■ In September 2019 the research icebreaker Polarstern, searching for the ideal floe, forges her way through the ice.

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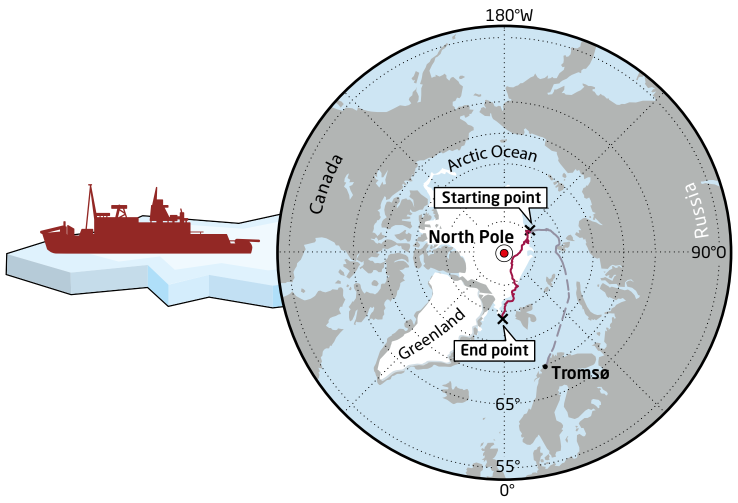
Is this floe the one? AWI sea-ice physicist Stefan Hendricks bores a hole through the ice in order to examine its structure.

Despite the snow flurries, cold and dark: researching the Central Arctic in winter is a once-in-a-lifetime opportunity.

Ropes as thick as an arm secure RV Polarstern to the ice floe. The ship and ice drift an average of 10.7 kilometres per day through the Arctic.

By the light of her headlamp, AWI atmospheric researcher Anja Sommerfeld hecks one of her measuring instruments. During the Polar Night, it is permanently dark, so you lose all sense of time.



Embarking on the voyage of a century

Spending an entire winter researching on an ice floe in the Arctic Ocean was, until now, just a pipe dream for most sea-ice experts. It was always assumed that such an expedition would be too costly, the polar weather too unpredictable. But September 2019 saw the start of something that had long been considered impossible. The German research icebreaker Polarstern allowed itself to become trapped in the Arctic sea ice, offering researchers from 20 countries a once-in-a-lifetime opportunity. In a camp on the Central Arctic ice, around the clock they investigated the sea ice, ocean, atmosphere and life in the sea. They witnessed a dramatic transformation of the North Pole region, the consequences of which are likely to affect the sea ice first.

The Arctic Ocean's most prominent characteristic is its sea ice. For at least 18 million years, i.e., since the dawn of humanity, the world's smallest ocean has been covered in ice in both summer and winter. The ice area waxes and wanes with the seasons. As a rule, at the end of winter it is two to three times greater than at the end of summer.

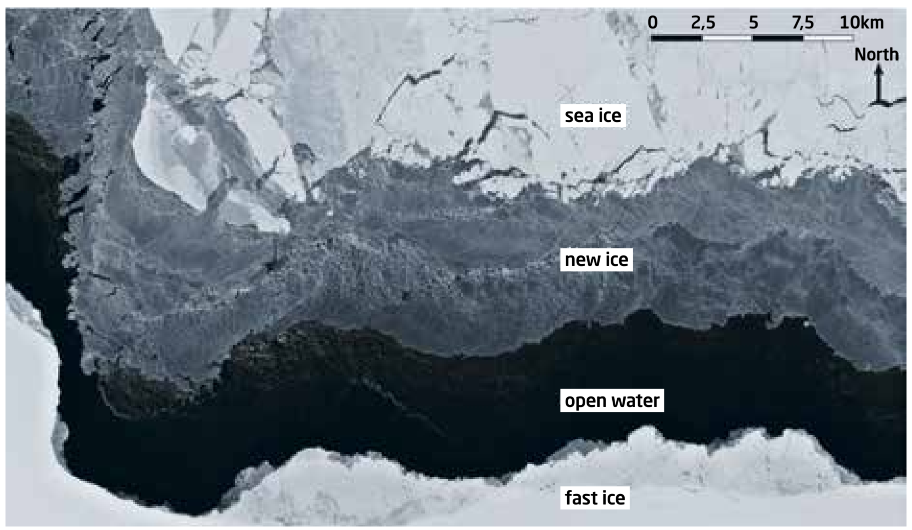
The Arctic sea ice is one of the most important components in Earth's climate system: the white, snow-covered ice reflects up to 90 percent of the solar radiation back into space. As a result, the ice and snow not only cool the North Pole region; they also form the basis for global wind and ocean currents, which distribute heat from the tropics over the entire globe and make the planet inhabitable for us humans.

We now know that the Arctic sea ice influences the weather and climate in the entire Northern Hemisphere. What happens in the Arctic is therefore highly relevant for millions of people south of the Arctic Circle.

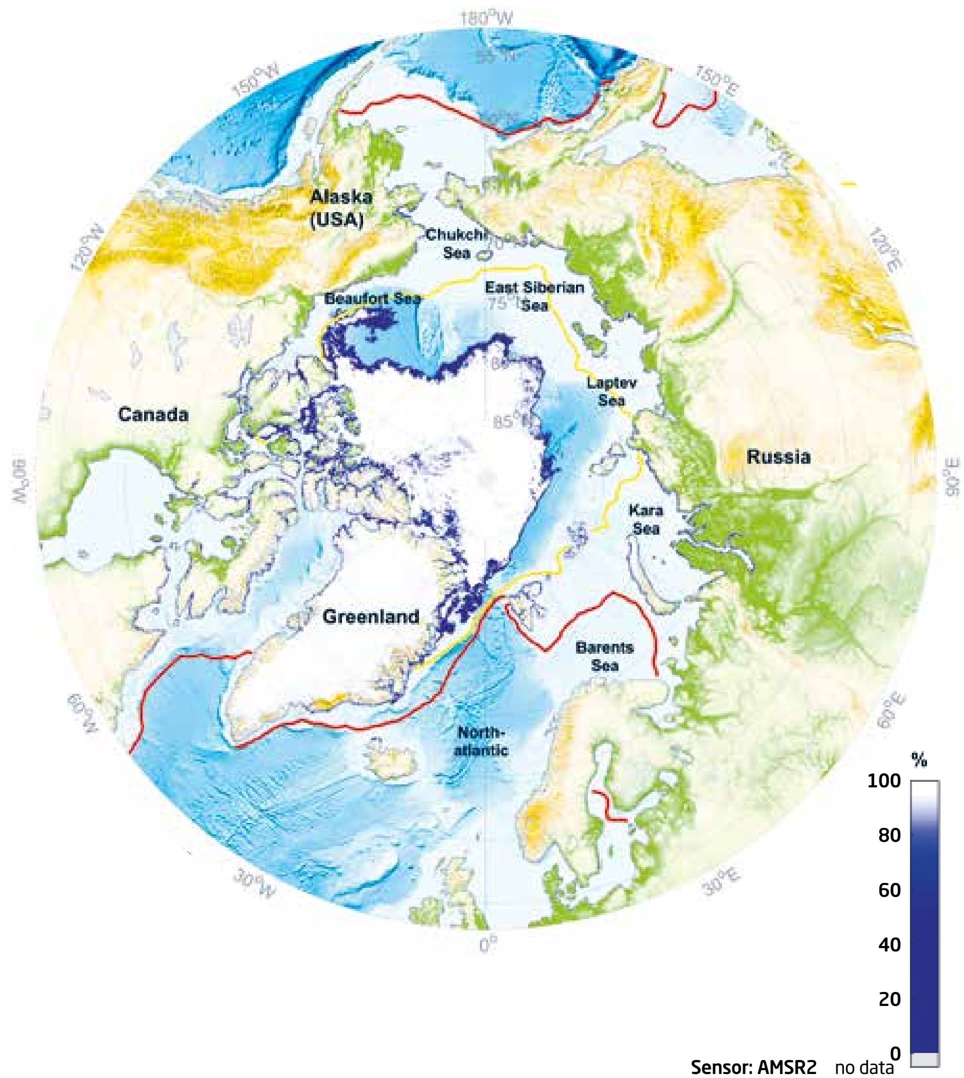
IN THE NURSERY OF SEA ICE

Sea ice mainly forms in coastal areas of the shallow Russian marginal seas of the Arctic Ocean. There, in the Kara Sea, Laptev Sea and East Siberian Sea, strong offshore winds with air temperatures as low as minus 40 degrees Celsius blow over the sea in winter. These constantly allow open areas of water to form, the surface of which freezes to ice, breaks up and is driven out to sea by the wind. The cycle can then start again from the beginning, and sea ice is formed as if on a conveyor belt.

Most of the ice that eventually forms the sea-ice cover in the Central Arctic originates in this region. The remainder forms directly in the vicinity of the North Pole or off the coasts



This satellite image, taken over the Laptev Sea, shows the process of new sea-ice formation in March 2019. Sea ice that is frozen to the coast is known as fast ice.



