a sprinkling of icebergs.

Because of their exposed location in the flat surrounding ice shelves, ice rises act as topographic barriers to atmospheric flow. Many islands in the open ocean have windward-facing areas covered in vegetation fed by persistent rainfall, whereas the downwind sides are often dry and much sunnier. New Zealand, Hawaii and the Canary Islands are well-known examples of such strong atmospheric gradients linked to local topography and atmospheric circulation patterns. Although the conditions are not exactly the same, ice rises also have strong gradients with more snowfall on the upwind side than the downwind side.

Compared to the polar desert in the Antarctic Plateau, ice rises belong to a more warm and humid climate, which brings more snow, resulting in thick annual layers that are clearly distinguished in the ice cores. But the ice cores drilled on ice rises do not go as far back in time as their widely reported counterparts drilled on the Antarctic Plateau, which can provide information about the climate 800,000 years ago. Nevertheless, climate records from some cores collected from ice rises can provide very detailed recent climate information, making them ideal for studying the details of human-induced global climate changes since the 19th century.

Did you know …

… how ice rises are named?

They were identified early on and their naming reflects the history of their discovery. Some, like the Derwael Ice Rise, were named after their discoverers. Others, including the Dvořák and Ives ice rises, were named in honour of musical composers. The Crary, Fowler and Fletcher ice rises take their names from scientists, logistics personnel and administrators. Some derive their names from how they look, such as Blåskimen (blue glint).

Not always guardians

Ocean water provides very little resistance to the flow of the ice shelves, so they move quite uniformly over the ocean until they hit a grounded ice rise. An ice rise causes an abrupt slowdown in the ice shelf flow. An ice rise located in the centre of an ice shelf works like a police horse standing in the middle of a protest march. The flow goes around the obstacle and slows down the movement coming upstream. In glaciology, this effect is called ice shelf buttressing. Because the ice is quite rigid, this even affects the speed and direction of glaciers and ice streams feeding into the ice shelf.

On the other hand, the ice can speed up when it goes around the ice rise. This causes stretching and crevasses, which can weaken the ice shelf and promote iceberg calving. This limits the extent of the ice shelf. These effects – limiting the ice shelf extent and facilitating ice calving – are opposite to the buttressing effects of ice rises. The net impact of these competing effects is highly variable and depends on the location of the ice rise within an ice shelf.

A hand auger is tested for shallow coring on an ice rise.

Little sisters of ice rises

Ice rises have little sisters called ice rumples. They also form where shallow banks support the floating ice shelves from below. However, the contact area is much smaller than for ice rises so the surface expressions are usually only a few kilometres in diameter and just a few tens of metres high. Though ice rumples do not form a local flow regime, they do slow down the ice shelf.

Although more than 500 ice rumples are known around Antarctica, they are less investigated than ice rises. This is partly because, lacking a local flow regime, they are less useful for investigating past climate in ice cores. Also, extensive surface crevassing makes many of them dangerous to access.

What if ice rumples are lost?

A rising sea level may cause ice rises and rumples to lift off from their supporting shallow banks. Reduced ice mass discharged from the ice sheet makes the ice shelf thinner, which can result in similar lift-off of ice rises. Should that happen, the buttressing effect will decrease, the ice flow may instantly accelerate and the ice sheet will discharge more ice into the ocean than before. Lift-off and loss of buttressing happen abruptly, when a tipping point of rising sea level and ice sheet thinning is passed. If much of Antarctica's inland ice flows into the ocean, the sea level will increase significantly all over the globe.

Such changes can occur quickly, perhaps over decades or centuries. This is very fast compared to other processes in the ice sheet. Reconstructions of past sea level changes have shown rapid variations for which ice shelf buttressing may be one explanation.

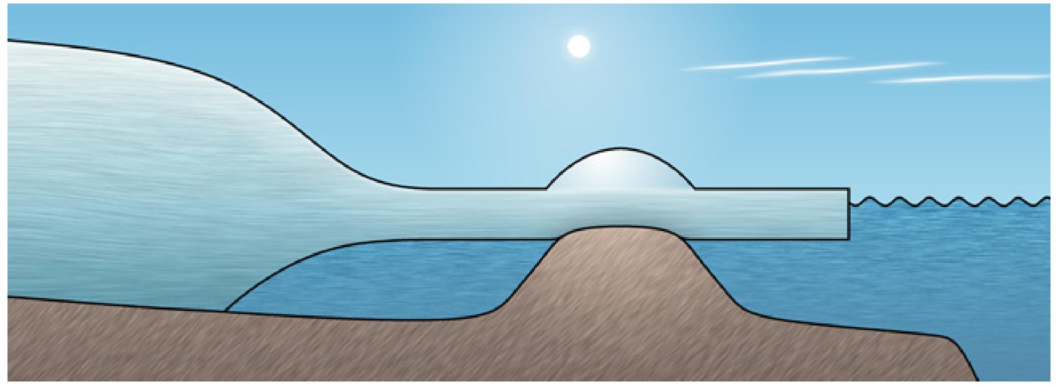
Ice rises slow down the flow of floating ice shelves. The consequences for the global sea level may be significant should ice rises disappear.

Streaky ice shelves

As ice shelves collide with ice rises and ice rumples, they are left with wounds and bruises in the form of crevasses and rifts. These can extend for many tens of kilometres and are visible as ice flow stripes in satellite images. They line up with other flow features and stripes imprinted on the ice inland.

When the shelf ice was still part of the grounded ice sheet, undulating bed topography caused local changes in the thickness of the ice. Subglacial water flows

Little sisters of ice rises, ice rumples, can harbour dangerous crevasses like these seen here.



An ice rise is part of the ice shelf that rests on a raised bump of the seafloor. It hinders the flow of ice from the continent into the sea. Should the ice shelf become so thin or the sea level so high that the base of the shelf is no longer grounded, the ice rise may be lost.

in the conduits carved into the ice at the base of the ice sheet. These conduits become larger near the grounding line. Such thin ice regions made by inland bed topography or subglacial water flow can form long channels in the undersides of ice shelves. Sometimes the channels are more than 100 m tall, reaching one-third or even half of the height of the ice shelf. When such water channels are wide, the overlying layer of ice sinks somewhat. Major channels underneath the ice shelf can therefore be seen at the surface as depressions and mapped by satellite imagery or altimetry.

The guardians of the Antarctic ice shelves – ice rises and ice rumples – have yet a story to tell, and it will be of critical importance to us all that they keep serving as gatekeepers of the Antarctic ice.

Ocean eats ice shelf

The lower surface of the ice shelves defines the ceiling for the ocean. Channels curved into the ice, as well as valleys in the seafloor, provide natural flow paths for circulating seawater underneath the ice shelves.

When warmer seawater meets the colder ice shelf base, the shelf ice is melted into the sea. The efficiency of this process is closely linked to how much heat is brought to the ice shelf from the offshore ocean, which varies greatly in different regions around Antarctica. In some regions, mainly west of the Antarctic Peninsula, the Antarctic Circumpolar Current brings warm water close to the coast and rapidly melts the ice shelves from below. Other regions, such as the vast embayments of the southern Ross and Weddell seas, as well as most parts of East Antarctica, are currently protected by colder waters so that the Circumpolar Current does not come into direct contact with the ice shelves.

Understanding the ocean processes that drive melting from below the ice shelf is one of the greatest challenges to understanding Antarctica's contribution to sea level rise in a warming climate.

In places where the relatively warm Circumpolar Current has access to the continental shelf, troughs and deep seafloor valleys in the continental shelf act as warm seawater highways. These often continue to the grounding line of the ice shelf, where the floating ice is thickest. Ice melts easier under thicker ice because of the high pressure from the ice and ocean above, so that even seawater that would otherwise freeze at the ocean surface can melt the ice at the grounding line.

In these regions, ice shelves can melt at rates of several tens of metres per year. If there is not enough ice spilling from the ice sheet to counterbalance this basal melt, the ice shelf will become thin. This balance is fragile, and increased melting due to warmer seawater can result in widespread ice shelf thinning and retreat. This leads to loss of buttressing, allowing the inland ice to flow more rapidly towards the coast, as has been observed in several regions in West Antarctica over the last few decades.

Understanding how the melting pattern at the base of the ice shelves around Antarctica will respond to future climate changes is one of the major challenges when assessing future sea level rise. The mechanisms by which the

This seaward view from the grounding line of an ice shelf shows the flow stripes that mirror the topography of the bottom of the ice shelf hundreds of metres below. The two tooth-like features are ice rises. In this modelled image the vertical dimension is greatly exaggerated in comparison to the horizontal.

climate affects the transport of ocean heat into the ice shelf cavities several hundred metres below the ocean surface involve complex interactions between the atmosphere, sea ice and ocean around Antarctica.

Heat pumps under ice shelves

Warm seawater brought from offshore may reach the ice shelves at different depths, depending on its density. In the coastal Southern Ocean, the density of seawater depends mostly on salinity, not temperature. The warmer, more salty water is located near the ice base far below the sea surface, and cooler fresher water is located near the sea surface. As warm water melts the ice shelf, this water is cooled down but also freshened, and thus gets more buoyant. As this water rises along the base of the ice shelf from the grounding line to the calving front, the reduced pressure retards melting.

This process works much like heat pumps in freezers and air conditioners in our homes, which pressurise gas and extract heat. In heat pumps under ice shelves, pressure differences determine the extent to which seawater at different depths can melt ice. Rising meltwater may even refreeze at shallower depths, forming so-called marine ice, which becomes part of the ice shelf again.

Different modes of ice-shelf melting

Details of these ice–ocean interactions have yet to be unravelled. Ocean turbulence near the ice shelf base is the key to determining how efficiently this heat pump works and therefore how much and how fast the ice melts at the bottom. By mixing up seawater, tides provide energy for basal melt. Seasonal variations, such as sea ice distribution, wind and sun radiation, affect the heat supply to underneath the ice shelves. At the global scale, ocean circulation connects the Earth's deep oceans and conveys heat from lower latitudes to the poles.

When warm ocean water meets the cold ice shelf, it melts the ice shelf from below.

Resolving these processes and estimating their impacts in a future warming world is a formidable challenge. Computer models used to predict the future of the climate tell us little if their results are not assessed with ground truths. But accessing the sea beneath several hundred metres of ice shelves in remote Antarctica to make direct observations is no easy task.

The weather and the ocean hollow out grottos in long-lived icebergs.

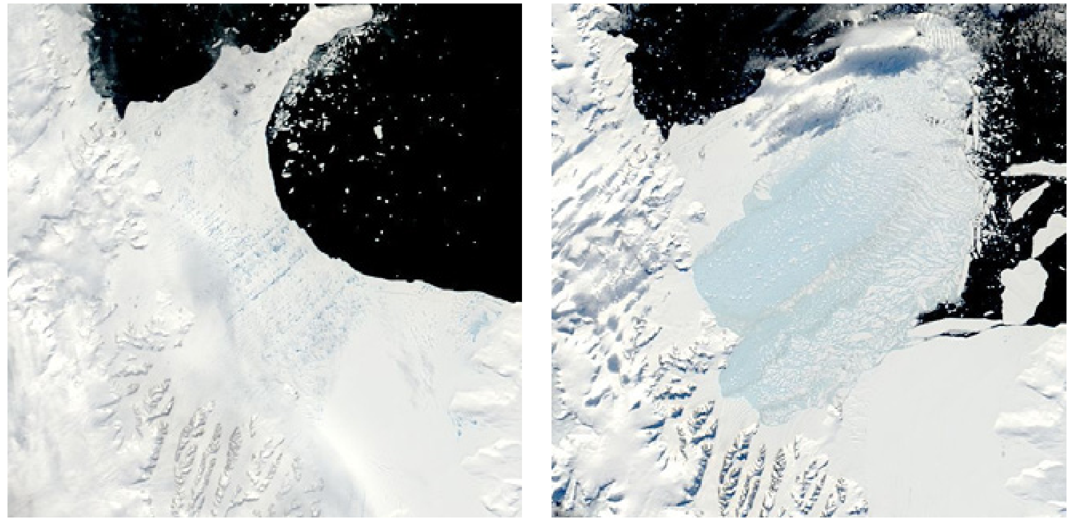
When do ice shelves calve?

Whereas snowfall, melting and ice discharge from the ice sheet are relatively steady processes, iceberg calving occurs abruptly from once every few years to once per many decades. In most cases, icebergs calve from longstanding rifts. Such rifts are often associated with thinner or cracked-up ice originating at ice rises and rumples.

The rifts spread through multiple flow bands of the ice. These flow bands have distinct characteristics stemming from when the ice was still grounded further inland. Even after the ice gets afloat, it undergoes complicated stretching, compression and ice–ocean interactions resulting in both melting and marine ice accretion. Although locations of future ice calving are somewhat predictable in many cases, it is very difficult to predict the timing of calving and the exact volume of a prospective iceberg.

The ice shelf system as a cork-stopper

Until the iceberg is suddenly calved from the long-lasting rift, the ice shelf keeps advancing. If major calving events reduce the ice shelf buttressing, it can result in a sudden speed-up of the upstream ice shelf. However, ice rises and rumples or other parts of the ice shelf can provide significant buttressing, reducing the impact of the calving event. This was a highly debated topic during the massive calving from the Larsen C Ice Shelf on the Antarctic Peninsula in July 2017, when an iceberg twice the size of Luxembourg broke off from the ice shelf. It remains to be seen how the inland glaciers react to this, but so far no major acceleration has been observed.


27 JANUARY 2002

7 MARCH 2002

Before and after the collapse of the Larsen B Ice Shelf, Antarctic Peninsula, as seen from space. The ice shelf broke into countless chunks of ice within a month's time in the summer of 2002.


The rescue training that research teams working in Antarctica receive improves the odds that they will escape harm on this hazardous continent.