The consequences of a far-too-warm summer

Long-term average sea ice extent 1981 – 2010

March

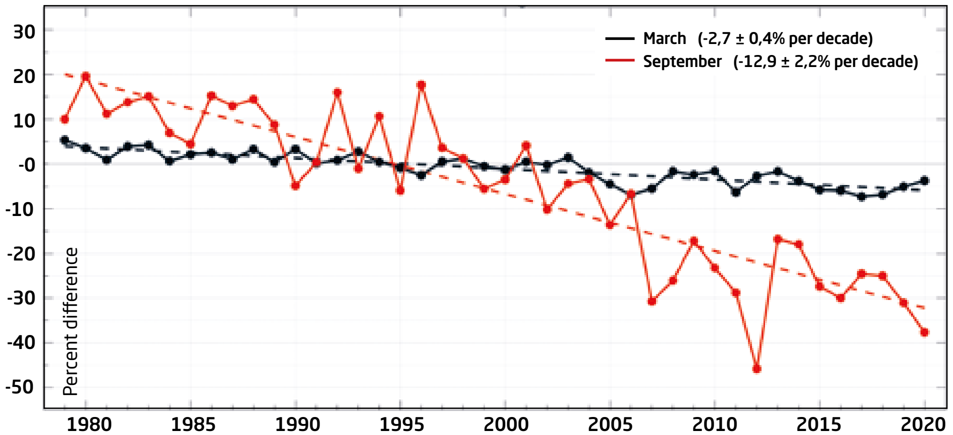
September

During the MOSAiC expedition, the Arctic experienced one of its warmest summers since weather records began. As a result, by September the sea-ice extent had shrunk to the second-lowest level ever measured by satellite – 3.8 million square kilometres of remaining ice. For comparison: at the end of the winter (March 2020) ice covered an area four times as large (15.2 million square kilometres). The figure above shows the minimum sea ice concentration 9 September 2020.

of Greenland and North America. Since the wind blows landwards in many coastal areas, it doesn't push the ice out to sea, but instead compacts it along the coast, making the ice there especially thick.

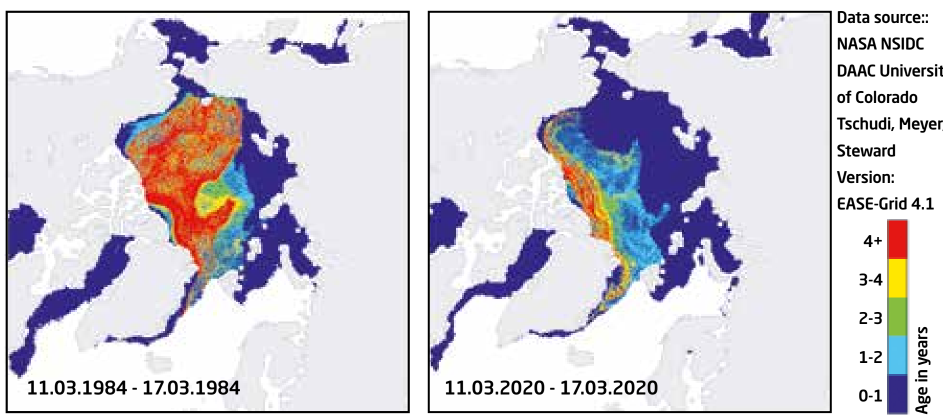
The statistics of change

SEA ICE EXTENT ANOMALY TO LONG-TERM MEAN 1981-2010



In the Arctic, the rule is: the older, and therefore thicker, sea ice is, the longer it can withstand the warmth of the sun and ocean in summer. Since now only a fifth of the ice is older than two years (bottom), the sun and ocean have an increasingly easy time melting it. In summer, ever-larger areas of ice melt as the top graph shows (development of sea ice extend compared to the long-term mean of 1981-2010) and the various melt ponds on the ice indicate (photo right); in winter, the ice forms later and barely reaches the thickness needed to survive the next summer.

SEA ICE AGE



Data source:: NASA NSIDC DAAC University of Colorado Tschudi, Meyer, Steward Version: EASE-Grid 4.1

THE BEGINNING OF THE END

Young sea ice grows as long as the air above its surface is cold enough for heat from the water beneath it to escape upwards. When this is the case, the water on the underside of the floe freezes; the sea ice grows from below. But as a result of climate change, these initial conditions – consistently cold air and cold surface water – aren't always given. Dramatically rising air and water temperatures in the Arctic have created a downward spiral for sea ice, which is likely to end in the Arctic Ocean being ice-free in summer in the foreseeable future – probably even before the middle of the 21st century, i.e., in less than 30 years. The Arctic is warming more than twice as fast as the global average.

If you compare today's Arctic with conditions 30 years ago, now only half as much of the sea ice survives the summer. The 14 lowest summer sea-ice extents since satellite observations began in 1979 were recorded in the last 14 years (2007 – 2020). The ice quantity – or volume – has declined by three quarters (75 percent), because the sea ice is significantly thinner today. At the same time, there are hardly any floes that are older than two years and have therefore had time to grow into massive ice floes, more than three meters thick.

Today, in the Russian marginal seas only thin new ice forms in winter, and melts in the following spring before it even reaches the central Arctic Ocean. That means significantly less sea ice begins the long journey known as the transpolar drift, which carries ice from the Russian marginal seas across the Arctic Ocean – and past the North Pole – to the region between East Greenland and Svalbard. There, in the Fram Strait, the ice leaves the Arctic Ocean and melts in the warmer waters of the North Atlantic.

The dimensions that climate change has now assumed in the Arctic have rarely been as evident as in 2020. In January, researchers from the Alfred Wegener Institute (AWI) observed the second-lowest sea-ice volume since the beginning of recordkeeping; further, the maximum winter sea-ice extent in March was well below average. In April the first heat wave of the year spread across Siberia. At the time, air temperatures over the Russian Arctic were up to 6 degrees Celsius higher than normal.

The heat continued throughout the summer: while on the mainland, the Siberian tundra burned and meteorologists reported record temperatures of up to 38 Grad Celsius in the Arctic, the sea ice rapidly retreated. In July, the extent reached a historical low. The ice-free regions, which were then completely exposed to the sun, warmed to such an

For scientists, the Arctic Ocean is considered to be ice-free when the remaining ice area in summer amounts to less than 1 million square kilometres. The reason: the thick ice near the coast in Greenland and Canada melts later than the drift ice in the Central Arctic. As such, the definition represents a compromise.

extent that the ocean and atmosphere together caused the Arctic ice cover to shrink to its second-lowest summer extent to date. Subsequently, the warm waters delayed winter ice formation by nearly four weeks.

THE MOSAiC EXPEDITION: AN UNPRECEDENTED OPPORTUNITY

There can be no doubt: the Arctic is more intensively affected by climate change than virtually any other region on Earth, and is currently undergoing a rapid transformation. The once eternally frozen realms of the Far North are steadily losing their protective shield of ice and snow. Researchers are observing these sweeping changes with satellites, on expeditions, and with the aid of numerous monitoring stations on the ice and in the ocean. But until now, they were unable to create a cohesive and above all conclusive picture of changes in the Arctic, because as a rule their fieldwork was done in various places and at different times of the year, and almost never examined the sea ice, snow, atmosphere, ocean and biology simultaneously.

MOSAiC stands for Multidisciplinary drifting Observatory for the Study of Arctic Climate, the expedition's English title.

Addressing this serious gap in our data and knowledge called for an exceptional research approach. An expedition to the Central Arctic, on which experts could spend an entire year measuring and recording relevant environmental parameters in the same surroundings – on (and in) the sea ice itself, high above and far below it.

It soon became clear to the experts involved that the plan could only succeed through collaboration; in response, 20 countries engaged in polar research, led by Germany's Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research, joined forces for MOSAiC – the expedition of a century.

meereisportal.de is an independent science and data platform, launched by the Helmholtz Climate Initiative Regional Climate Change and Humans (REKLIM) and the Climate Office for Polar Regions and Sea Level Rise at the Alfred Wegener Institute. It offers real-time data from the Arctic and Antarctic, as well as the latest information on sea-ice conditions, for everyone.

For an entire year – from October 2019 to October 2020 – the German research icebreaker Polarstern drifted through the Arctic Ocean moored to an ice floe. The scientists on board erected an extensive research camp on the ice, where they conducted for the first time interdisciplinary experiments on the sea ice, snow, ocean, and atmosphere, as well as biological investigations – using state-of-the-art research methods, and in the face of adversities like darkness, storms and bone-chilling polar temperatures.

TEN TALES FROM THE RESEARCH CAMP ON THE ICE

The editorial team of the meereisportal.de (seaiceportal.de) accompanied the sea-ice specialists taking part in the expedition during their work on the ice and reported on their backgrounds, methods, advances and findings in the portal's DriftStories.

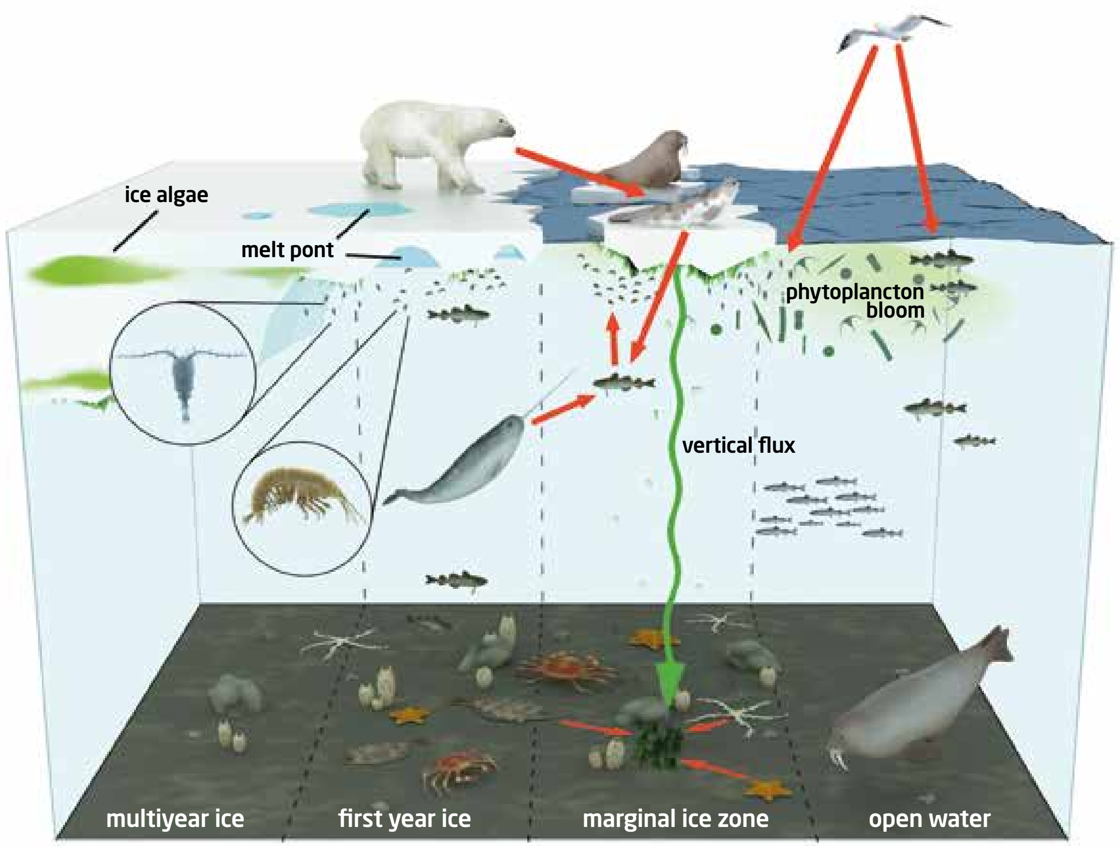
This publication brings together all ten stories with the goal of offering interested readers insights into the fascinating and surprisingly complex world of Arctic sea ice. Like our protagonists, you, too, can witness the transformation of the Arctic and experience, perhaps for the last time, the drift of the Arctic sea ice as we know it: the days of the Arctic's hallmark snow and ice are numbered.

DR. KLAUS GROSFELD
Managing Director, REKLIM

DR. RENATE TREFFEISEN
AWI Climate Office

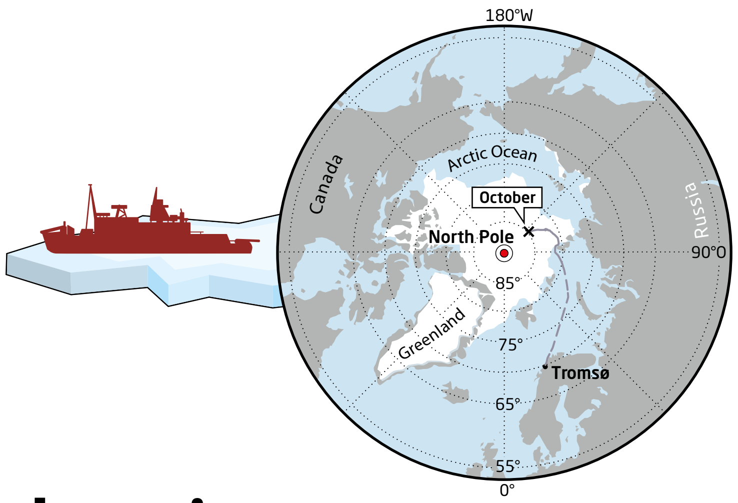
SINA LÖSCHKE
Science writer

Shelter and pantry



The sea ice influences not only the Arctic's heat balance; it also provides the basis for life in the Arctic Ocean, serving as a shelter for ice algae and microorganisms (zooplankton) and as a pantry. Both groups of organisms endure the harsh winter in the sea-ice's brine channels. With the return of the sun in spring, the ice algae reproduce and provide copepods and other zooplankton with a rich source of nutrients. In turn, the zooplankton provide food for fish such as the polar cod, which is one of the key species in the Arctic Ocean, since it is hunted by whales and seals, as well as puffins and other seabirds (l.). Walruses (r.) on the other hand find their prey on the seafloor, whose species communities live on the remains that sink to the depths from the surface – the ice is therefore vital for their survival, too.

Early in the MOSAiC expedition, an international team of experts on board the Russian research icebreaker Akademik Fedorov (r.) supported RV Polarstern (l.) in her search for the ideal floe.



DriftStory 01

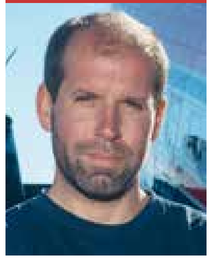
Detective work on ice that's far too thin

Whoever hopes to unlock the mysteries of the sea ice has to first know its past. Accordingly, sea-ice physicist Thomas Krumpen started looking for clues, and traced the history of the MOSAiC floe back to the beginning – even to the exact day it was formed.

AWI sea-ice physicist Dr Thomas Krumpen is the 'profiler' in the MOSAiC Sea-Ice Group. Even if the largest-scale Arctic expedition in history isn't a whodunit, where the goal is to bring the wrongdoer to justice, nevertheless most of the researchers on board the icebreaker RV Polarstern, which serves as the base of operations for the expedition, are preoccupied with two fundamental questions: where did the sea ice that we're living and working on actually come from? And just what type of ice is it composed of? Finding the answers as early in the expedition as possible is a key priority, since this information is essential for nearly all model-based studies and satellite validations, not to mention the investigations into the material flows and food webs that will be carried out in the course of the year-long drift experiment.

Accordingly, in September 2019 Krumpen was one of the first members of the AWI's Sea-Ice Group to depart for the Central Arctic, and was tasked with profiling the 'scene of the crime' – in other words: describing the sea ice in MOSAiC's starting region in painstaking detail, and determining its origins. The 41-year-old conducted his detective work on

The MOSAiC drift experiment began on 4 October 2019, when the research icebreaker Polarstern moored at the selected ice floe. The starting coordinates: 85° 04.582' North / 134° 25.769' East.



DR THOMAS KRUMPEN
is a sea-ice physicist at the Alfred Wegener Institute in Bremerhaven. The 41-year-old is an expert on ice formation in shelf seas and has developed a method for reliably retracing the routes of drifting ice.

board the Russian research icebreaker Akademik Federow, as it was engaged together with RV Polarstern scouting of the region, located ca. 950 kilometres north of the New Siberian Islands.To gain a first impression both ships went to coordinated search regions and followed the same procedure. From Akademik Federow Thomas Krumpen and two other sea-ice observers began by documenting from the ship's bridge how many ice floes were in the target region, roughly how old and thick the ice was, at which points channels were forming in the pack ice, and whether the ice was covered with meltwater pools, or whether the floes had collided, forming pack ice hummocks. In the next step, the researchers used the ship's on-board helicopter to fly to five larger floes within a 40-km radius, surveying the ice thickness and amount of snow cover on each. Krumpen compared the team's on-site readings with extensive weather satellite and ice satellite data on the Russian Arctic, which he had gathered from a variety of sources prior to the expedition. In this regard, the weather data came from a meteorological monitoring station on Kotelny Island, the largest of the New Siberian Islands.

A HISTORY OF EXTREMES

The results of the initial analysis in both search regions were sobering: the ice in the starting region was less than a year old, had a mean thickness of only 30 centimetres, and had undergone substantial melting during the summer, as a result of which it showed heavy weathering and was littered with meltwater pools. The ice's life story read like a string of negative records. "The summer of 2019 was the warmest in the Russian Arctic since the beginning of weather observations on Kotelny Island, back in 1935. Air temperatures over the Laptev Sea and East Siberian Sea beat the previous record high by two to four degrees Celsius," Krumpen reports.

Since the previous winter had been one to three degrees Celsius warmer than the average in the reference period 1981 to 2010, the ice that formed in the 'nursery' for Arctic sea ice – the Laptev Sea and adjacent East Siberian Sea – was far thinner than in the past. Strong offshore winds then rapidly blew it out to the open sea. As Krumpen recalls, "When the air temperature quickly rose in the spring of 2019, this extremely thin ice melted so rapidly and extensively that we not only saw the earliest break-up of the ice cover since 1992, but also the rapid and unexpected northward retreat of the ice edge."Consequently, in the autumn of 2019 it took longer than ever before for the surface water, warmed by the summer sun, to grow cold enough for new ice to form. According to the sea-ice physicist: "At the beginning of the expedition, roughly 80 percent of the sea ice in MOSAiC's starting region was only a few days old. Floes that had survived the summer, and were therefore thick enough for us to work on, were definitely the exception, and hard to come by." Finally, the scientists were successful in the RV Polarstern's search region. The expedition leader chose one of the most stable floes in this sector of the Arctic as home for the expedition.