Ice shelves work as cork-stoppers to maintain "healthy" ice discharge from the ice sheet.

An example of buttressing loss and consequent acceleration of outlet glaciers is the former Larsen B Ice Shelf, the northern neighbour of Larsen C. Larsen B suddenly disintegrated within a matter of weeks in 2002. Although the area of disintegrated ice shelf was about half the size of the iceberg that calved from Larsen C in 2017, the outlet glaciers responded almost instantly, speeding up over many years until they reached peak speed. They are now slowing down towards a new state of balance.

The Fimbulisen Ice Shelf, edging Dronning Maud Land, takes its name from a prefix in Old Norse – the language of the Vikings – that means "giant" or "mighty". It is about 200 km long and 200 km wide, fed by the Jutulstraumen Glacier.

These destabilised glaciers are too small to cause a noticeable sea level rise, but they clearly demonstrate the potential of rapid changes in ice discharge from the Antarctic Ice Sheet if coastal processes erode the fringing ice shelves. The ice shelves can be said to be corks in an Antarctic bottle, keeping the inland ice in place.

Antarctic fronts fighting surface melt

Prior to the disintegration of the Larsen B Ice Shelf, its northern neighbour, Larsen A, broke off in 1997. These disintegrations were not directly related to rifts opened by ice rises and rumples but rather to regional warming. Warming increased the ice melting at the upper surface of the ice and thinned the ice shelf, creating rifts and widening crevasses, which weakened the ice shelf. At the beginning, the crevasses were more like shallow and narrow cracks. But as surface meltwater gathered in pools and flowed into such cracks, they formed wide, deep crevasses that made the ice shelf collapse under its own weight.

The collapsed Larsen A and B ice shelves were in the northeastern part of the Antarctic Peninsula, the warmest region in Antarctica. Why is this area warmer than the rest of the continent? It is situated in the most northern part, the lowest latitudes in Antarctica, but this is not the whole story.

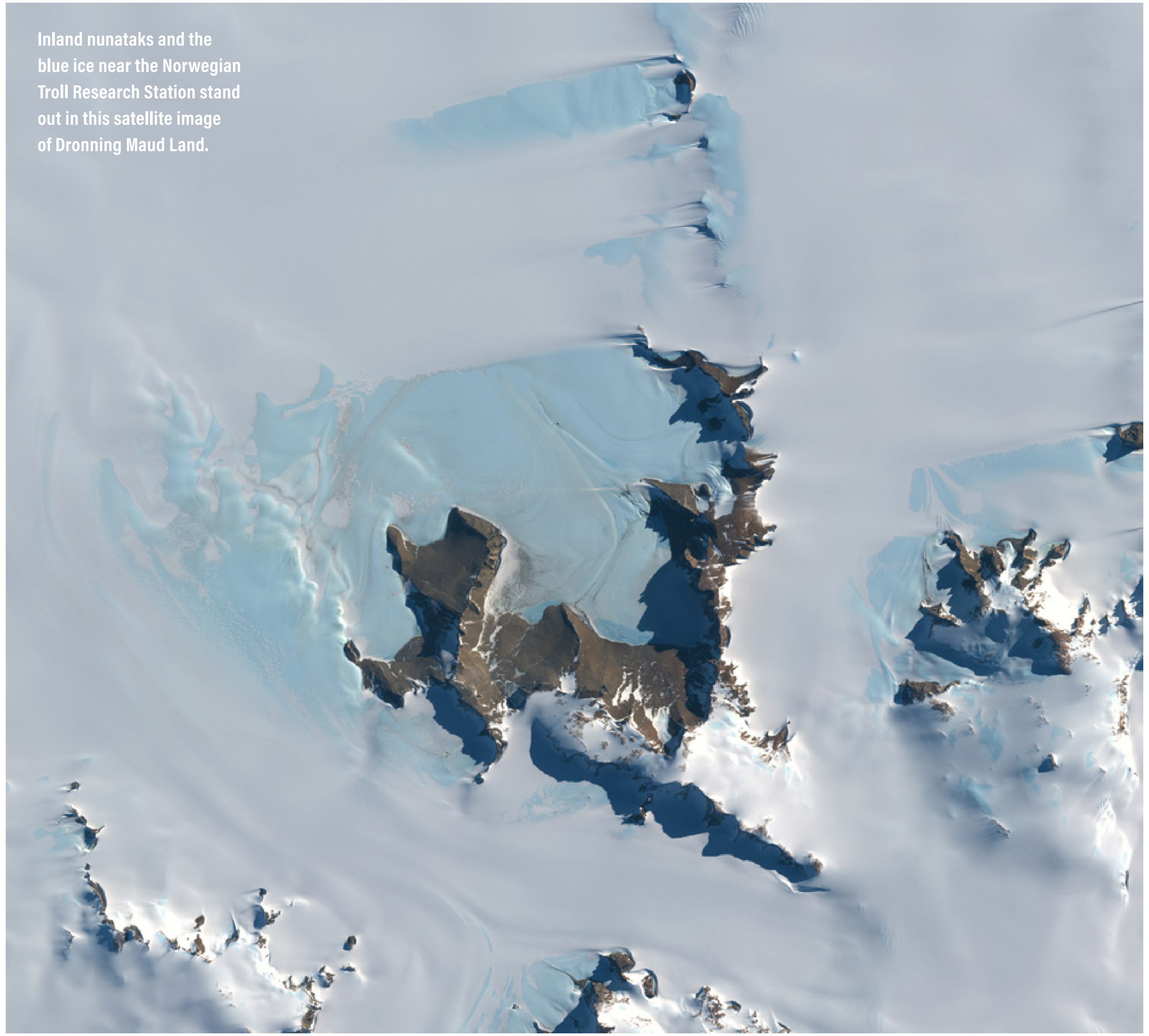
Strong circumpolar winds from the west nearly continuously bring mild, moist air masses around the Antarctic coast. In most regions, they flow freely over the ocean or over flat ice shelves. Ice rises are topographic barriers to this air flow. Something similar, but more extreme, happens on the Antarctic Peninsula. Here, as the mild, moist air rises more than 2 km to cross the peninsula, it cools and therefore releases moisture. So the highest Antarctic snowfall rates, in excess of 10 m per year, are found on the west coast of the Antarctic Peninsula.

On the east side, where the now drier air descends towards the ice shelves, the annual snowfall is only one-tenth of that on the windward slopes. Moreover, foehn winds – the warm, dry air that flows down the leeward slopes of mountains around the world – can raise the air temperature at the foot of the mountains to over +10°C, even during the dark, non-summer months. Meltwater runs down steeper ice, forming pools on flatter ice.

Did you know …

… that the highest temperature ever recorded on the Antarctic continent is 18.3°C?

This happened at Argentina's Esperanza Station, at the northeastern tip of the Antarctic Peninsula, which is situated on a dark, snow-free surface. It was generated by foehn winds on 6 February 2020.



Inland nunataks and the blue ice near the Norwegian Troll Research Station stand out in this satellite image of Dronning Maud Land.

The sand from rocky outcrops causes melt near the blue ice in inland Dronning Maud Land.

Rocks + blue ice = further melting

Not only foehn winds cause melt in Antarctica. Ice-free rock outcroppings and mountain peaks, known as nunataks, occur in some areas near the margins of the ice sheet, for example, along the Antarctic Peninsula and the Transantarctic Mountains. These dark nunataks absorb four times more radiation from the sun than the highly reflective white snow around them and grow so hot in summer that the ice melts around the rocky outcrops.

Other comparatively dark surfaces in Antarctica are areas of glacier ice that katabatic winds have swept clear of snow, exposing so-called blue ice. Comprising roughly 2% of the ice sheet, this darker blue ice absorbs almost three times as much solar energy as fine-grained snow, causing the ice to melt or to turn directly into water vapour. It has recently been discovered that in coastal Dronning Maud Land meltwater from blue ice areas on the ice sheet slope collects in large water pockets, known as buried surface lakes, inside the ice shelves. In Victoria Land, in the Ross Embayment, meltwater from blue ice areas on the grounded ice sheet has been observed to cross the Nansen Ice Shelf in river-like systems, pouring over the edge as waterfalls.

Melting in Antarctica sometimes also occurs in the more elevated, inland Antarctica. When the conditions are just right, elongated north–south atmospheric "rivers" carry relatively warm and moist air into the ice sheet's inland for hundreds of kilometres, up to 1500 m above sea level. The snowpack here is so cold that all meltwater quickly refreezes, so this meltwater does not reach the ocean.

Since ice shelves, together with grounded ice rises and rumples, work like cork-stoppers of the gigantic Antarctic ice reservoir, their health will be decisive for how much the Antarctic Ice Sheet will contribute to a rising sea level.

The health of the cork-stopper

Ice shelves grow by ice discharge from the ice sheet and by local snowfall on top, and they shrink by oceanic ice melting at the base and iceberg calving at the front. Snow melting at the surface can be locally important for ice shelf stability, but most meltwater refreezes in the snow, without removing or adding mass to the ice shelf. Ice shelves also stretch out and thin by their own weight, but that only changes the shape of the ice shelf, not the mass. The sum of the first four main processes – ice discharge from the ice sheet, local snowfall, oceanic ice melting and calving – is known as the ice shelf mass balance.

Ice shelf mass balance is a good indicator of the health conditions of the cork-stopper of the Antarctic ice reservoir. When the ice shelf mass balance is negative, the ice shelf shrinks, may lose ice rumples and eventually gives less buttressing to the ice sheet. When the balance is positive, the opposite happens. To determine the ice shelf mass balance and predict its near future we need to better understand how the ice sheet, the ice shelf and the ocean interact.

Future climate change will certainly affect ice shelves through atmospheric and oceanic melting and will consequently affect the stability of the ice sheet more dramatically than what we see today.

IceRises

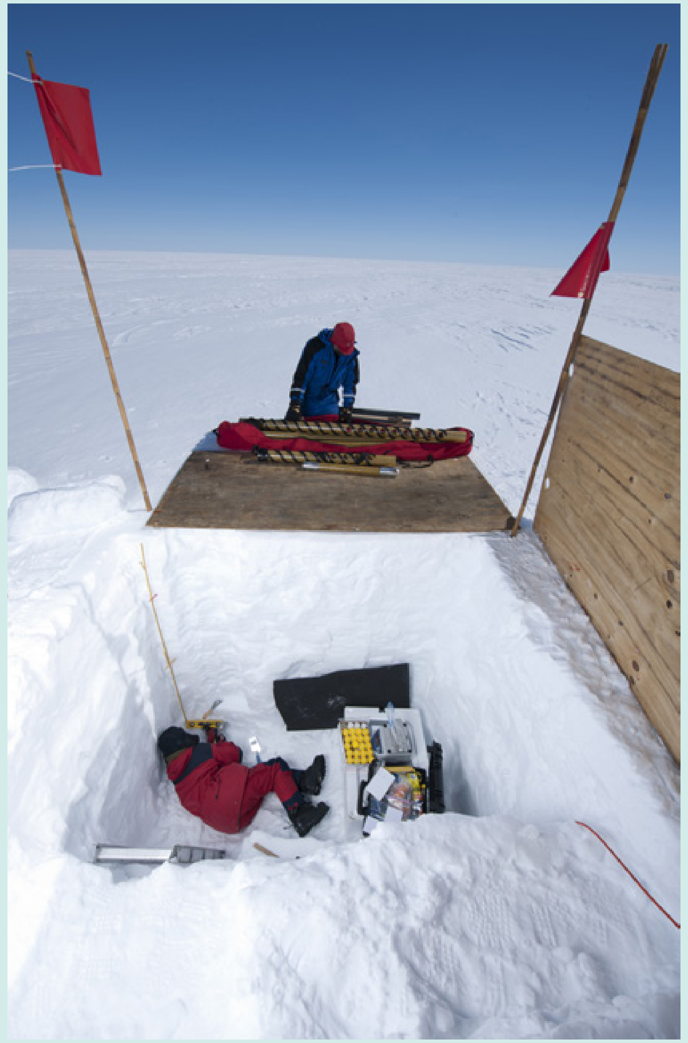
A science project with historic roots

Ice rises have played a role in Norwegian polar history. In 1911, Roald Amundsen erected an overwintering hut near the edge of the Ross Ice Shelf without fearing for his team's safety. As a keen reader of accounts by whaling captains, he knew that this part of the ice shelf, the Bay of Whales, moves much less than other parts, so there was little risk that it would calve during their wintering. We now know that this bay is associated with Roosevelt Island, Antarctica's second largest ice rise.

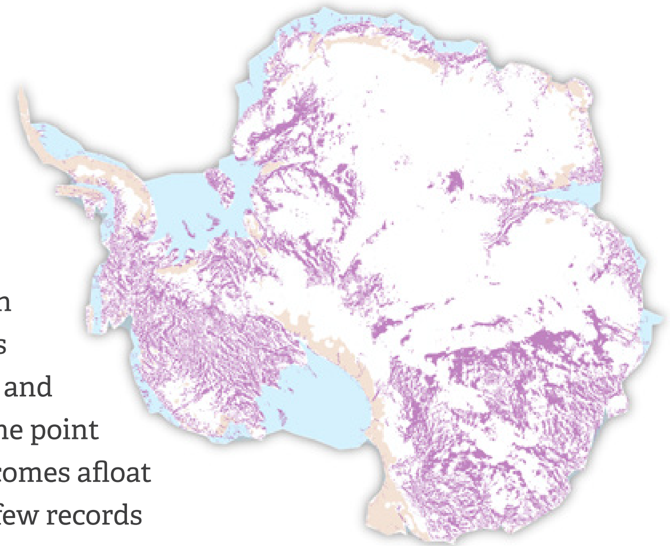
Some 40 years later, a Norwegian–British–Swedish expedition established Maudheim Station near the ice shelf edge in Dronning Maud Land. Making one of the earliest seismic surveys in Antarctica, they crossed over an ice rise to measure ice thickness – well before radar became standard equipment.

Dronning Maud Land has numerous ice rises and rumples along its 2600 km long coast, but by 2011 only a few had been investigated, by Germany and Belgium. Carrying forward the Norwegian association with ice rises, the Norwegian Polar Institute's IceRises project (2011–15) investigated three ice rises in the Fimbulisen Ice Shelf, which is fed by Jutulstraumen, one of the largest glaciers in Dronning Maud Land.

Located within 200 km of each other, these ice rises have similar climates even though one is next to the glacier outlet, one is at the calving front and one is in the middle of the slowly moving ice shelf. Analysing their rich data sets, scientists found that the three ice rises were generally stable for a few millennia, but their recent histories have diverged.



The map shows regions of possible rapid retreat due to marine ice sheet instability.



What if cork-stoppers are not healthy?

When the cork-stoppers are not in good condition, and buttressing is weakened, more ice is discharged and eventually the grounding line – the point where the grounded ice sheet becomes afloat – may move landward. There are few records of substantial grounding line migration in Antarctica observed by satellites.

A small bump in the bed beneath the ice can buttress the grounding line and stabilise it. This feature makes a health check-up very difficult. Some glaciers "dock" at such bed bumps for a long time, even though all the other conditions indicate that the grounding line should be much more landward.

At a certain point, when the mass balance is negative enough to detach the ice from this bed bump, the grounding line "sails" backward, retreating very rapidly until it meets a new bed bump, where it can dock again for an extended period. So observed docking and sailing features do not immediately imply whether the cork-stoppers are healty or ailing. Predicting this behaviour requires very detailed bed topography and precise modelling of buttressing provided by small bumps at various locations across the glacier front.

Parts of the ice sheet in West Antarctica may already have entered into an unstable retreat phase. If this is the case, they will keep retreating and thinning over the coming decades and centuries, irrespective of climatic and oceanic changes.

Marine ice sheet instability

In West Antarctica, much of the ice sheet rests on a bed below sea level. In some places the bed slopes downwards away from the coast, toward the centre of the ice sheet like the sides of a soup bowl. If the ice that is resting on such a retrograde bed melts back down the slope, a larger cavity is opened up to new melting. This does not happen where the ice is resting on an uphill slope.

As the grounding line pulls back into thicker parts of the ice sheet, more ice is discharged past the grounding line. The ice sheet loses mass, and the grounding line retreats further in a self-reinforcing loop known as marine ice sheet instability.

Several recent studies suggest that parts of the ice sheet in West Antarctica, mainly the Thwaites and Pine Island glaciers flowing into the Amundsen Sea, have already entered an unstable retreat phase. Most probably they will continue to retreat and shed mass over the coming decades and centuries no matter how the climate and ocean change in the future.

Marine ice cliff instability

Should West Antarctic ice shelves melt away or disintegrate in the future, the remaining grounded ice will form huge ice cliffs at their ocean fronts. The ice cliffs might become more than a kilometre tall from its bottom to the top.

No one knows exactly how these ice cliffs will behave. Such very tall ice cliffs may be unstable and collapse under their own weight. This proposes yet another mechanism for rapid ice sheet degradation and, together with marine ice sheet instability, could explain why sea level changes in the past have sometimes been faster than ice sheet models have indicated.

East Antarctica in less danger than West Antarctica?

Shifting focus to the mighty East Antarctic Ice Sheet, the story is different. Much of the ice sheet in this part of Antarctica rests on land above sea level, and the access of warm deep-water to ice shelf cavities is limited by the protective shield of the surrounding continental shelf.

Recent ice sheet changes here have been much smaller than in West Antarctica and the Antarctic Peninsula, but some regions in East Antarctica are also vulnerable to thinning and retreat caused by the ocean. Also, a recent study revealed that much of the coasts of Wilkes Land, regions flowing into the Ronne-Filchner Ice Shelf and coastal Dronning Maud Land are subject to marine ice sheet instability. East Antarctica is an enormous reservoir of ice, so even small changes in the ice shelves could severely influence the global sea level in the future.

Even in East Antarctica, some glaciers are affected by the ocean. For example, warm deep-water has reached the grounding line of the Totten Glacier in Wilkes Land, which alone contains enough ice to raise the global sea level by about 3.5 m if melted.

Top2Bottom and iMelt

The future of ice shelves

One reason why ice shelves in West Antarctica are losing ice rapidly is that they are exposed to warm ocean water. This is not the case for most parts of East Antarctica, where ice shelves meet cold ocean water. The Fimbulisen Ice Shelf, the largest ice shelf in Dronning Maud Land and the seventh largest in Antarctica, is one of these "cold" ice shelves. It takes about two days by snow vehicles to reach there from the Norwegian Troll Research Station, and only one day from the South African Station SANAE. The projects Fimbul Top2Bottom and iMelt (2009–22) focus on this ice shelf.

Why bother to study cold ice shelves, which are not undergoing the dramatic changes that other ice shelves are experiencing? The short answer is that we need to know when the ocean water becomes warmer under these shelves. This will help us understand when global climate change could cause large changes in these ice shelves that change only little today. The process that brings the warm water to the base of the ice shelves was poorly understood, but a series of field surveys using various instruments has increased our knowledge.

After drilling through the 200-300 m thick ice shelf with a hot-water drill, researchers installed three moorings under the ice shelf to measure temperature, salinity and ocean currents near the ice-shelf base and the bottom of the ocean. These records have been maintained since 2009, and they now form the longest ocean records under an ice shelf. Every other year, people fly out from Troll Research Station by helicopter or propeller airplane, dig several metres deep in the snow to retrieve the boxes with data loggers and batteries, and exchange these with new ones. In 2019, an ocean mooring was installed in front of the ice shelf to shed light on the relation between the open ocean and the episodic presence of warm water under the ice shelf.

Despite advances in satellite monitoring, theory, field evidence and numerical models, we still struggle to understand how much Antarctica contributes to the global sea level, and at what rate Antarctica will contribute to the sea level in the future.

On the sea ice by Sledeneset, Dronning Maud Land, emperor penguins slide on their bellies, propelling themselves along with their flippers – a more efficient mode of locomotion for long distances than waddling on their short legs.

Hiccups: hardly predictable

Although the marine aspects of ice sheet instability get the most attention, it is also important to consider such conditions as the presence of sediments and the amount of subglacial water on the ice bed, as these reduce friction under the ice sheet and cause it to slide like an ice highway.

Some mountain glaciers in regions like Alaska, Svalbard and the Himalayas cycle between periods of slow and fast flow – "sleeping" and surging phases. During the fast phase, glaciers can move 10–100 times faster than during the slow phase. Slow phases last much longer than fast phases.

Whereas a surge cycle of a mountain glacier can be observed within a human lifetime, it may take hundreds or thousands of years for an ice stream in Antarctica to make the same transition. The best known example in Antarctica is the Kamb Ice Stream on the Siple Coast off the Ross Sea, which "shut down" some 180 years ago and is now thickening by about half a metre per year because the ice flow is too slow to keep up with the snowfall.

The reasons for these phases are not fully understood but freezing and thawing of the ice bed, in combination with water and sediments, certainly play a key role. Understanding these mechanisms is a major research focus for improving ice sheet models and projections of future change. No one knows when the Kamb Ice Stream will wake up from its hibernation.

The Antarctic Ice Sheet is highly complicated. Inland ice, outlet glaciers and ice shelves all need to be better understood. How these subsystems in Antarctica interact with each other, such as the transition from inland ice to glaciers, migration of the grounding line, and ice–ocean interactions underneath the ice shelves, is not well known. A few features – such as hiccups and dock-and-sail features – are apparently disconnected from climate factors, but are important to estimate Antarctic mass balance. It is still difficult to read the signals that are the causes, consequences or both of ice sheet changes in Antarctica.

4

Ancient Antarctica

The first time Antarctica glaciated was halfway back to the dinosaur age. Since then, the ice has shrunk and expanded many times. This history has set the stage for today's Antarctic Ice Sheet and can be used as a textbook to learn how the Earth System works, helping us understand the future Antarctic Ice Sheet.

Tropical Antarctica

Although the ice found in Antarctica so far is less than 2 million years old, Antarctica was glaciated much earlier. It happened when the Antarctic continent was separated from other continents about 34 million years ago. Before that, Antarctica had a warm, tropical climate. All the continents have moved over time in a process called Continental Drift. When the German scientist Alfred Wegener proposed the theory in 1912 it was a hot topic, but the idea languished until it was formally accepted in 1965.

The continents and ocean basins that we have today stem from a supercontinent that incorporated almost all landmasses on Earth about 290 million years ago. This supercontinent, called Pangea, started to break up about 200 million years ago into several tectonic plates that slowly drifted towards the geographical locations where we find them today. In this break-up process, the Antarctic continent was a part of Gondwana, one of two pieces broken from Pangea.

During this period, atmospheric carbon dioxide (CO_2) levels were more than three times of what they are today. At that time, temperatures during the austral winter exceeded +10°C in Antarctica. Antarctica was covered by tropical and mixed forests, and there was no ice at all. Computer models show that the climate was too warm to glaciate any parts of the planet.

When Antarctica was in such tropical conditions about 50–60 million years ago, the continent was still connected to Australia, and the Drake Passage between South America and the Antarctic Peninsula was not yet opened or was only very narrow and shallow. As Australia and South America slowly drifted northwards, the Drake Passage and the Tasmanian Gateway gradually opened up about 40 million years ago, allowing the Southern Ocean to flow around Antarctica. Thus, the famous Antarctic Circumpolar Current came into being.

The Antarctic Ice Sheet is born

The opening of those two oceanic gateways induced dramatic changes in global oceanic circulation. Soon after that, Antarctica was glaciated for the first time – around 34 million years ago. It is hard to imagine, but this was 30 million years after the dinosaurs' mass extinction that occurred 65 million years ago.

Did you know …

… that the theory of Continental Drift is as old as the human footprint on the South Pole?

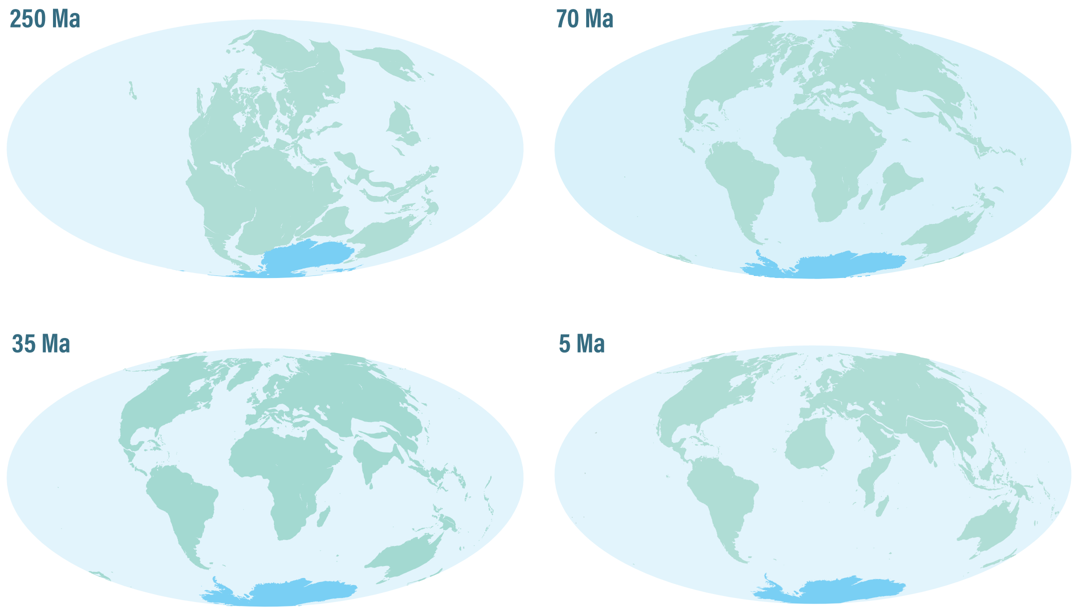
The German scientist Alfred Wegener launched his controversial theory in 1912, just after the Norwegian explorer Roald Amundsen and his party reached the Pole in December 1911. The team led by British explorer Robert Scott that followed soon after collected geological samples which showed that Antarctica was part of the ancient, tropical supercontinent Gondwana.

Geological evidence shows that atmospheric CO_2 levels dropped when the gateways were open and Antarctica was glaciated for the first time. Were these events coincidental or were they the consequence of unknown processes? If they were linked, which one triggered the others?

The first computer modelling of those ancient climates suggested that it was the drop in atmospheric CO_2, rather than the opening of the oceanic gateways, that triggered large-scale glaciations across Antarctica. However, more recent experiments suggest that the ocean could have played a larger role than previously thought in the initial Antarctic glaciations.

Carbon dioxide: the pacemaker of the Antarctic ice

The Antarctic Ice Sheet has grown and shrunk in the past 34 million years. When the Antarctic Ice Sheet was still young, it grew very wide during cold times and almost completely disappeared when the planet heated up again. The most influential climatic factor for the long-term ice sheet behaviour is greenhouse gas



Ancient Antarctica and other continents drifted to their current locations during the past 250 million years (Ma).

concentration in the atmosphere, especially the concentration of CO_2, which to a large extent determines global temperature.