Once these initial conditions had been established, Thomas Krumpen's real detective work began. The goal was to trace the course of the pack ice in the starting region back to its point of origin. To do so, the remote-sensing expert used a time series of high-resolution

satellite data, which allowed him to identify the MOSAiC floes and therefore reconstruct their journey from the **marginal seas** of the Arctic Ocean to the Central Arctic – down to the exact day. "The ice floes that we set up the MOSAiC monitoring network on were formed off the northern coast of the New Siberian Islands on 5 December 2018, and in a shallow region with a depth of less than ten metres. When RV Polarstern dropped anchor at one of the floes, on 4 October 2019, the ice was exactly 318 days old and had travelled a total distance of 2240 kilometres, on a zigzagging course determined by the wind," says Krumpen.

These new insights into the ice's provenance are supported e.g. by sediment and particle deposits that the researchers found in the sea ice. These trapped deposits, referred to as inclusions, can only be found in sea ice that forms in coastal waters less than 30 metres deep: in shallow waters, the intense winter winds stir up large amounts of sediment from the seafloor, which are subsequently locked into the newly formed ice. Alternatively, the particles can be acquired when the young ice comes into contact with the seafloor in the surf zone. Chemical tests, which will likely tell us exactly which section of coastline the deposits hail from, aren't yet complete.

The following shallow bodies of water in the eastern part of the Arctic Ocean are considered to be marginal or shelf seas: the Barents Sea, Kara Sea, Laptev Sea and East Siberian Sea.

Finding the right floe: a Russian transport helicopter drops off researchers for scouting work on the sea ice.

ONE LAST LOOK AT THE OLD ARCTIC

The unexpectedly high number of inclusions has given the participants the chance to thoroughly analyse the role of Arctic sea ice as a means of transport for sediments, nutrients, climate-relevant gases and toxins – and an opportunity that, in Krumpen's opinion, is very unlikely to come around again in the future: "Due to climate change, the majority of the sea ice formed in the marginal seas now melts before it can reach the Central Arctic. As a result, essential transport processes are now faltering, producing changes in the material flows of the Arctic Ocean. In MOSAiC we're now taking one last look at the Arctic as we know it, and as we've investigated it over the past several decades. At the same time, we're getting a first impression of what things will look like in the future." For the sea-ice profiler, one thing is certain: the old Arctic's days are numbered. ■

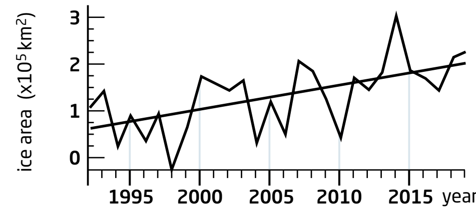
For safety reasons, the experts always worked in teams: they needed to be alert in case any polar bears approached.

The MOSAiC floe: Its first year was far too warm

The following environmental processes are part of the reason the MOSAiC floe, at the age of one year, was far thinner and much more unstable than the experts had expected.

Wind-driven ice export (March-April, 1992-2019)

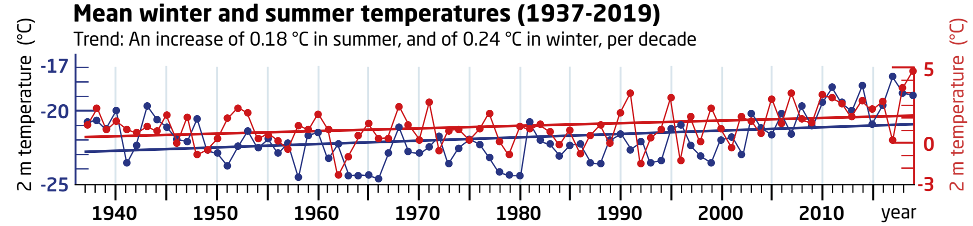
Trend: Increase of 53,000 km² per decade



At the end of winter 2018/2019, intense offshore winds rapidly moved large quantities of ice from Russia's marginal seas toward the Central Arctic (ice export). As a result, new patches of open water – called polynyas – appeared near the coast, and new ice formed within them.

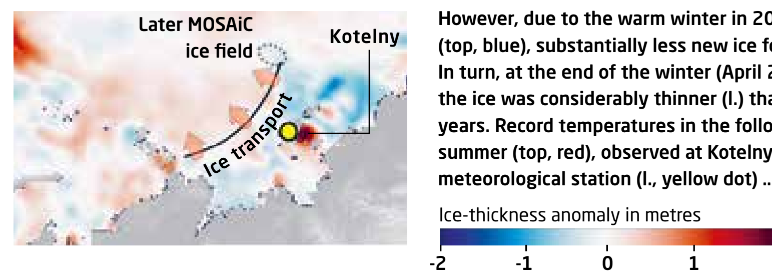
Mean winter and summer temperatures (1937-2019)

Trend: An increase of 0.18 °C in summer, and of 0.24 °C in winter, per decade



Differences in ice thickness

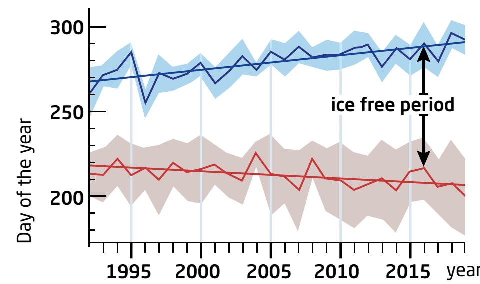
(CryoSat/SMOS data: Difference between April 2019 and April 2010-2018)



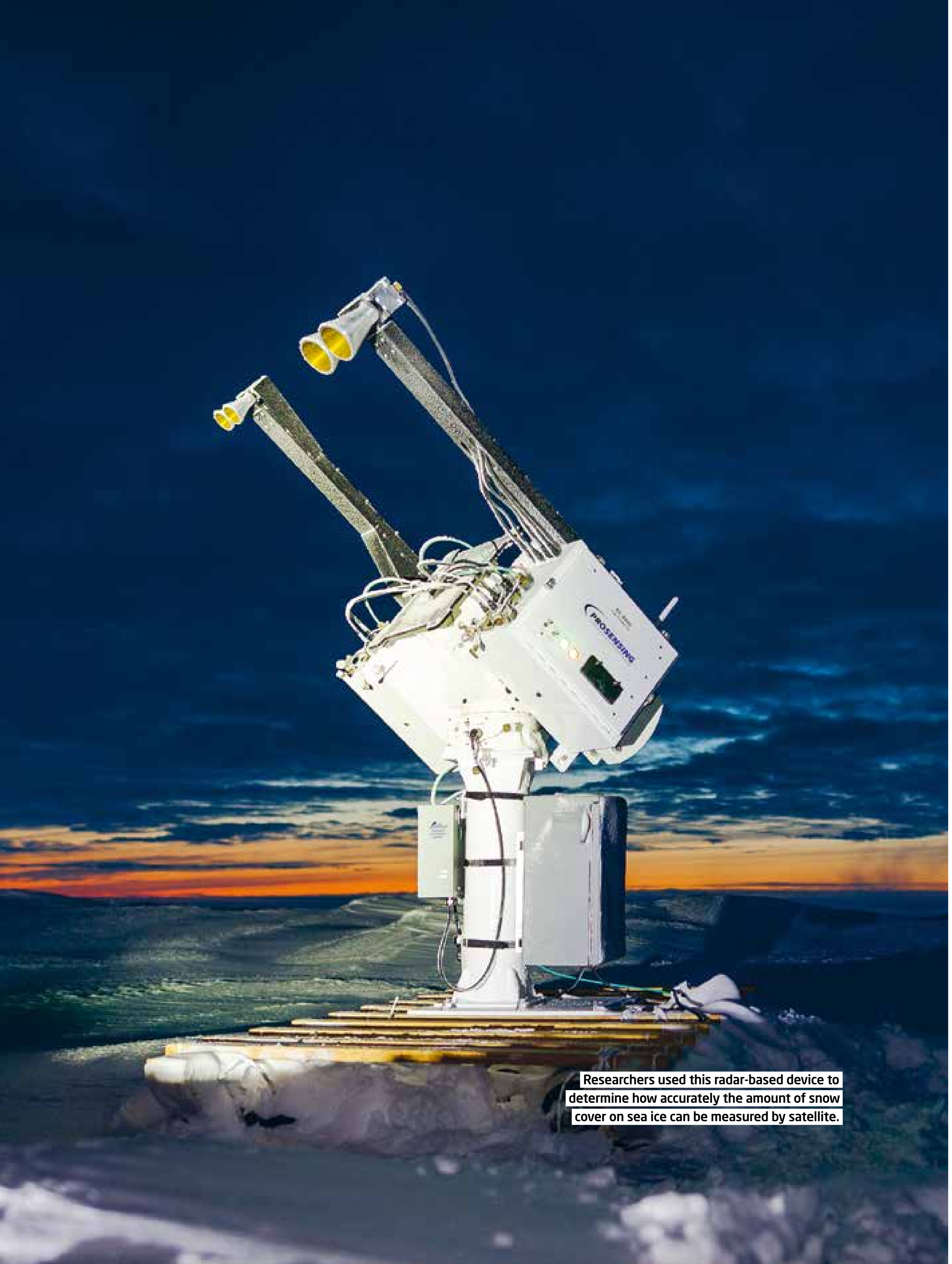
However, due to the warm winter in 2018/2019 (top, blue), substantially less new ice formed. In turn, at the end of the winter (April 2019), the ice was considerably thinner (l.) than in past years. Record temperatures in the following summer (top, red), observed at Kotelny meteorological station (l., yellow dot) ...

Start of break-up and freezing in the marginal seas

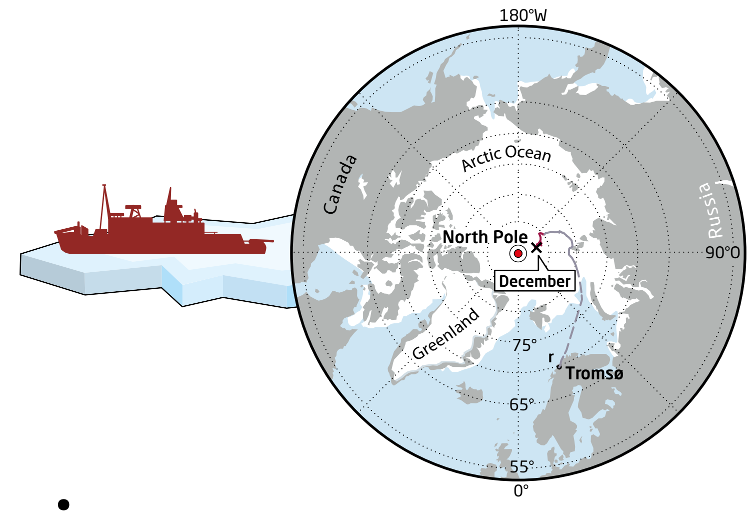
Trend: Start of freezing (blue) 8.5 days later, and start of break-up (red) 3.8 days earlier, per decade



... soon melted the remaining, thin ice. In 2019 satellites captured the earliest ice break-up in the Laptev Sea since the beginning of recordkeeping. Due to the prolonged high summer temperatures, researchers also documented record high water temperatures. In September 2019, this heat delayed new ice formation in the marginal seas.



Researchers used this radar-based device to determine how accurately the amount of snow cover on sea ice can be measured by satellite.



DriftStory 02

For a clearer view from space

Satellite observation is the only way to effectively monitor the Arctic sea ice on a broad scale. Yet this approach still has its fair share of weaknesses. Unparalleled control measurements gathered during the MOSAiC expedition will now help to overcome them.

As Dr Gunnar Spreen stood on the bridge of the research icebreaker Polarstern on the evening of 19 November 2019, in the ship's spotlights he suddenly saw the section of the MOSAiC floe where his remote sensing group's measuring instruments normally stood – drifting right past the ship! Thankfully, the ice movement along a long lead stopped after ca. 500 metres. Nevertheless, the physicist from the University of Bremen (Institute for Environmental Physics – IUP) knew that his group would now be forced to look for a new location; the ice where the instruments had been installed was now crisscrossed with small cracks, and seeping seawater had turned the snow on the ice into a briny mush.
As a result, the snow cover that the researchers had planned to use as the basis for a range of tests and experiments over the next several months was now useless. Today, snow remains one of the greatest sources of uncertainty in the remote sensing of sea ice, and one of the reasons why satellite experts joined the largest-scale marine expedition to the Central Arctic in history.

On the bridge of the Polarstern, physicist Gunnar Spreen uses its ice radar to check the ice movements near the ship (l.). He and his team have already been forced to relocate the ten remote monitoring stations once, after a large lead formed in the ice nearby.

THE IDEAL TOOL

Satellites have been used in sea-ice research for over 40 years. Some of the most important findings on climate change, e.g. regarding the wide-scale retreat of Arctic sea ice, were made with the help of satellite data. Satellite-based ice charts are now used in polar shipping, and are available to everyone, quasi in real-time, at online portals like meereisportal.de.

Today, more than 20 satellites provide constant sea-ice coverage for the polar regions. The majority of them orbit at altitudes of 600 to 800 kilometres and reach speeds of up to seven kilometres per second (25,000 km/h), allowing them to circle the planet roughly 14 times a day. Some satellites use optical sensors to monitor the Arctic and Antarctic; in other words, they produce images similar to those from a camera. But they can only be used in the spring, summer and autumn, when the sun is above the horizon, illuminating the polar landscapes. Moreover, clouds can block their view.

Instead, Gunnar Spreen and his team use microwave sensors to observe the sea ice. These sensors can deliver essential data, even in the long Polar Night and through cloudy skies. In this regard, two fundamentally different measuring techniques are used – one with active microwave sensors (radar measuring) and one with passive sensors (radiometer measuring).

If a given satellite is equipped with active microwave sensors, they emit long-wave (millimetre to decimetre), invisible electromagnetic radiation toward the Earth and measure either how much of the signal is reflected back by the sea ice, or how much time it takes for the signal to reach the ice and be bounced back to its source. The amount of energy reflected allows the experts to draw conclusions regarding the ice's age and surface structure; in turn, they can use the signal's travel time to deduce how far the sea ice extends above the surface. Based on its height, they can then determine how thick the ice is.

In contrast, passive microwave sensors don't emit any signals; instead, these radiometers measure how much long-wave radiation the sea ice emits on its own, simply because of its temperature: every body with a temperature above absolute zero (minus 273.15 degrees Celsius) emits both infrared and microwave radiation. Snow and sea ice have a base temperature of between minus 1.8 degrees Celsius on the underside of the ice and minus 30 degrees Celsius on the surface, and accordingly emit radiation. Though the amount of microwave radiation produced is only a fraction of the infrared radiation, the microwaves can pass through clouds and the atmosphere with virtually no interference.

As a result, satellites can measure them very precisely from space – around the clock, 365 days a year. "Satellites are the only tool that allows us to observe sea ice in the polar regions on a broad scale, and at any time," says Gunnar Spreen. "Yet the great challenge is that we can never use them to directly measure important ice properties like the area, thickness, age or concentration. Instead, the satellites record physical parameters like the microwave brightness temperature, which we have to convert in order to draw conclusions about the sea ice," the physicist adds.

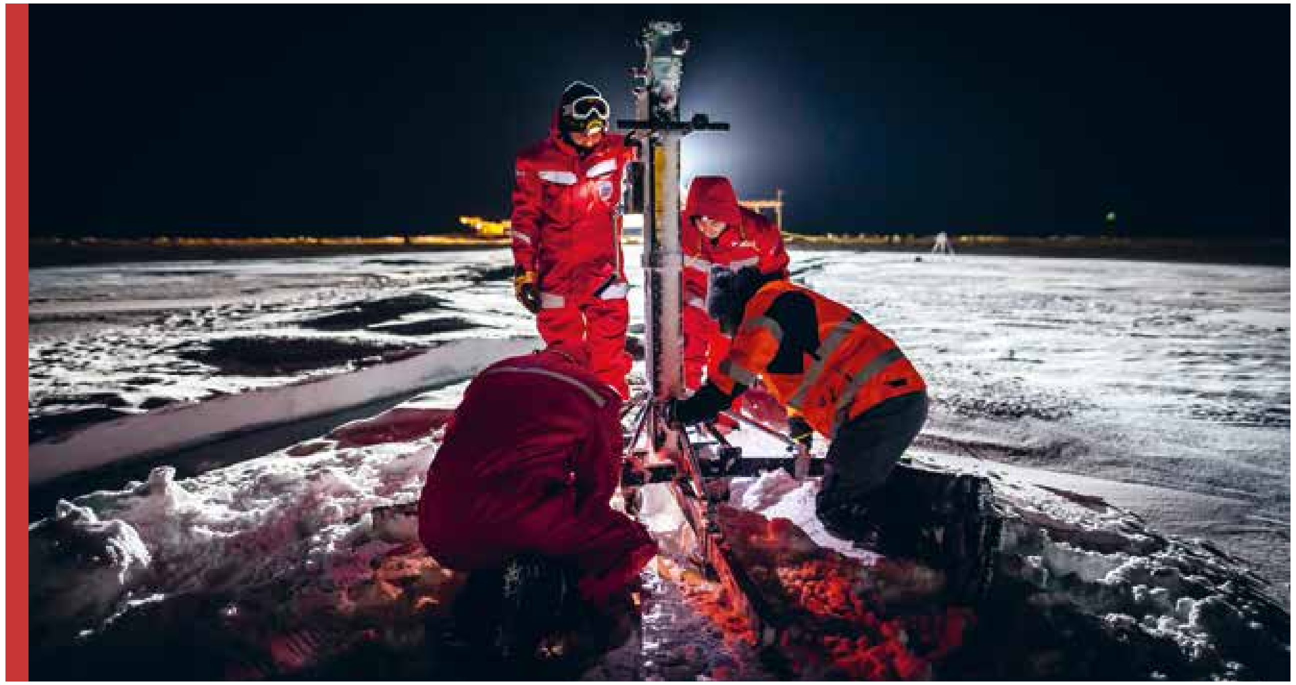
NOT ALL SNOW IS THE SAME

CryoSat-2 is the name of a satellite from the European Space Agency, which solely focuses on monitoring our planet's ice masses. It is equipped with a radar altimeter, which can measure both the thickness of the sea ice and height differences in the Greenland and Antarctic Ice Sheets.

To make these conversions, the experts use special algorithms that include equations on e.g. which physical processes are triggered when microwaves hit snow and penetrate it, or are scattered and reflected by it. Unfortunately, these methods are lacking in accuracy, because snow isn't a reliable constant; on the contrary, it changes continually, and so do its backscatter properties.