When Antarctica was glaciated about 34 million years ago, atmospheric CO_2 levels were around 700 parts per million (ppm), which is much lower than the 1500 ppm in the air before the glaciation. Since the onset of the Antarctic glaciation, CO_2 levels have never exceeded 700 ppm. During the last 1 million years – a period that witnessed the development of the ice sheets in the Northern Hemisphere – CO_2 levels have ranged between 200 and 300 ppm, until recent decades, when the level of CO_2 in the atmosphere has spiked upward as a consequence of the Industrial Revolution.

The atmospheric CO_2 level measured at the Mauna Loa Observatory in Hawaii, a global reference site, reached 411 ppm as the 2019 annual average. This was far beyond the range globally during the last 1 million years. The last time there was this much CO_2 in the atmosphere, the Antarctic Ice Sheet was much smaller than today and the sea level was 15 m higher.

Since the Antarctic Ice Sheet started to grow, there have been repeated growing and shrinking cycles, largely controlled by greenhouse gases in the atmosphere.

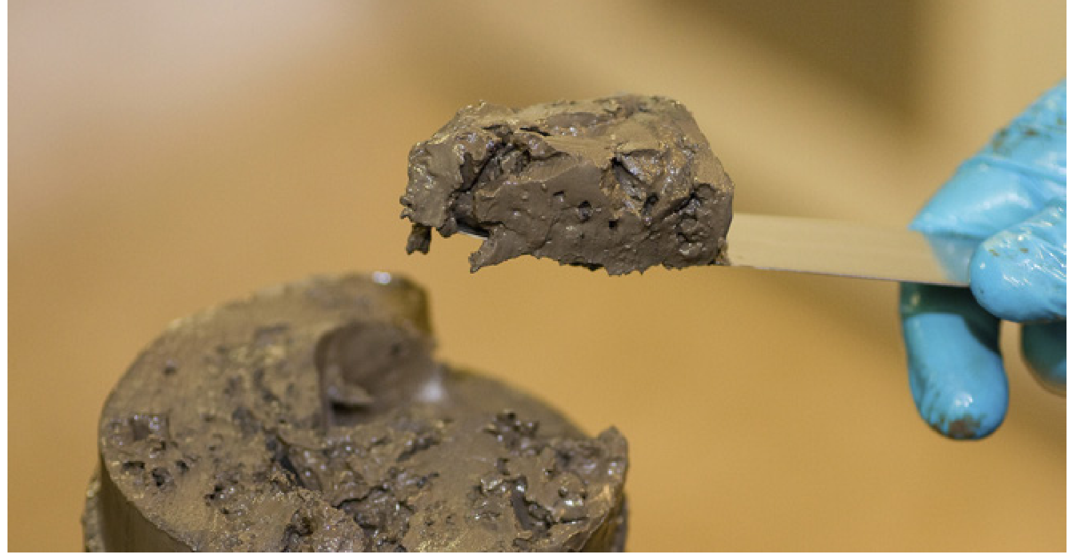
Marine sediments: a telescopic view of the past

The evolution of the Antarctic Ice Sheet during the past 34 million years is recorded in offshore marine sediments near Antarctica. Like ice layers within the Antarctic Ice Sheet, marine sediments "remember" what happened in the past. In fact, the storehouse of sedimentary information at the seafloor extends much further back into the Earth's history, although the way these sediments accumulated means that they do not always yield the finer record that scientists find in ice cores.

Sediments build up on the seafloor much more slowly than the snow that eventually turns into the ice in ice cores. Although marine sediment cores do not allow scientists to distinguish events that occurred on short timescales, they provide a good picture of long-term conditions that occured over a large area – a "telescoped" view.

While radio waves are used to visualise ice stratigraphy, acoustic waves show the layers within marine sediments below the ocean. Scientists on research vessels generate acoustic waves in the water, which penetrate the sediments and bounce back from the seafloor surface and boundaries of sediment layers.

A flock of Antarctic petrels flies over Trolltinden mountain in Jutulsessen, Dronning Maud Land.



Colour and grain size in marine sediment cores, as well as micro-organism fossils, offer clues about global warming and cooling.

In this way, acoustic surveys reveal morphological features of the past seafloor, which can help us understand the processes that shaped the seafloor. An example of this is the scars left behind when the keels of huge tabular icebergs drag across the seabanks beneath them.

Just like ice layers are first surveyed by radar and then ice cores are extracted, marine sediment cores are drilled after the sediment layers have been acoustically mapped. Because each sediment core is only 10 cm in diameter, looking at a single core is not enough to get a proper picture of the environment at a given time. Many cores are needed, together with acoustic mapping. Core analysis tells us facts about the environment such as sea ice coverage, distance to the ice sheet at that time, water temperature, speed of ocean currents and benthic ecosystems on the seafloor.

Clues from debris

A clear sign of ice sheet dynamics appears in sediment cores in the form of debris transported from the ice sheet bed to the ocean. As the ice sheet flows, rocks, pebbles and soft sediments are scraped up and trapped within the ice. When the ice eventually becomes an iceberg, drifting with the wind and ocean currents and melting from below, debris trapped at its base is released and settles on the seafloor.

Rivers can also transport rocks and pebbles to the ocean but only icebergs move them over long distances into the deep ocean, beyond the continental shelves. Icebergs are formed regardless of whether the ice sheet is growing, stable or shrinking. Nonetheless, the quantity of iceberg-rafted debris in seafloor sediments indicates the magnitude of mass discharge in terms of icebergs.

Sediment cores closer to Antarctica can tell us more directly about the environment in the Antarctic. Sediment erosion obscures part of the climate history contained in a core but also indicates dramatic environmental changes, such as ice sheet advances. The cores tell stories about the open and the sea-ice-covered ocean, and about the ocean under ice shelves and the bed under the ice sheet. For example, sediment comprising a mixture of fine-grained and coarse sand that includes broken pieces of rock rather than broken fossils indicates that the material was released from the ice sheet.

The underside of an ice sheet picks up rocks and pebbles as it creeps along the ground and icebergs eventually carry this material out to sea. This kind of rubble on the seafloor is a tell-tale sign of an ice sheet.

A heart of stone? This geological formation was found at the mountain Armlenet in Dronning Maud Land.

Combined analysis of core sediment layers and acoustically mapped seafloor morphology can reveal whether the past ice sheet had a frozen or wet bed, subglacial water channels and outwash meltwater sediments. Fossil organisms at the bottom of the sea reveal details about the past geochemical composition of the seawater and the timing of the sediments' deposition.

Sediment drilling from the poles to the tropics

The world's oceans are interconnected in such a way that sediment cores in the mid- and low latitudes, far away from polar regions, offer information about what happened in Antarctica and how such events are linked to climate change. Indeed, not only marine sediments but also fossilised coral reefs and other markers of past shorelines in mid-latitudes and tropical regions are used to reconstruct the volume of the Antarctic Ice Sheet at various times in the past.

Internationally coordinated marine sediment drilling started in the late 1960s. Before these projects, climatologists believed that all ice sheets – Antarctic, Greenland, former Scandinavian and North America's former Laurentide – began to grow only 3 million years ago. Nowadays we know that the Antarctic Ice Sheet was initiated 34 million years ago and the others about 4 million years ago.

Since the 1970s, more Antarctic-oriented scientific drilling campaigns have been carried out on seasonal sea ice or ice shelf platforms. The Cape Roberts Project in 1997–99 and the Antarctic Drilling Project (ANDRILL) in 2006–07 collected the longest ever sediment cores from the margins of the continent. The cores were extracted from 1 km into the sediments and gave climate information dating back about 40 million years, suggesting that the West Antarctic Ice Sheet has retreated substantially many times in past warm periods.

Antarctica started to glaciate 34 million years ago. The Greenland Ice Sheet started to grow only 4 million years ago.

34 million years of yo-yoing

Over the past 34 million years the Antarctic Ice Sheet has significantly expanded and shrunk many times. It diminished particularly 25–26 million years ago, 15–17 million years ago and 3–3.3 million years ago.

About 25 and again 14 million years ago, the West Antarctic Ice Sheet and some sectors of the ice sheet in East Antarctica grounded on the part of the bed

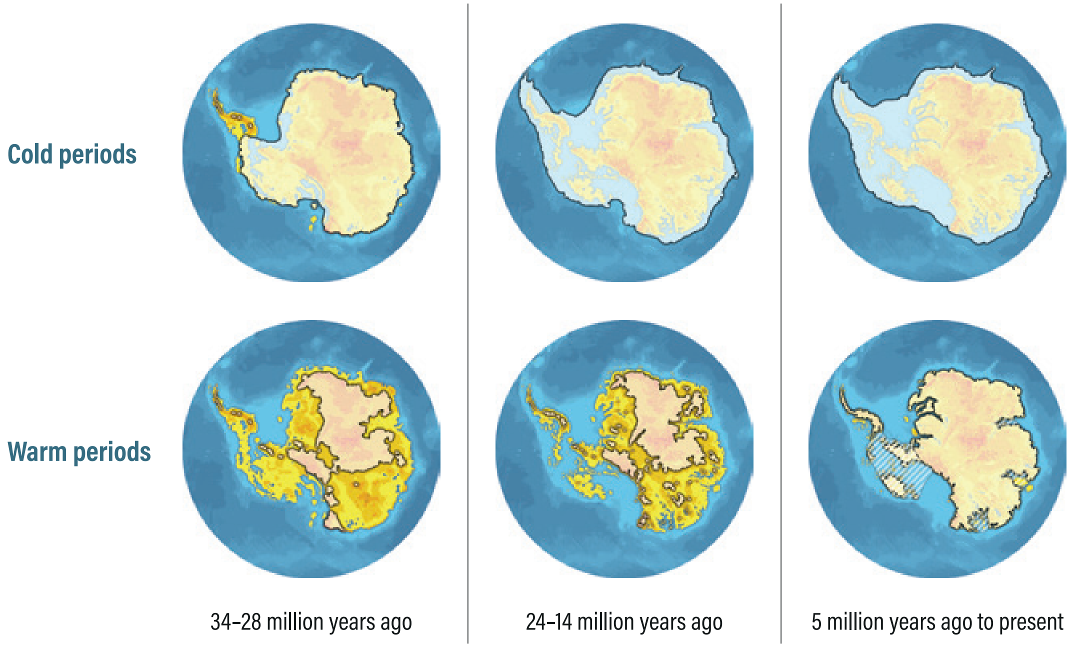
The Norwegian Polar Institute's 2018 geology expedition set up its kitchen tent in front of the mountains Hoggstabben – composed of grey monzonite rock – and Vedkosten, which is reddish brown charnockite.

which was well below sea level. Since then, the Antarctic Ice Sheet has also been influenced more directly by the ocean temperature, which is linked to CO_2 levels in the atmosphere. Some marine sediment cores show that large parts of the Antarctic Ice Sheet resting on the below-sea-level bed disappeared some 3 million years ago, and that this could have been mainly triggered by ocean warming.

Making its own bed

The ice sheet can expand only if the bed is high enough so that the ice can ground, rather than float over the ocean. Like any other continent, the Antarctic continent is surrounded by shallow ocean to the continental shelf break, where the seafloor rapidly falls off to about 4–6 km depth at the deep underwater plain that covers about half of the Earth's surface.

Ice is a ruthless bulldozer, eroding its inland bed and filling the seafloor, so that the continental shelf has expanded during the cycles of growth and shrinkage of the Antarctic Ice Sheet. Such a filling effect was particularly active in the early days of the Antarctic Ice Sheet. For the last 5 million years, the extent of the Antarctic Ice Sheet has mostly been limited to the edge of the continental shelf.



34–28 million years ago

24–14 million years ago

5 million years ago to present

Antarctica's ice sheet and bed topography have evolved dramatically during the last 34 million years. In each of the three time periods illustrated, the ice sheet grew and shrank many times as the Earth's climate see-sawed between warm and cold.

The ANDRILL drill site piques the locals' curiosity on the Ross Ice Shelf. A vessel used by the International Ocean Discovery Program was equipped with a bore tower for drilling long sediment cores.

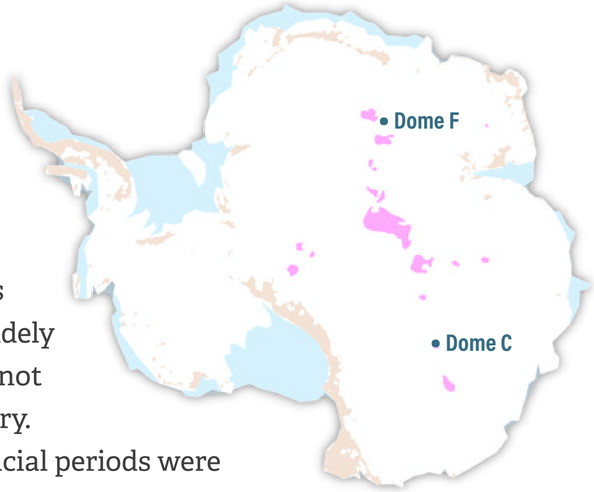
By wearing away the continent's inland bed and adding the eroded material to the continental shelf, the Antarctic Ice Sheet has expanded its own size limit.

The bed of the Antarctic Ice Sheet has kept moving up and down as the ice sheet above has changed, like a mattress that yields under your weight and then bounces back up again when you get up. This rebound happens only slowly and is related to the stiffness of the Earth's mantle, which is not uniform under the Antarctic Ice Sheet. Because the inland region is more often covered by thicker ice, the bed is lower in the centre of the continent compared to the edges, which is the opposite of the other continents.

Solar radiation – another key factor

Over timescales of several million years, the atmospheric CO_2 level has been the chief factor determining the global climate and the extent of the Antarctic Ice Sheet. The variation that the Antarctic Ice Sheet undergoes within shorter spans of time – less than 1 million years – can be attributed to astronomical factors. Earth's orbit and rotation axis have varied over geological timescales, altering the amount of incoming solar radiation.