"For instance, freshly fallen snow consists of light, fluffy flakes, which makes it virtually transparent for microwave radiation, so we only see the ice below it," Spreen explains. But as snow grows older, the flakes clump together into larger grains, which can definitely reflect back microwave signals. Similar effects can be produced when the wind, as it did in the first few weeks of MOSAiC, whips over the snow cover, compressing its surface. "Then the backscatter properties undergo a fundamental change. Not all snow is the same."

In turn, Spreen gives an example of the errors that a compacted snow surface can produce: "When we use the CryoSat radar altimeter to measure the ice thickness, we work



Relocating the equipment: While one of the instruments was being dismantled, the lead in the ice was less than two metres away. The instruments are mounted on sledges, which means moving them across the ice is strenuous but not impossible.

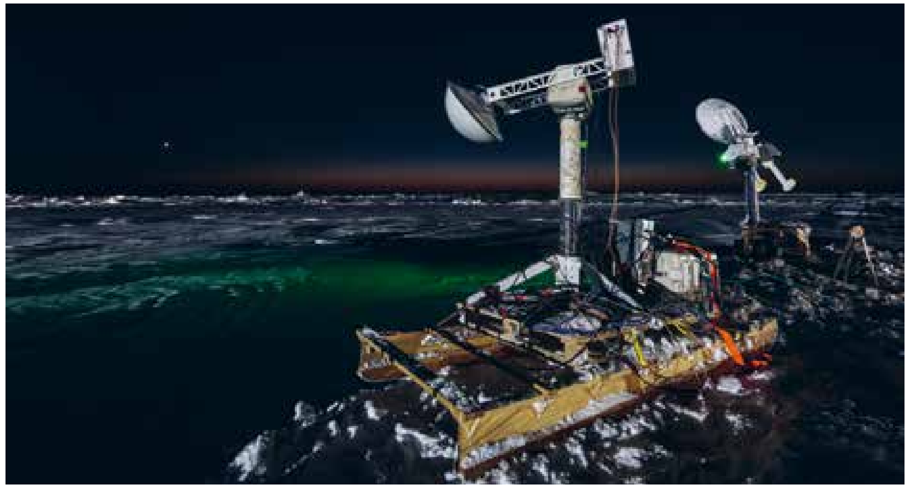
under the assumption that the satellite signal is reflected at the snow/ice interface. But we now know that that's not always true. If the snow's surface layer is compressed by wind, or if ice lenses form in the snow, our signal might no longer be reflected back at the snow/ice interface, but instead higher up in the snow. If we then base our ice-thickness calculations on this distance measurement, it automatically introduces a source of error."

BRINGING SATELLITE TECHNOLOGY DOWN TO EARTH

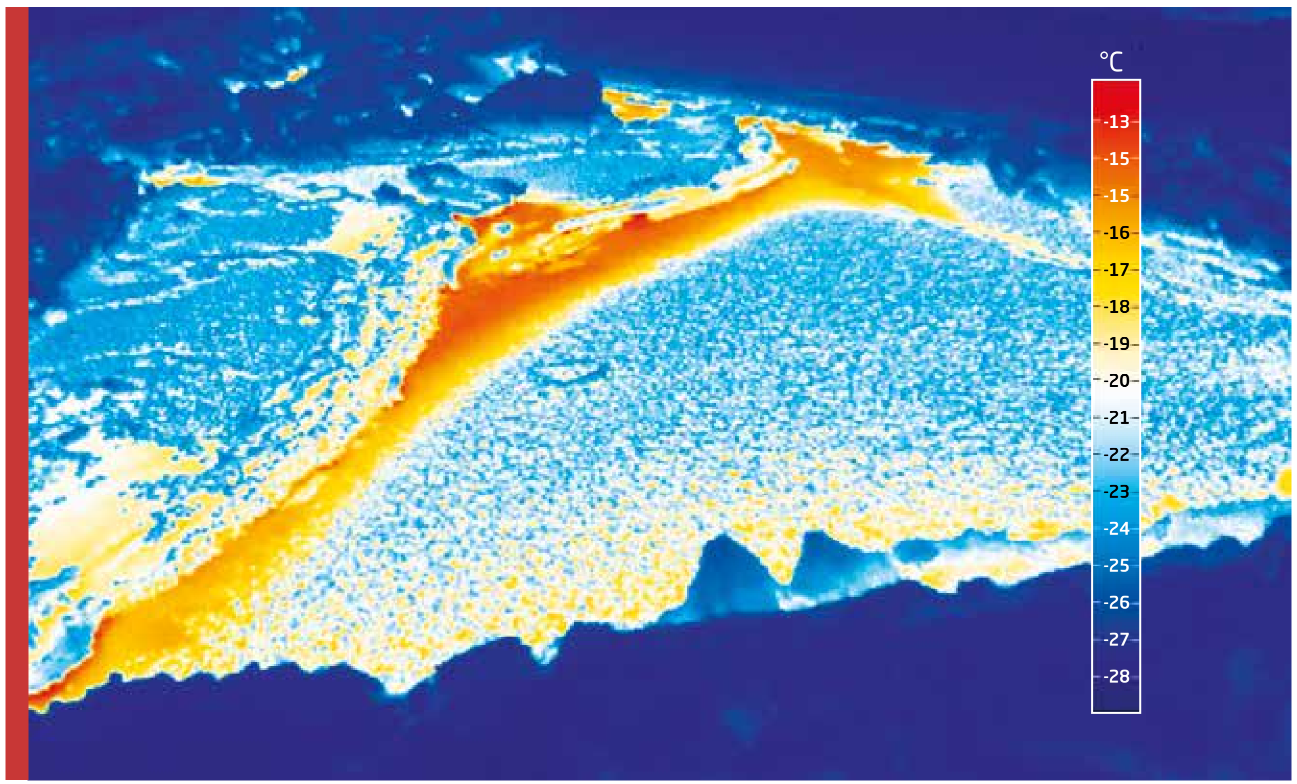
In order to identify this and other sources of error, for the MOSAiC expedition the experts had to bring their satellite technology "down to earth". The Remote Sensing Site is home to ten high-precision instruments, which use the same sensors as satellites. All ten are aimed at the same patch of ice and snow, allowing the researchers to gather a range of different readings simultaneously, and to scan the ice and snow using microwave signals at various frequencies. In addition, the sea-ice physicists use conventional methods to record ice parameters like the floe's thickness, salinity and snow cover, and subsequently compare the results with the parameters derived from the microwave data.

In the Arctic, the Polar Night refers to the phase of the year in which the sun never rises above the horizon. Though there is still a bit of twilight south of the 78th parallel, to the north of it, it remains pitch black nearly 24 hours a day.

"Our goal is to understand exactly what happens to our satellite signals in snow and ice, and how backscatter and radiation change with the seasons," says Gunnar Spreen. This hasn't been possible to date because essential data was lacking, especially from the Polar Night. Thanks to MOSAiC, for the first time the experts will be able to observe the processes at work in the ice and snow on a sea-ice floe for an entire year: from winter, with snowstorms and bone-chilling air temperatures down to minus 30 degrees Celsius; to spring, when the snow will grow warmer and contain more liquid water; and lastly to summer, when meltwater pools will form, and the ice will have more holes than Swiss cheese. Given the unprecedented opportunities that the expedition offers, 13 research centres have contributed satellite equipment, making the MOSAiC satellite validation programme



the largest coordinated international endeavour to improve the accuracy of remote sensing methods for sea ice in history. But the participating researchers have a great deal of hard work to do before they can announce any major gains – and not just because sudden ice movements in November made it necessary to relocate the entire Remote Sensing Site. "Once we've gathered all the on-site data on the interactions between microwaves, snow and ice, we will analyse it in an effort to better grasp the physical processes. Then the next step will be to integrate the processes in our data analysis algorithms, in the form of improved equations. Once that's complete, we can apply the algorithms to the same satellite data and check whether there is now less uncertainty," Spreen explains.
Nevertheless, the snow and ice readings taken during MOSAiC have already yielded one concrete finding: a new dual-frequency technique for measuring the snow cover height on sea ice has proved its value during fieldwork on the MOSAiC floe. As Spreen relates, "The dual-frequency radar altimeter will soon be used in the new European satellite CRISTAL. The signal in the higher frequency is reflected near the snow's surface, while the waves in the lower frequency are reflected at the snow/ice interface." The difference between the two values represents the snowcover height, with a minor degree of uncertainty. "In our test runs on the ice, we could see precisely how the two signals were reflected. We can now transfer these insights to the algorithms, so as to reduce the uncertainty before the satellite is ever launched."
Besides CRISTAL, MOSAiC's Remote Sensing Group will provide on-site ice data for a second future ESA satellite mission. The Copernicus Imaging Microwave Radiometer – CIMR for short – will measure ice and snow properties at five different microwave frequencies, helping scientists to monitor the ice area and thickness, snow cover height, and ice movements.
In the meantime, Gunnar Spreen can even see a positive side to the fact that a runaway slab of ice almost made off with all his monitoring equipment back in November: "Just a few days earlier, a two to three-metre-wide channel had appeared at our site. Since the air temperature was minus 30 degrees Celsius, the uppermost water layer quickly refroze, which gave us a unique opportunity to investigate this extremely thin ice and its ice flowers. Working on the Arctic sea ice during the Polar Night and getting to see and hear how quickly conditions can be changed by the wind and ocean was a truly fascinating experience!" ■



This infrared image shows newly formed, thin ice. Seawater, which is much warmer, is rising up through a lead in the ice.