There are three astronomical mechanisms that have distinct rhythms from 20,000 to 400,000 years. Together, these astronomical rhythms make up significant variations in solar radiation at high latitudes, causing glacial periods when the polar regions were covered with large ice sheets.



The map shows computer-predicted locations of the oldest ice near the Antarctic bed, 1–2 million years old.

The most recent glacial–interglacial cycles have a duration of about 100,000 years. In the 1920s, Milutin Milanković, a Serbian mathematician, postulated that ice sheets can grow and expand only when astronomical conditions lead to cold summers with little ice melting in the Northern Hemisphere. He noted that such conditions broadly occurred every 100,000 years. His theory is now widely accepted as a driving force of Earth's climate change, but not all glacial–interglacial cycles are explained with this theory.

A major remaining mystery is that glacial–interglacial periods were once on a 40,000 year cycle before changing to 100,000 years. This adjustment occurred about 1 million years ago. Scientists are now working toward extracting ice core records for 1–2 million years ago to understand this and similar rhythm shifts that have happened many times in the geological timescale.

Rapid shrinking but slow growing

Repeated warming and cooling cycles are not symmetrical. The dropping of the CO_2 level, global cooling and the expansion of the Antarctic Ice Sheet all happened at a much slower pace than the planet's earlier shift to a warm period.

These slowly growing – but rapidly shrinking – features occur mainly because the global climate system reacts differently to solar radiation during cooling and warming periods. For ice sheets, a small increase of solar radiation can increase melting, but a more significant cooling is necessary for glaciation. This is like having to prepare ice cubes in your freezer for a party half a day in advance to give them time to set, but the ice melts in your cocktail in less than an hour.

In the last one million years, there has been a shift between glacial and interglacial periods every 100,000 years or so. The last glacial period reached its height 21,000 years ago.

Rich data but still few answers

Antarctica probably contributed to a global sea level rise of about 5 to 20 m during warm periods in the last 34 million years, but these figures are uncertain. The Last Glacial Maximum, about 21,000 years ago, was the highpoint of the most recent glacial period. At that time, both the Antarctic and Greenland ice sheets spread almost all the way to the edge of the continental shelf, except for a few basins, which were probably affected by the intrusion of warm ocean water. During the interglacial period around 128,000 years ago – just before the last glacial period – global mean sea level was 5–13 m higher than it is today. Scientists are still working out the different contributions of the ice sheets in Antarctica and the Northern Hemisphere to the sea level during that time.

Following the Last Glacial Maximum the Antarctic Ice Sheet experienced its most recent growth spurt. Evidence of occurrences on short timescales – centuries and millennia – after that event are well recorded because the evidence is relatively fresh and undistorted by following glaciations.

Ice and sediment cores show climate shifting back and forth every 500 to 2000 years in the Arctic as well as in Antarctica. This is especially visible within the well-preserved Holocene records, the period after the Last Glacial Maximum. Indeed, 25 such oscillations were identified in Greenland ice cores; they are

Did you know ...

... that the oldest ice discovered so far was found near the surface of the ice sheet?

It is located at Allan Hills in the Transantarctic Mountains. Elevated beds there hinder the ice flow so that most of the ice has to flow around the mountains, but some of it gets stuck there.

At the upstream side of the mountains where we find such stuck ice, strong katabatic winds blow away surface snow and expose the blue ice. As ice is lost at the surface, the ice underneath moves upwards – quite contrary to the normal behaviour of glacial ice. This unique local ice flow has pushed glacier ice about 1–1.4 million years old up to near the surface.

A Weddell seal yawns and stretches on the ice. The species is found around the entire continent.

Oldest Ice

International hunt for the oldest ice on the planet

Ice cores are time capsules. Greenhouse gases like CO_2 and methane trapped within air bubbles in the ice reveal what Earth's climate was like in the past, sometimes the very distant past. The Antarctic Ice Sheet is about 34 million years old, but that does not mean that we can retrieve 34-million-year-old climate information from ice cores. The tremendous weight of the overlying ice has compressed the records of million years into layers too thin to decode or too deformed to be used for climate research. Some of the deepest ice has melted away.

There are now major international efforts to drill ice cores in inland Antarctica for a full, continuous record stretching back to about 1–2 million years ago. This will greatly outdo the oldest ice core that we have so far, which goes 800,000 years back in time.

Norway (a member of the European science consortium Beyond EPICA Oldest Ice) had the good fortune to join a Japanese Antarctic research expedition to search for very old ice on Dome Fuji (Dome F) using special ice-penetrating radar developed by the universities of Alabama and Kansas. European nations and Australia are working on Dome C, which is also on the inland plateau of East Antarctica. A few more nations are readying their own deep drilling projects. The array of oldest ice cores produced by these multi-national drilling efforts will be rigorously analysed, furthering our understanding of the Earth's climate system.

Did you know …

… that the Earth adjusts as the ice disappears?

The elevations of the bed under the ice have changed along with the changes in the ice sheet. This is because the weight of the ice sheet presses down the Earth's crust – by one third of the ice thickness.

When the ice sheet withdraws, the mantle and the crust rise. This happens slowly. Scandinavia and North America, for example, are still rising today, even though their large ice sheets disappeared about 20,000 years ago. The crust of Antarctica and Greenland are also rebounding, because their ice sheets are much smaller today than they were during the last glacial period.

Antarctic petrels feel at home in the unforgiving conditions of Antarctica's pack ice, icebergs and ice floes as well as on the continent.

characterised by steep warming for a few decades, followed by a gradual cooling, similar to glacial–interglacial changes but at a faster beat.

These millennial-scale climate shifts did not occur at precisely the same times in Greenland and Antarctica; sometimes what was happening in Antarctica was the opposite of what was going on in Greenland. This was probably related to how ocean circulation transfers heat between the Northern and Southern Hemispheres. Understanding the mechanisms that caused such abrupt rapid climatic shifts in the past will shed light on how global sea level and the world's climate will be affected by the release of large volumes of freshwater from Antarctica in the form of discharged ice.

5

Antarctica's future is our future

After time-travelling 34 million years since the birth of the Antarctic Ice Sheet, let's look at the ice sheet today, how it may change in the coming centuries and what is needed to protect it. The level of atmospheric carbon dioxide (CO_2), the main controlling factor of the global climate and the Antarctic Ice Sheet, is currently higher than it has been for the last one million years and is on the rise.

Climate change before the industrial era

Atmospheric CO_2 level and astronomic changes in solar radiation to the Earth are the main sources of climate evolution over glacial and interglacial periods. At millennial and centennial timescales, volcanic eruptions and ocean circulation also play important roles in climate fluctuations. Climate is the balance of interactions between the atmosphere, oceans, biosphere and land surface. Each of these contributors to the climate system undergoes change at its own time- and spatial scale.

Over the past few thousand years, people recorded signs of climate change and its impact on their lives, such as early harvest and tree blooming in warm periods, and freezing rivers, long-lasting seasonal sea ice and mountain glaciers advancing down valleys in cold periods. Such centennial-scale climate changes occuring during human history have been caused by combinations of various natural causes, which are still being unravelled.

Predicting climate change is a big challenge as the climate depends on both the natural evolution of the Earth and human activities.

People impact the climate

The rise of the industrial era ushered in a new world in which people impacted the climate in a manner never seen before. The period prior to 1850, referred as pre-industrial, therefore serves as a baseline for current climatic conditions. At that time, the atmospheric CO_2 level was around 280 ppm. Since then, CO_2 in the atmosphere has been consistently increasing to the present-day value exceeding 400 ppm. Most of this rise is attributed to human activities. The average global temperature has now climbed by more than 1°C above the pre-industrial average. Natural causes have affected the temperature but they cannot explain the warming that we are experiencing. The results that climate models spit out replicate this recent warming only when the CO_2 that people are pumping into the atmosphere is taken into the calculations; when human-made CO_2 is removed from the equations, the models fail to reflect the changes that we are observing in the world.

In the past decade, extensive research on the climate system revealed that the consequences of high CO_2 levels in the atmosphere are more complicated than once thought. Extreme weather events tend to occur more often and become even more extreme and of longer duration. Rainfalls during summers in sub-tropical and mid-latitudes have become more like water bombs. Tropical cyclones are stronger and more frequent, wreaking much more damage. Instability of the polar vortex – the area of low pressure and cold air that circulates anticlockwise over the Arctic – causes Arctic air to penetrate farther south than before and tropical air to extend farther north than usual, leading to extreme climatic conditions over North America and Eurasia. These are embedded in more gradual changes such as ocean warming and the melting of glaciers and ice sheets.

From 1901 to 2014, the average global temperature was measured to have gone up by about 1°C (blue). The steepest rise has occurred since the 1970s and can be replicated by climate models only when CO_2 and aerosols emitted by human activities are folded into the calculations (light blue). When the models consider only natural sources (solar radiation and volcanos) they mistakenly show that there has been virtually no warming (pink), contradicting what has actually been observed. The white bar shows zero increase of temperature over time.

The period before the year 1850 is referred to as pre-industrial and is a baseline against which we measure today's climate. The increase of CO_2 in the atmosphere comes mostly from human activities.

Highest CO_2 levels ever experienced by humans

Predicting future climate evolution is a big challenge because the climate depends largely on human activities that are dramatically modifying atmospheric CO_2 levels. Projecting the climate over the next decades and centuries entails predicting human activities combined with the natural evolution of the Earth's system.

Scientists have proposed a series of scenarios based on different levels of carbon emissions in the future and accounting for different states of economic growth up to the year 2100. The first of these scenarios, published in 2000, predicted that CO_2 levels would reach between 500 and 1000 ppm or even more by the end of 21st century. Those scenarios were the basis of the climatic projections given by the Intergovernmental Panel on Climate Change (IPCC).

In 2014, the IPCC presented adjusted emission scenarios and for its upcoming report in 2021 the scenarios have been re-adjusted, taking into account many socio-economic indicators, such as demography, urbanisation and economic developments, which vary from one country to another. These scenarios are used to design targeted CO_2 emissions for the COP21 Paris Agreement, with the aim of keeping global warming from exceeding +1.5°C compared to the average pre-industrial temperature.

Ongoing sea level change

As well as an increase in atmospheric CO_2 levels, the average sea level around the world has gone up by about 20 cm in the period 1900–2010 – an average of about 1.8 mm per year over the past century – according to the satellite measurements since the 1990s and a global network of tide gauges for the pre-satellite period. But sea level changes are not globally uniform. In some regions, the sea level is rising faster than in others, and in some regions the level is even falling. Local sea level variations are affected by changes in the gravity field due to the changes in ice sheets and oceans, as well as by the uplifting of the Earth's crust after deglaciation. Ground water extraction in many major cities lowers the land and adds a local sea level rise to the global mean.

Amongst many factors affecting the sea level, ocean warming was the dominating factor until 2005. Because warmer seawater is less dense than cold seawater, a warmer ocean occupies more space, so the sea level rises. However, since 2006, meltwater from glaciers and ice sheets has become the main contributor to sea level changes. More importantly, the pace of sea level rise has increased considerably over the past century. It was 1.4 mm per year from 1900 to 1990 but 3.7 mm per year between 2006 and 2013.

Did you know …

… how much ice is equivalent to 1 mm of sea level rise?

The answer is 360 trillion kg. This is based on the fact that the world's oceans cover an area of 360,000,000 km^2. Because ice is about 10% less dense than water, 360 trillion kg of ice works out to 393 km^3 of ice. Keep in mind that neither melting sea ice nor ice shelves add to sea level, only land-based ice does.

Ice sheet health check

How much ice has recently been lost or gained in Antarctica, contributing to global sea level change? It is not an easy task to make a comprehensive health check of the vast ice sheet. The Antarctic Ice Sheet qualifies as a desert because so little snow falls there. But the area is so vast that even light sprinklings of snow add up to a huge amount, which makes the ice sheet grow. The difference between the snowfall and the ice discharge – the Antarctic Ice Sheet's mass balance – is not big, but it is currently negative. This means that more ice is being discharged than is being added to the ice sheet, and the negative balance is large enough to impact current global sea level.

This makes a continuous health check-up of the Antarctic Ice Sheet one of the most important monitoring tasks that scientists carry out. How do we keep a close eye on a continent that is roughly 1.5 times the size of the USA or China but has only 40 year-round research stations? How do we monitor ice discharge

The speed of sea level rise has increased considerably over the past century.

All animals in Antarctica, including emperor penguins, the biggest of all penguins, are seriously affected by ongoing rapid changes in Antarctica.

SCAR – coordinating Antarctic research for over 60 years

One major outcome of the momentum generated by the International Geophysical Year in 1957–58 – which was also the third International Polar Year – was the Scientific Committee on Antarctic Research (SCAR). Soon after its establishment, SCAR served a crucial role in the negotiations leading to the signing and ratification of the Antarctic Treaty. This international organisation promotes high quality research in Antarctica and the Southern Ocean in disciplines spanning glaciology, geology, climate science, oceanography, space science, biology, the social sciences and more.

In addition to its role as a science coordinator, SCAR provides scientific advice to the Antarctic Treaty Consultative Meetings as well as other processes, such as the climate change governance discussions under the United Nations Framework Convention on Climate Change and the Intergovernmental Panel on Climate Change. In this manner SCAR brings key issues emerging from greater scientific understanding of the region to the attention of policy-makers.

SCAR's members are the 44 (as of 2020) nations that are engaged or in the process of engaging in science in, and concerning, Antarctica and the Southern Ocean.

During the dark winter months, scientists and support personnel overwinter at the 40 year-round stations in Antarctica, here shown as bright dots.

When more ice is discharged into the ocean from the ice sheet than the amount of snow deposited on top, the ice sheet is shrinking and adding to sea level rise.

through the grounding line around an ice sheet that is approximately 50,000 km long, which is greater than the distance around the Earth?

There are three methods to monitor Antarctic mass balance and they all involve instruments mounted on satellites. One method uses gravity measurements to assess the ice sheet's mass changes. The second calculates ice thickness changes by measuring the altitude of the ice sheet. And the third, called the Input–Output Method, calculates the difference between snowfall and ice discharge through the grounding line.

There are many complicating factors that need to be taken into account, such as the motion of the ground underneath the ice sheet. Like a mattress sinking when you lie on it, the Earth's crust is depressed under the ice sheet. When the heavy blanket of ice gets thinner, the land surface below the ice very slowly rises. This adjustment is happening not only in Antarctica but all places that have been glaciated in what geologists would call the recent past. For example, the North American and Scandinavian land surfaces keep rising a few millimetres to a few centimetres per year, even though the Laurentide and Scandinavian ice sheets largely disappeared more than 10,000 years ago.

These changes to the Earth's crust and the ice loss bring changes in gravity that can be measured from satellites: gravity increases where the crust is rebounding but decreases as ice is lost. Any upward motion in the crust must be taken into calculations of ice thickness based on ice sheet altitude, so scientists use data from many satellites and field investigations to get the most reliable results.

The Input–Output Method estimates mass input and output separately and calculate the difference. In many cases, mass input is estimated using regional climate models and mass output is estimated using satellite-measured ice flow speed and ice thickness at the grounding line. Unlike the Greenland Ice Sheet, which mainly loses mass by surface melting, Antarctic atmospheric temperatures remain below freezing even during the Antarctic summer in most regions, so the amount of surface meltwater discharged to the ocean is very small. This means that nearly all mass gained by snowfall is kept on the ice sheet surface and mass discharge happens through ice outflow instead of meltwater runoff. If the volume of discharged ice exceeds the mass added to the ice sheet from snowfall, then the ice sheet is shrinking and contributing to sea level rise.

All of these methods have different drawbacks and therefore produce slightly different estimates. Nonetheless, their mass-balance estimates are in agreement overall.

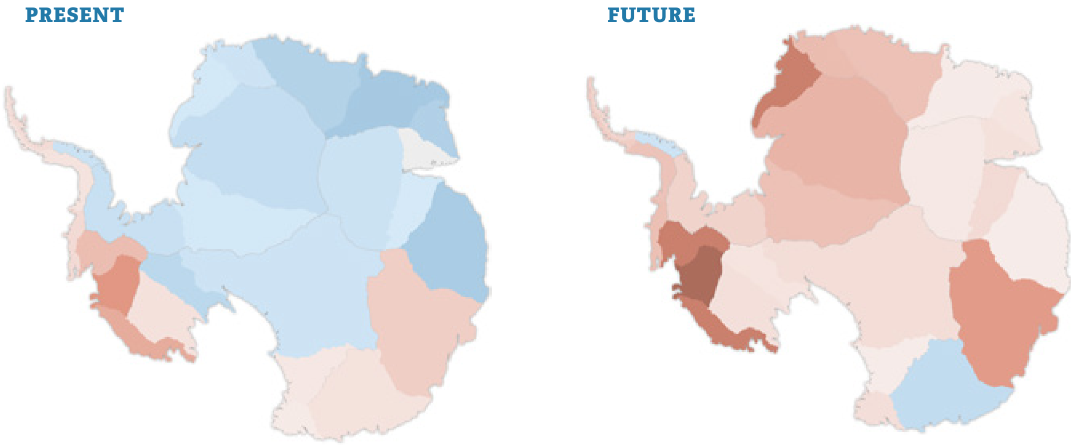
Antarctica's ice is shrinking

Crunching all the data leads to an estimate of more than 2,000 km^3 of ice discharged from Antarctica per year. This is less than 0.01% of the total mass of the ice sheet but still more than any freshwater river in the world except the Amazon. The difference between mass input and output tells us that more ice is lost than gained. Most recent studies point to an annual mass loss of 100–200 km^3, implying that every year about 10% more ice is discharged into the ocean than what falls as snow on the ice sheet, which contributes 0.3–0.6 mm per year to global sea level rise.

If human activities keep emitting as much CO_2 as they do today, Antarctica alone could cause a global mean sea level rise of up to 8 cm by 2100.

The rate of mass loss has increased over the last few decades following an acceleration of several major glaciers in the Amundsen Sea region of West Antarctica, which may have started as early as the 1940s. Especially in West Antarctica, the accelerating retreat of some glaciers is often triggered by the loss of buttressing given by ice rumples and ice shelves, which can happen when warm ocean water thins the ice shelves.

These controlling factors in Antarctic mass balance vary in different parts of the continent. Most of the mass loss comes from only a few areas. Some regions are gaining ice, whereas others are close to a state of balance, neither gaining nor losing, according to the most accurate measurements we have. We still need to know these regional sea level contributions more accurately, and how they are controlled by climatic and environmental conditions. This is vital in order to predict future changes.



The reddish colours show basins in Antarctica losing ice mass, whereas shades of blue show the basins gaining mass as of today (observations) and at the end of the 21st century (a computer model prediction for a business-as-usual CO_2 emission scenario).

What happens next?

Since the first research expeditions in the early 20th century, the Southern Ocean and the Antarctic continent have revealed more and more of their secrets, but they are still data deserts compared to other parts of the world.

Most of our understanding of the future evolution of the Antarctic Ice Sheet and its surrounding ocean and atmosphere stems from computer models that are based upon the processes we can observe today. It was thought that the West Antarctic Ice Sheet is vulnerable to rapid changes, whereas the East Antarctic Ice Sheet is much more stable. It is now clear that this view is only partly true.

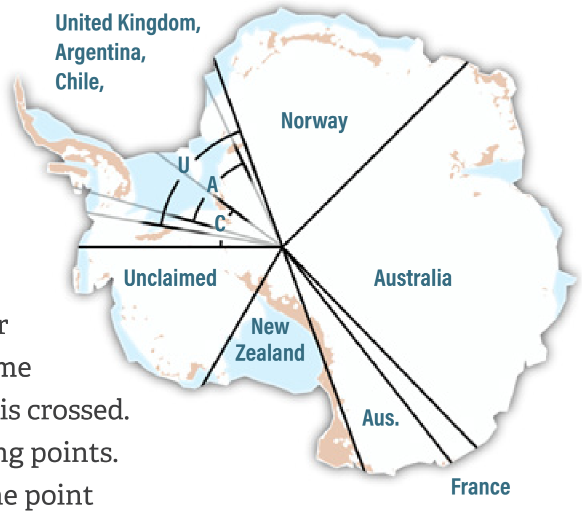
Recent geophysical research reveals that some parts of the ice sheet in East Antarctica are grounded on deep subglacial basins well below the sea level, similar to West Antarctica. Although these glaciers are currently changing much less than those in West Antarctica, they are thought to have significantly raised the global sea level in the past, when the Earth's climate was warmer than today. These recent findings remind us of the need for a more comprehensive understanding of the entire Antarctica, past and present, and the processes that have shaped its ice sheet.

Tipping elements

Individual elements in the climate system respond neither linearly nor on the same timescale to CO_2 increases in the atmosphere. Instead, some elements respond abruptly and dramatically when a certain threshold is crossed. These are called tipping elements and such thresholds are called tipping points. When the tipping element exceeds the tipping point, it goes beyond the point of no return and enters into a new state.

Major tipping elements include the Antarctic and Greenland ice sheets, Arctic sea ice, mountain glaciers and permafrost, which all have different tipping point timescales. These ice masses diminish gradually at first, but upon reaching the tipping point they shrink much faster. Understanding tipping elements in the climate system is crucial to precisely predicting the future climate. How the West Antarctic Ice Sheet responds to ongoing and future climate changes is highly uncertain. According to various projections it could already have crossed its tipping point, which means that it will keep losing ice even without further warming, or it could cross that threshold 300 years from now. We need to better identify tipping elements and understand what conditions set their tipping points and how rapidly the climate system changes before and after tipping points are crossed.

The Antarctic Ice Sheet and Southern Ocean probably have multiple tipping points. These tipping elements mostly impact sea level, ocean circulation, the global ecosystem and the overall climate system. The ocean's tipping elements also directly impact ecosystems in the ocean. Detailed processes before and after these tipping points are crossed remain largely unknown, so it is still hard to make precise projections about the extent and timing of Antarctica's contribution to the global sea level.



The map shows territorial claims made by seven countries.

Did you know …

… that before the Antarctic Treaty came into effect, seven sovereign states made territorial claims to parts of Antarctica?

As long as the Antarctic Treaty exists, all these claims have been put on ice, so to speak, and the Treaty Parties have "agreed to disagree" on this issue. No country may be considered to have renounced any claim, nor may any new claims be made.

The Antarctic Treaty – dedicating a continent to peace and science

The International Geophysical Year and the establishment of SCAR provided a way forward for the discussions about the governance of Antarctica and consequently the negotiations that resulted in the Antarctic Treaty. The Treaty was signed on 1 December 1959, a date celebrated as Antarctica Day, and established a cooperative multinational regime that marked a new era in Antarctica's history. The key principle is that Antarctica is set aside as a continent dedicated to peace and science. The Treaty contains provisions that preserve the status quo of the territorial claims asserted by states regarding their right of sovereignty.

Collaboration under the Treaty has worked well. It has held an entire continent outside the dynamics of world politics, opened the way for remarkable international scientific cooperation and laid a foundation for cooperation to conserve Antarctica's fragile natural environment. Freedom of scientific investigations and exchange of scientific knowledge are fundamental.

In 1991 the Parties agreed to a separate Protocol on Environmental Protection. The Environmental Protocol, which entered into force in 1998, designates Antarctica as a "natural reserve, devoted to peace and science" and provides a framework for the planning and conduct of all activities in Antarctica so they have the least possible negative impact on the environment.

Currently (2020) the Antarctic Treaty has 29 consultative parties and all in all 54 countries representing over 80% of the world's population have become contracting parties to the Treaty. Antarctic Treaty meetings take place annually, where Parties exchange information, consult on matters of common interest pertaining to Antarctica and make recommendations to their governments. All decisions are arrived at by consensus, a system that ensures that all well-founded proposals receive due consideration.

One possible tipping point is the collapse of ice shelves and loss of ice rumples. This can result from oceanic melting at the base of ice shelves. If the ice shelves and ice rumples now serving as bottle corks were suddenly lost, the grounded ice sheet would discharge more ice. This could pull back grounding lines, where the ice sheet becomes afloat, potentially triggering another key tipping point called marine ice sheet instability. This occurs when the withdrawing grounding line reaches where the bed under the grounded ice is below sea level and slopes down towards the interior, so that the grounding line retreats rapidly.

These are just a few examples of ice sheet tipping points, which are sensitive to local bed topography and other environmental conditions. We need to know bed topography and current oceanic, atmospheric and glaciological conditions much better to predict exactly when and where marine ice sheet instability is triggered.

How do such rapid changes along the Antarctic coast impact the colossal ice mass resting on the interior of the continent? Rapidly increased ice discharge may at first thicken the ice shelf or make it move faster. What conditions bring on ice shelf thickening or acceleration, and will thicker ice shelves buttress the grounding line to counteract marine ice sheet instability? How does greater melting underneath the thicker ice shelf affect the ocean circulation around Antarctica and in other connected oceans and their ecosystems? Scientists strive to gather the information they need to answer these questions.

Antarctica in the 21st century

IPCC projections published in 2019 indicate a global average sea level rise ranging from about 43 cm to about 84 cm by the year 2100, depending on different estimates of future emissions. This means that the sea level is likely to rise by at least about half a metre by the end of the 21st century. For these scenarios, Antarctica's contribution is about 10–15%. Over the coming century, the speed of worldwide mean sea level rise will accelerate, likely reaching values between 4 and 15 mm per year, depending on the emission scenarios and models used for predictions. The rising speeds could even exceed several centimetres per year in the 22nd century, which could lead to metres of sea level rise in the 2300s.

When tipping elements such as the Antarctic Ice Sheet and the Southern Ocean cross a certain threshold, they go beyond the point of no return. Scientists are working to determine whether the West Antarctic Ice Sheet has already crossed this point or when it may happen in the coming centuries.

At the calving front of ice shelves such as Fimbulisen Ice Shelf, shown here, the ice from the interior of Antarctica at last reaches the coast. This is the starting point for a new journey on the ocean, as icebergs.

One of the main reasons for the large uncertainty is that we are not sure about how and when individual tipping points are crossed. According to some optimistic scenarios – predicting a recovery phase after stabilisation of atmospheric CO_2 levels – Antarctica could lose very little mass and cause a global mean sea level rise of only about 5 cm by the end of the 21st century. But if our emissions continue on the same pathway as today – a business-as-usual scenario – Antarctica could increase the average sea level three times more.