How satellites measure sea ice

Passive Remote Sensing

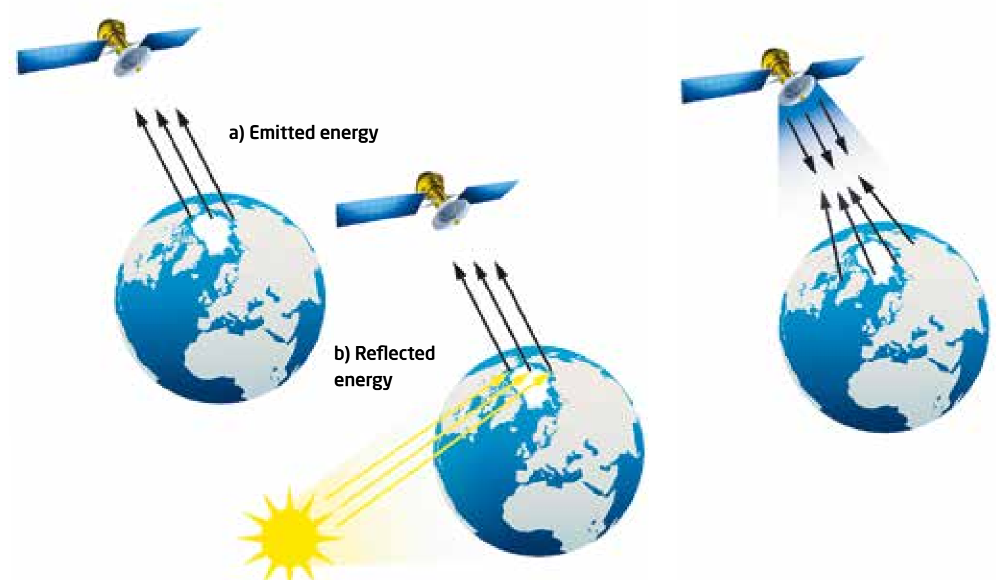
Measure energy that is naturally avaibable

- Emitted energy (a): Visible wavelength (day only)
- Reflected energy (b): Infrared, Microwave wavelength (day or night)

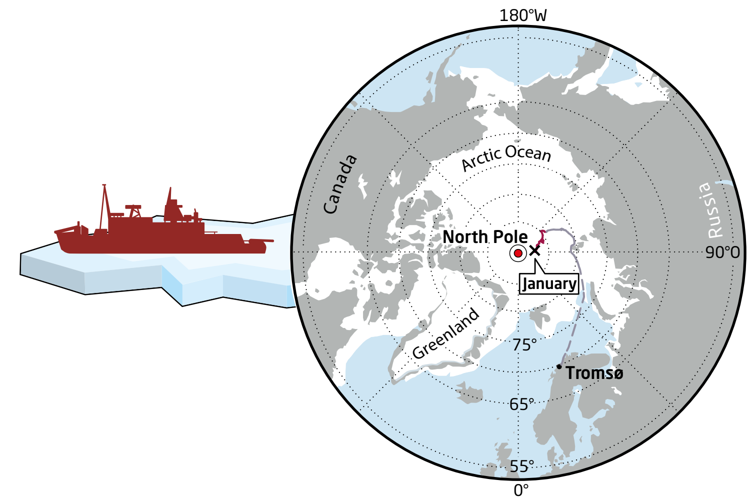
Active Remote Sensing

Satellite sensor emits radiation und records backscattered an reflected radiacion

- Independent of sun, day and night
- Often higher resolution than passive systems



Arctic sea ice is hardly a level, smooth surface. On the contrary: wherever floes collide or are pushed together, so-called pressure ridges are formed. Though they can reach up to 20 metres tall, only the topmost ten percent can be seen on the surface.



DriftStory 03

Shaking and Quaking

The thickness of the sea ice doesn’t just depend on how much seawater freezes into ice in winter. Another critical factor is how frequently the ice shakes and breaks, how often floes collide and pile up. In the following interview, AWI sea-ice experts Luisa von Albedyll and Stefan Hendricks explain why this happens, and why we need to know more about the background of such phenomena.

meereisportal.de: Ms von Albedyll, Mr Hendricks: in the course of the MOSAiC expedition, you’re both investigating how Arctic sea-ice thickness changes throughout the year. Why is this aspect so important for understanding the Arctic?

Stefan Hendricks: In the current climate debate, people often ask us at what point the Arctic’s summertime sea-ice cover will melt so dramatically that the Arctic Ocean can essentially be considered ice-free. To date, it’s been difficult to make this type of forecast, because we still know far too little about the actual thickness of the ice. And this parameter is what mainly determines whether or not certain parts of the ice survive the summer; as we all know, thick ice takes far more time to melt than thin ice.

Luisa von Albedyll: Ice thickness can be increased by two processes: one is naturally, by the cooling and freezing of seawater on the underside of the ice cover, which continues to work as long as the air temperature is sufficiently low and the ice cover doesn't become so thick that it prevents a further cooling of the water. Depending on the thickness of the snow cover, in many parts of the Arctic this can be the case at ice thicknesses of three metres or more.
The second process is much faster, and involves the movement and deformation of the ice, caused by wind and waves. When this happens, ice sheets are compressed and collide, forming pack-ice hummocks where the ice thickness can range from 10 to 20 metres.

meereisportal.de: ***But everyone keeps saying the Arctic sea ice is getting thinner and thinner …***

Luisa von Albedyll: It is. But at the same time, it's getting faster and more mobile. And that means ice movements and deformations are becoming more and more important for the overall ice thickness; in many places, they're responsible for 50 percent of the ice thickness.

Two researchers dig out a power cable that was buried when a pressure ridge formed nearby.

But these processes still aren't represented particularly well in our climate models, which is why one of our goals on the MOSAiC expedition is to gain a better understanding of deformation processes and adapt climate models accordingly.

meereisportal.de: ***How can you actually monitor how fast the ice is moving and to what extent it's deforming?***

Luisa von Albedyll: We combine a broad range of techniques. For example, I'm analysing sea-ice images from the Sentinel-1 satellite: a radar-supported satellite that uses microwaves to produce images with a resolution of 50 metres. So that means whenever the satellite flies over the MOSAiC target region, we can be sure to get an excellent image of it. My job now is to find out how much the ice moved between two consecutive images. To do so, I use an algorithm that compares image 1 with image 2, looks for a certain pattern in both images, and then calculates how far the pattern has moved. This tells me the ice's drift speed, and has allowed me, for instance, to reconstruct how the RV Polarstern moved through the Central Arctic.
The ship's coordinates are a great resource, which I can always use to check whether or not my algorithm's calculations are accurate. I also use data from the ship's on-board ice radar, which allows me to see in high resolution how the ice in a five-kilometre radius has moved.

meereisportal.de: ***Can your algorithm also tell you something about ice deformations?***

Luisa von Albedyll: Yes, it can. When I compare the movements of neighbouring floes, I can see where the ice has been compressed, where it's drifted apart, where two floes have passed by one another, and where none of the above has happened. Interestingly, the ice in those zones where the sea ice is deformed is often relatively flat and thin. That means when the sea ice is compressed, it doesn't behave like a soft sponge, with the whole block being affected; it's more like wood when put under too much pressure. It breaks and splinters, with all the pent-up force being released at a certain point or along a certain edge; most often, wherever the ice is thinnest. Then the sheets stack up one atop the other, piling into a pack-ice hummock.

Stefan Hendricks: In that moment, major tremors permeate the ice cover; on the surface, you can hear them even from far away. Accordingly, our Russian cooperation partners deployed seismic monitoring devices on the MOSAiC floe, to detect these deformation events and the resulting icequakes. We've also moored 'stress buoys' in the ice, which measure the stress inside it. These data-gathering efforts are complemented by regular ice-thickness measurements, which we've been taking every week since the start of the expedition – on foot, dragging our surveying sledges behind us.
In this regard, we staked off two routes on the floe right at the beginning – one on the thicker part of the floe, and one on the thinner ice that just barely survived the summer of 2019. Until November, both routes were characterised by smooth, level ice. But when a storm hit us in mid-November, a lead formed in the thinner ice. The sections of the floe began moving

DR STEFAN HENDRICKS
is a sea-ice physicist at the Alfred Wegener Institute. Although he has specialised in measuring sea-ice thickness with the aid of satellites, he also frequently takes part in ship-based and aerial expeditions to the Arctic.

On a level and undeformed part of the floe, measuring the ice thickness is a fairly straightforward task: one researcher walks ahead and measures the snow thickness with the so called MagnaProbe. The second follows, dragging the measuring sledge behind them.

back and forth, and ultimately began stacking up on a massive scale. What had once been a level, smooth sheet of ice now looked more like a field of rubble.

meereisportal.de: ***Did this force you to cancel the ice-thickness measurements?***

Stefan Hendricks: No, on the contrary; the deformation event was an extremely interesting development for us. Once we were allowed back onto the ice, we climbed over the pack-ice ridges, staked out the old route again, and resumed our survey work, right where we'd left off. After all, this gave us a great opportunity to precisely record how the total ice thickness changes when a level sheet of ice is transformed into chaotic debris.