Steps towards better predictions

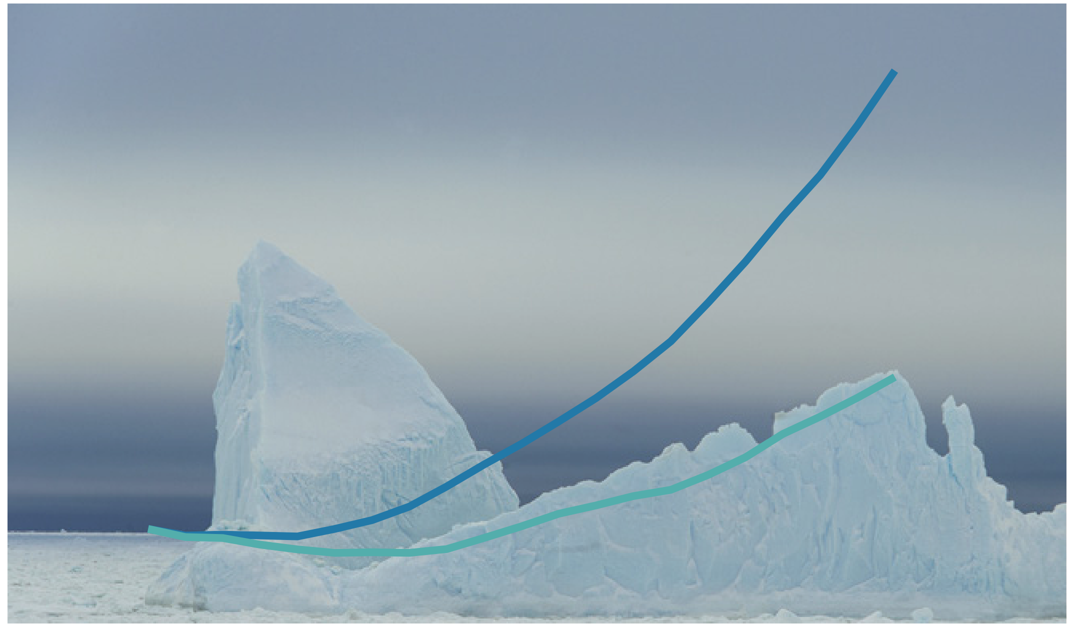
To what extent are these future predictions realistic and plausible? It is hard to say, but we know that Antarctica has undergone dramatic transformations in its history when atmospheric CO_2 levels were as high as what is expected for the near future.

Modelled reconstructions of the climate in earlier times – combined with geological archives – suggest that the West Antarctic Ice Sheet partly disintegrated many times in the past when the amount of atmospheric CO_2 was similar to what is predicted for the coming centuries.

Projections have become more sophisticated since the first IPCC report in 1990, as our knowledge of the climate system has improved. In computer models used for these projections, individual components of the climate system, such as the atmosphere and the ocean, were not linked up but stood alone. In reality, they strongly impact each other. Recent climate models couple together components within the same framework. Each climate component talks to the others within the model, so that interactions between elements are more precisely estimated. However, ice sheets are not yet fully integrated in climate models. The next generation of climate models should comprehensively integrate the ice sheets.

In 2007, the IPCC bemoaned the lack of information about ice sheet flow and its impacts on the ocean. Rising to the challenge, scientists have since then delivered cutting-edge information to improve our understanding of the role of Antarctica in the global climate system, boosting our confidence in future predictions. However, there is still a long way to go. Future super-powerful computers will help us meet the challenge. We need better to grasp the past and ongoing ice sheet changes and the mechanisms behind them.

To help determine whether a vehicle can safely drive across a snow bridge, a safety specialist rappels down into the crevasse below to study its width and direction.



The curves show projected ice loss from Antarctica for high and low CO_2 emission scenarios in the 21st century.

Protecting the icy environment

Ice is really what defines the Antarctic landscape (or ice-scape) and is the reason why this continent at the edge of the world has remained relatively pristine and natural. The desire to maintain Antarctica as an untouched area of unique beauty has grown in parallel with the constant expansion of human activity into new and remote areas of the world.

Antarctica has no natural human population. Scientists and science support personnel at research stations and field camps are temporary residents for stretches of a few months to a year at a time, very rarely more than that. In addition to science teams, ever growing numbers of tourists are attracted to Antarctica. The human footprint in Antarctica is getting bigger.

As a consequence, Antarctic policy-makers, through negotiations within the framework of the Antarctic Treaty, have agreed to protect the unique Antarctic environment, including its aesthetic values, for future generations. Protecting the region's natural wildlife is a part of this commitment. Many Antarctic species, including krill and some species of penguins, depend on ice, in particular sea ice

Antarctica's contribution to the sea level rise in the 21st century may amount to 8 cm, but it can be mitigated if CO_2 emissions are significantly reduced.

A Weddell seal takes a nap on the ice.

The Antarctic Treaty countries have agreed to protect the continent's wildlife, such as the snow petrel. Many species depend on sea ice and shelf ice for their survival.

Antarctic krill is a crustacean found in the Southern Ocean.

and shelf ice. Changes to this ice will alter the foundation of the Antarctic ecosystem. Understanding how ice shapes the natural environment will be critical for ensuring that the Antarctic governance bodies responsible for protecting Antarctica base their decisions on sound science.

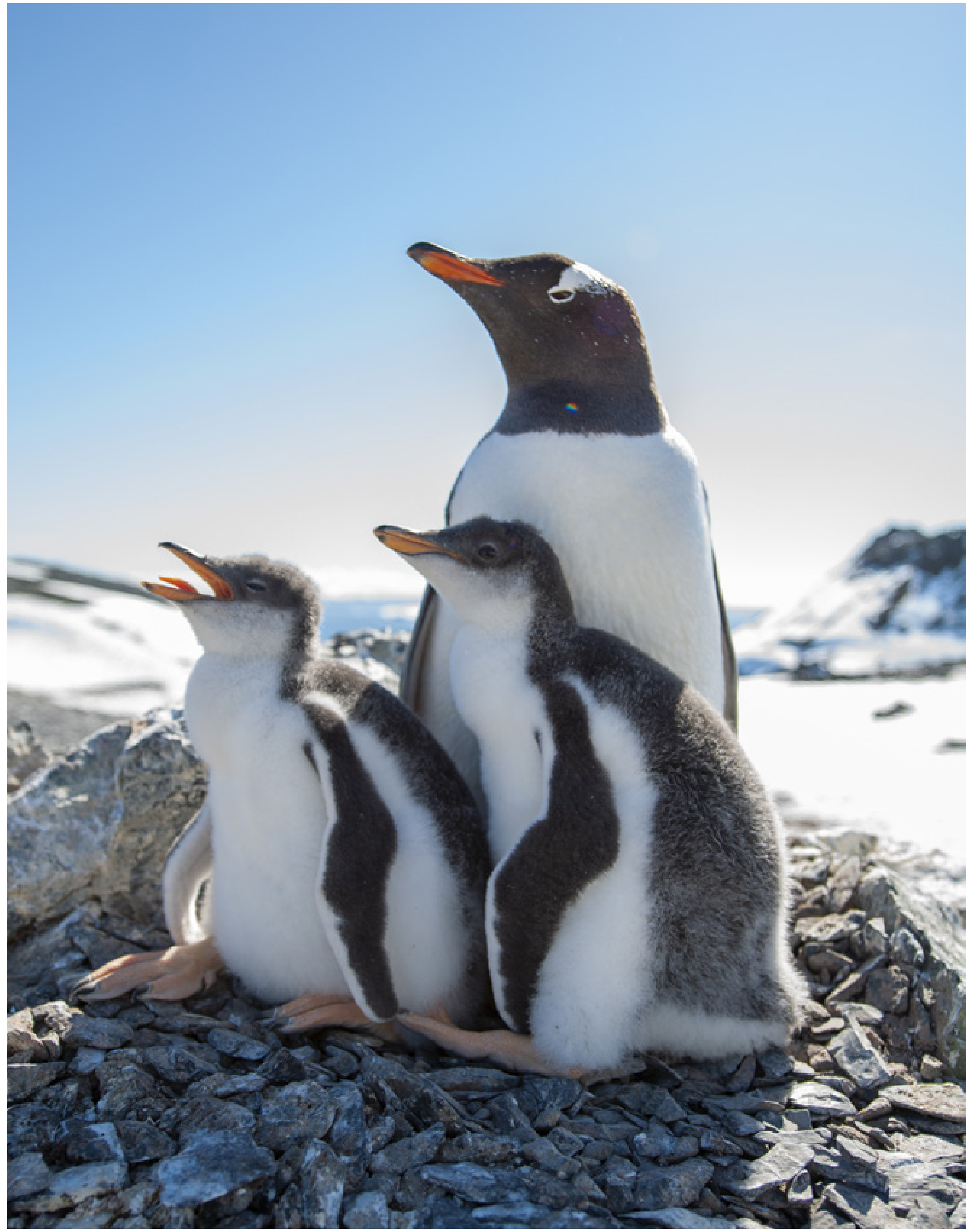
Antarctica impacts our lives

Antarctica is geographically remote and is beyond the horizon of what most people think about as they go about their daily lives. However, sea level rise will pose a serious problem for the many millions of people living along the world's coasts. We are already seeing the effects in different parts of the world.

Many major cities that have the role of economic powerhouses are situated in coastal lowlands. A warmer, higher sea carries a greater risk of extreme weather events that impact people living in coastal areas. So predicting the future of Antarctica is not an academic problem confined to a remote area but a serious problem facing the world's people.

The leopard seal is the second largest species of seal in the Antarctic.

A gentoo penguin looks after its chicks on Kopaitic Island, Antarctic Pensinsula.

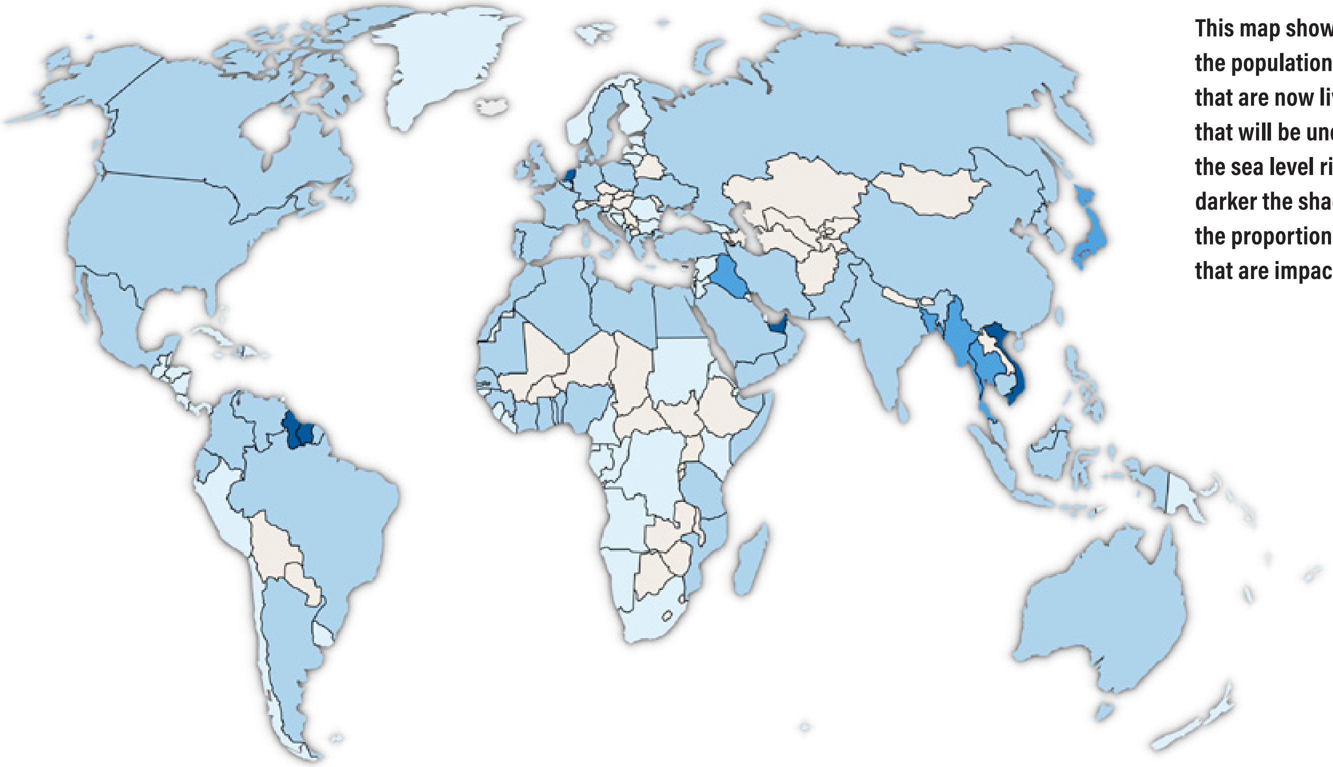


Predicting the future of remote Antarctica tackles a serious problem of global concern.

Antarctica and our future

In 2100, following a business-as-usual scenario of CO_2 emissions, land areas where about 165 million people currently live will be submerged by the sea. Extreme climate events will affect food and shelter for far more people. The complexities of the Antarctic and Southern Ocean systems hinder our ability to make robust predictions about the influence of the Antarctic on global change overall.

Predictability and stability are requirements for maintaining sustainable and safe societies. We need robust decision-making to achieve these goals. Knowledge about the influence of the changes in the Antarctic ice system and their potential consequences is essential to making the best possible choices to minimise the changes in Antarctica – and to mitigate their consequences for human society.



This map shows the proportion of the population in individual countries that are now living in coastal areas that will be under water by 2100 if the sea level rises as predicted. The darker the shade of blue, the larger the proportion of the nation's people that are impacted.

The flags of the original 12 Antarctic Treaty signatory nations surround the Ceremonial South Pole marker, a short distance from the Geographic South Pole.

If this is understood and acted upon, national and international governance bodies will make the right decisions. The Antarctic ice plays a more central role than most of us are aware of when it comes to fundamental needs of societies around the world.

We have come a long way in unravelling the complexities of Antarctica since people first saw the continent 200 years ago, but it is equally fair to say that we know far too little. Research must remain high on the agenda. Our future requires predictability, which in part depends on our grasp of the lifecycle of the Antarctic ice, from its inland origins until it breaks off into the sea and becomes part of the World Ocean.

Did you know …

… that the United Nations' sustainable development goal No. 13 is "Climate action"?

To achieve this, the world's decision-makers must understand what is happening in Antarctica, its role in the global climate system and the need for further knowledge.

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Captions

Pp. 8-9: The gentle dome of an ice rise interrupts the flat expanse of an Antarctic ice shelf.

Pp. 10-11: Climbing Armlenet mountain, in Dronning Maud Land, is rewarded with a special view of glaciers flowing between the mountains that were shaped by the past glacier flow.

Pp. 30-31: The sun spices up the flat, white landscape of Antarctica's interior. The sun dogs seen here are atmospheric tricks that make bright spots appear on one or both sides of the sun.

Pp. 52-53: Sea ice and cold ocean dominate the habitat of Adélie penguins in coastal Antarctica.

Pp. 84-85: Geological layers in the mountains tell a story about ancient Antarctica.

Pp. 100-101: Sailboats lie at anchor at Winter Island in the Antarctic Peninsula.

Pp. 112-113: This panoramic view shows the area around Troll Research Station in Dronning Maud Land, 235 km from the coast.

Pp. 124-125: The waters off the Antarctic Peninsula are scenes of dramatic ice-scapes.

P. 131: The tip of an iceberg floats amid sea ice in the Southern Ocean.

Pp. 132-133: This glacier flowing into Penola Strait, Antarctic Peninsula, is heavily crevassed.

Sources for maps, satellite images and other illustrations

Most of the map data used in this book – and more – are available in the GIS data package Quantarctica, which can be freely downloaded from http://www.npolar.no/quantarctica/ and used on the free GIS package QGIS.

Where not otherwise stated, base maps were generated using the Antarctic Digital Database of the Scientific Committee on Antarctic Research (www.add.scar.org), Natural Earth (www.naturalearthdata.com) for global land themes, and global seafloor topography from the US National Oceanic and Atmospheric Administration's ETOPO1 global relief model (https://www.ngdc.noaa.gov/mgg/global/), the International Bathymetric Chart of the Southern Ocean (https://www.scar.org/science/ibcso/home/) and the International Bathymetric Chart of the Arctic Ocean (https://www.ngdc.noaa.gov/mgg/bathymetry/arctic/ibcaoversion3.html).

p. 15: (Top) REMA, I.M. Howat, C. Porter, B.E. Smith, M.-J. Noh & P. Morin 2019 ("The Reference Elevation Model of Antarctica", *The Cryosphere* 13, pp. 665–674). (Bottom) BedMachine, M. Morlighem & 36 co-authors 2020 ("Deep glacial troughs and stabilizing ridges unveiled beneath the margins of the Antarctic Ice Sheet", *Nature Geoscience* 13, pp. 132–137). Seafloor topography beyond the BedMachine coverage for these two maps is from IBCSO, J.E. Arndt, H.W. Schenke, M. Jakobsson, F.O. Nitsche, G. Buys, B. Goleby & 10 co-authors 2013 ("The International Bathymetric Chart of the Southern Ocean [IBCSO] version 1.0 – A new bathymetric compilation covering circum-Antarctic waters", *Geophysical Research Letters* 40, pp. 3111–3117).

p. 20: The base map in the Spilhaus projection was made with software G. Projector, provided by the US National Aeronautics and Space Administration (NASA) (https://www.giss.nasa.gov/tools/gprojector/).

p. 25: MODIS image taken on 19 December 2019. Downloaded from NASA Worldview (https://worldview.earthdata.nasa.gov/), part of the NASA Earth System Data and Information System.

p. 40: RADARSAT-1 Antarctic Mapping Project (RAMP) Data. K.C. Jezek principal investigator. Downloaded from https://bit.ly/37D0JQf in 2012, Byrd Polar and Climate Research Center, The Ohio State University.

p. 41: Sources: Blankenship et al. 2009, data set ID: NSIDC-0336, National Snow and Ice Data Center, Boulder, CO; A.M. Le Brocq, N. Ross, J.A. Griggs, R.G. Bingham, H.F.J. Corr, F. Ferraccioli, A. Jenkins, T.A. Jordan, A.J. Payne, D.M. Rippin & M.J. Siegert 2013 ("Evidence from ice shelves for channelized meltwater flow beneath the Antarctic Ice Sheet", *Nature Geoscience* 6, pp. 945–948); F. Pattyn 2010 ("Antarctic subglacial conditions inferred from a hybrid ice sheet/ice stream model", *Earth and Planetary Science Letters* 295, pp. 451–461), B.E. Smith, H.A. Fricker, I.R. Joughin & S. Tulaczyk 2009 ("An inventory of active subglacial lakes in Antarctica detected by ICESat [2003–2008]", *Journal of Glaciology* 55, 573-595), M. Studinger, R.E. Bell & A.A. Tikku 2004 ("Estimating the depth and shape of subglacial Lake Vostok's water cavity from aerogravity data", *Geophysical Research Letters* 31, L12401), A. Wright & M. Siegert 2012 ("A fourth inventory of Antarctic subglacial lakes", *Antarctic Science* 24, pp. 659–664).

p. 51: MEaSUREs InSAR-Based Antarctica Ice Velocity Map, ver. 2, E. Rignot, J. Mouginot & B. Scheuchl 2017, NASA National Snow and Ice Data Center Distributed Active Archive Center, doi: 10.5067/D7GK8F5J8M8R. The basemap is identical with the top map on p. 15.

p. 58: Inventory of Antarctic Ice Rises and Rumples, ver. 1., G. Moholdt & K. Matsuoka 2015, Norwegian Polar Institute, doi: 10.21334/npolar.2015.9174e644.

p. 58: Originally published in V. Goel, J. Brown & K. Matsuoka 2017 ("Glaciological settings and recent mass balance of Blåskimen Island in Dronning Maud Land, Antarctica", *The Cryosphere* 11, pp. 2883-2896). The cross-section shown is 4 km wide.

p. 62: Landsat8 image taken on 4 January, 2020, courtesy of the US Geological Survey. Downloaded from NASA's EarthExplorer website (https://earthexplorer.usgs.gov/).

p. 66: Designed by Anders Skoglund, Norwegian Polar Institute.

p. 67: REMA, I.M. Howat, C. Porter, B.E. Smith, M.-J. Noh & P. Morin 2019 ("The Reference Elevation Model of Antarctica", *The Cryosphere* 13, pp. 665–674), of Roi Baudouin Ice Shelf, Dronning Maud Land, with the vertical scale 100× the horizontal scale (that is, the horizontal and vertical scales are different, the vertical measurements being much greater in relation to the horizontal scale than they are in actuality). The flow stripes are several kilometres wide and tens of metres deep.

p. 70: MODIS images taken on 27 January and 7 March 2002. Downloaded from NASA Worldview (https://worldview.earthdata.nasa.gov/), part of the NASA Earth System Data and Information System.

p. 75: European Space Agency Sentinel-2 image taken on 26 February 2019. Copyright: Copernicus Satellite Data, 2019. Downloaded from NASA's EarthExplorer website (https://earthexplorer.usgs.gov/).

p. 79: BedMachine, Supplementary Information Section 5.3 in M. Morlighem & 36 co-authors 2020 ("Deep glacial troughs and stabilizing ridges unveiled beneath the margins of the Antarctic Ice Sheet", *Nature Geoscience* 13, pp. 132-137).

p. 87: Prepared by Florence Colleoni, National Institute of Oceanography and Applied Geophysics, Italy, using GPlates open source software (https://www.gplates.org/) to calculate plates motion for a cinematic reconstruction by R.D. Müller, S. Zahirovic, S.E. Williams, J. Cannon, M. Seton, D.J. Bower, M.G. Tetley, C. Heine, E. Le Breton, S. Liu, S.H.J. Russell, T. Yang, J. Leonard & M. Gurnis 2019 ("A global plate model including lithospheric deformation along major rifts and orogens since the Triassic", *Tectonics* 38, pp. 1884–1907).

p. 94: Adapted by Florence Colleoni, National Institute of Oceanography and Applied Geophysics, Italy from: J.-B. Ladant, Y. Donnadieu, V. Lefebvre & C. Dumas 2014 ("The respective role of atmospheric carbon dioxide and orbital parameters on ice sheet evolution at the Eocene–Oligocene transition", *Paleoceanography* 29, pp. 810-823) and R.H. Levy, S.R. Meyers, T.R. Naish, N.R. Golledge, R.M. McKay, J.S. Crampton, R.M. DeConto, L. De Santis, F. Florindo, E.G.W. Gasson, D.M. Harwood, B.P. Luyendyk, R.D. Powell, C. Clowes & D.K. Kulhanek 2019 ("Antarctic ice-sheet sensitivity to obliquity forcing enhanced through ocean connections", *Nature Geoscience* 12, pp. 132-137) for cold and warm extents 34–28 million years ago; E. Gasson, R.M. DeConto, D. Pollard & R.H. Levy 2016 ("Dynamic Antarctic Ice Sheet during the early to mid-Miocene", *Proceedings of the National Academy of Sciences* 113, pp. 3459–3464) and F. Colleoni, L. De Santis, E. Montoli, E. Olivo, C.C. Sorlien, P.J. Bart, E.G.W. Gasson, A. Bergamasco, C. Sauli, N. Wardell & S. Prato 2018 ("Past continental shelf evolution increased Antarctic Ice Sheet sensitivity to climatic conditions", *Scientific Reports* 8, article no. 11323) for cold and warm extents 24-14 million years ago; The RAISED Consortium, M.J. Bentley & 76 co-authors 2014 ("A community-based geological reconstruction of Antarctic Ice Sheet deglaciation since the Last Glacial Maximum", *Quaternary Science Reviews* 100, pp. 1–9) for the cold extent in the last 5 million years, and J. Sutter, P. Gierz, K. Grosfeld, M. Thoma & G. Lohmann 2016 ("Ocean temperature thresholds for Last Interglacial West Antarctic Ice Sheet collapse", *Geophysical Research Letters* 43, pp. 2675-2682) and R.M. DeConto & D. Pollard 2016 ("Contribution of Antarctica to past and future sea-level rise", *Nature* 531, pp. 591–597) for the warm extent in the last 5 million years. It remains uncertain whether the area indicated with dashed lines in the lower right panel became deglaciated at any time during the last 5 million years. Palaeo bed topography is taken from G.J.G. Paxman, S.S.R. Jamieson, K. Hochmuth, K. Gohl, M.J. Bentley, G. Leitchenkov & F. Ferraccioli 2019 ("Reconstructions of Antarctic topography since the Eocene–Oligocene boundary", *Palaeogeography, Palaeoclimatology, Palaeoecology* 535, article no. 109346).

p. 96: B. Van Liefferinge & F. Pattyn 2013 ("Using ice-flow models to evaluate potential sites of million year-old ice in Antarctica", *Climate of the Past* 9, pp. 2335-2345).

p. 103: The observed curve shows 1.01°C increase of a land–ocean temperature index smoothed over five years from 1901 to 2014, published as part of the Goddard Institute for Space Studies Surface Temperature product version 4 (GISTEMP v4) by N. Lenssen, G. Schmidt, J. Hansen, M. Menne, A. Persin, R. Ruedy & D. Zyss 2019 ("Improvements in the GISTEMP uncertainty model", *Journal of Geophysical Research—Atmospheres* 124, pp. 6307-6326). The two modelled curves show the simulated global mean surface air temperature anomaly in the 6th generation of Climate Model Intercomparison Project models (CMIP6) with different forcings, modified from K.B. Tokarska, M.B. Stolpe, S. Sippel, E.M. Fischer & C.J. Smith 2020 ("Past warming trend constrains future warming in CMIP6 models", *Science Advances* 6, eaaz9549), with permission from the journal *Science Advances*. All results are referenced to their values in 1901 and plotted from 1901 to 2014.

p. 107: Station locations are from the Council of Managers of National Antarctic Programs website (https://www.comnap.aq/).

p. 109: (Present) A.S. Gardner, G. Moholdt, T. Scambos, M. Fahnstock, S. Ligtenberg, M. van den Broeke & J. Nilsson 2018 ("Increased West Antarctic and unchanged East Antarctic ice discharge over the last 7 years", *The Cryosphere* 12, pp. 521-547). (Future) Projected mass loss by 2100 referenced to the modeled mass loss in 2000 for the RCP8.5 CO_2 emission scenario; N.R. Golledge, E.D. Keller, N. Gomez, K.A. Naughten, J. Bernales, L.D. Trusel & T.L. Edwards 2019 ("Global environmental consequences of twenty- first-century ice-sheet melt", *Nature* 566, pp. 65-72).

p. 118: Time series of predicted mass loss in the 21st century for the RCP4.5 and RCP8.5 CO_2 emission scenarios with melting feedback; N.R. Golledge, E.D. Keller, N. Gomez, K.A. Naughten, J. Bernales, L.D. Trusel & T.L. Edwards 2019 ("Global environmental consequences of twenty-first-century ice-sheet melt", *Nature* 566, pp. 65–72). The Antarctic sea level contribution since 2000 will reach 140.2 mm in the RCP8.5 scenario by 2100 but only 46.4 mm in the RCP4.5 scenario.

p. 122: The fractional population of current population in each country living in the coastal lowland that is predicted to be submerged under the ocean by 2100 for the DP16_RCP-85_2100 prediction for the RCP8.5 CO_2 emission scenario. Source: R.E. Kopp, R. M. DeConto, D.A. Bader, C.C. Hay, R.M. Horton, S. Kulp, M. Oppenheimer, D. Pollard & B.H. Strauss 2017 ("Evolving understanding of Antarctic ice-sheet physics and ambiguity in probabilistic sea-level projections", *Earth's Future* 5, pp. 1217–1233). In seven countries, more than 10% of the population resides in coastal lowlands; in another seven countries the proportion is 5–9% of the population.

This book is a publication of the Norwegian Polar Institute (NPI).
The Institute is a directorate of the Ministry of Climate and Environment and acts as an advisory agency on environmental management and administration of the polar regions. The NPI is Norway's executive environmental authority in Antarctica.

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