Luisa von Albedyll: When it gets brighter again in the spring, we'll also be able to survey the ice thickness using the on-board helicopter. For this type of work, we'll rely on our sea-ice thickness sensor EM-Bird and a laser scanner. The latter provides us with a high-resolution elevation model of the ice's surface. So we essentially receive a highly accurate 3D map of the surface, which we can then combine with the satellite data and all the other data. And that's exactly the great thing about MOSAiC – we have the opportunity to gather

data on everything we need to know in order to make major strides toward answering the question "How do ice deformations change ice thickness?".

meereisportal.de: ***What can you already tell us: how does the ice move on its journey through the Central Arctic?***

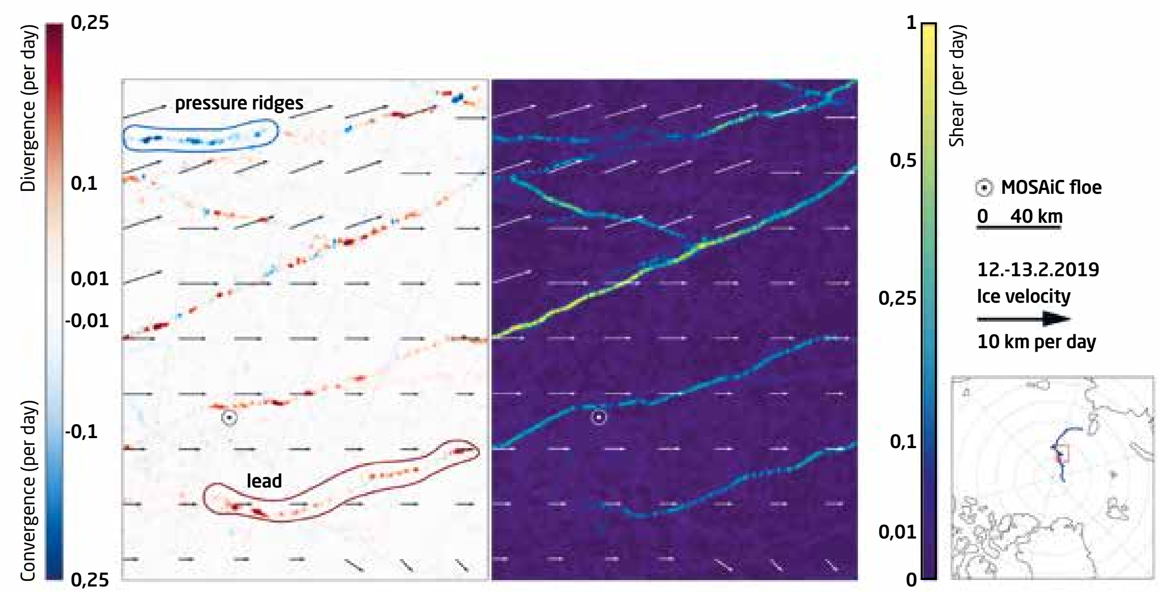
Luisa von Albedyll: A good deal of the Arctic sea ice forms in the Siberian marginal seas, and is then pushed out to the open sea by the wind. Once there, the Transpolar Drift carries it over the North Pole, bound for Greenland. But within this major ocean current, the ice doesn't all move at the same speed; it travels in large complexes, each of which can have its own speed. These ice sheets or groups of floes can measure thousands of square kilometres. At their edges, they constantly collide, shear, or drift apart, because one complex is moving slower or faster than the others in its immediate vicinity. This produces deformation zones, as we scientists call them.
Moreover, these groups of floes don't just stay the same; they can change over time, with the floes taking on new configurations or new weak points forming. Under these circumstances a large deformation zone can even form right in the middle of the MOSAiC floe, as we've seen in November 2019 and March 2020.

LUISA VON ALBEDYLL

Climate physicist Luisa von Albedyll is currently writing her dissertation at the University of Bremen on the topic of sea-ice deformation and ice-thickness changes. Though she could only follow the first half of the MOSAiC expedition from her office in Bremerhaven, in early April 2020 it was her turn to pack her gear and head for the Arctic!

Where the ice creaks and groans

Climate physicist Luisa von Albedyll uses an algorithm to locate so-called deformation zones in satellite images of sea-ice cover. The algorithm produces these coloured lines: where they are red, it indicates the floes have broken up; where they are blue, they have been compressed.



meereisportal.de: ***But if the ice travels in these tightly packed formations, how much room does it have to drift apart? Can you describe it for us?***

Luisa von Albedyll: It's a constant process of give and take. If the ice drifts away at a given spot, it has to stack up somewhere else. In other words, wherever a lead forms, it means a pack-ice hummock has formed somewhere else. The answer to the question of where the ice forms hummocks depends on where the ice cover was weakest: as a rule, if there's a point where the ice is substantially thinner, it gets compressed by the surrounding ice masses.

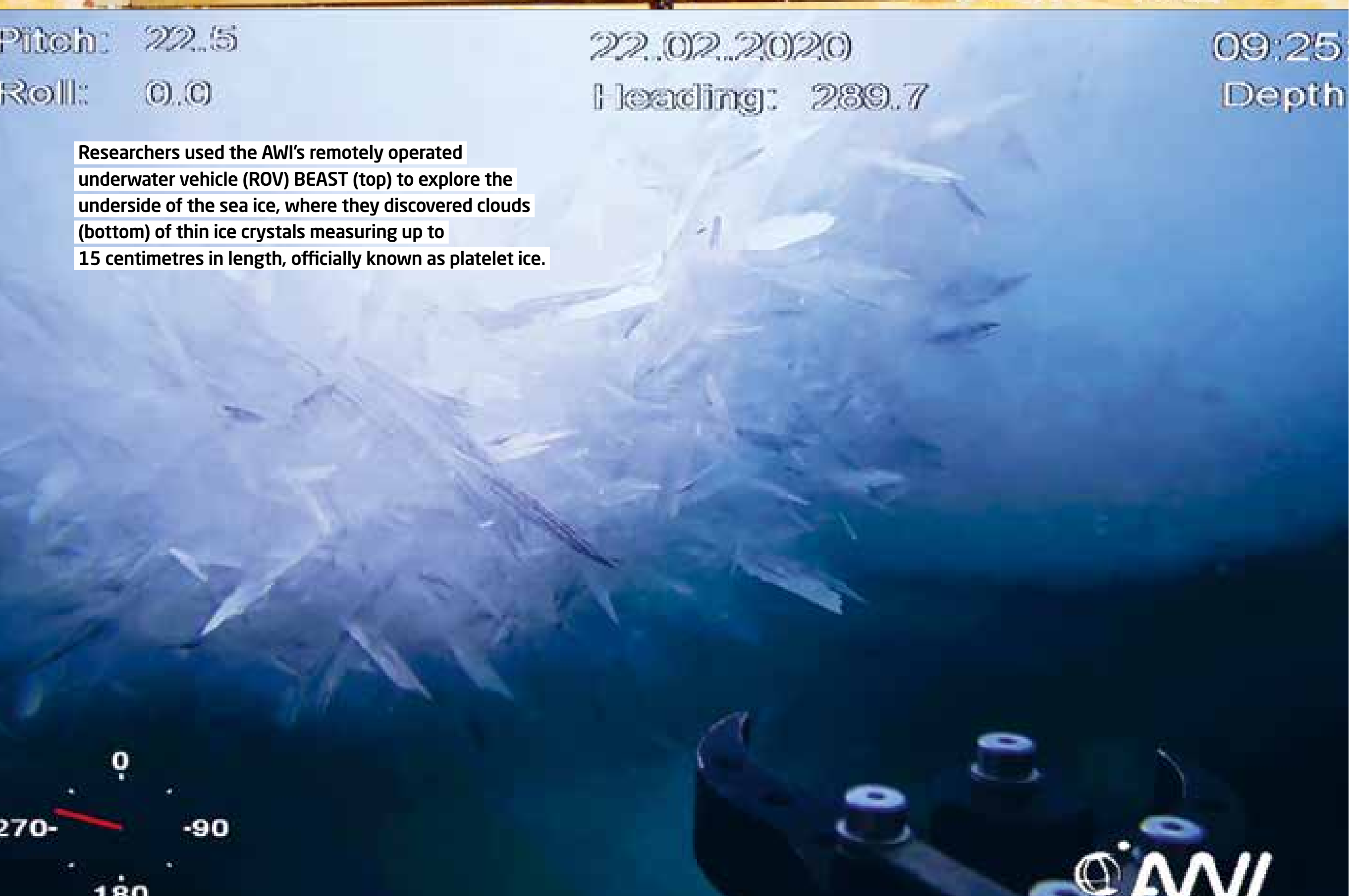
meereisportal.de: ***What is your takeaway from MOSAiC so far: were you surprised by how dynamic the Arctic sea ice was?***

Stefan Hendricks: I have to admit: so far, the ice has been much more dynamic than I expected. Except for the researchers from the Russian ice drift stations, no one has ever overwintered in the Central Arctic and taken readings then. While preparing for the MOSAiC expedition, I expected to initially find a few cracks in the ice, which would then freeze shut and that would be the end of it. But the reality was another story entirely. Even in March, a winter month, new leads formed in the ice.

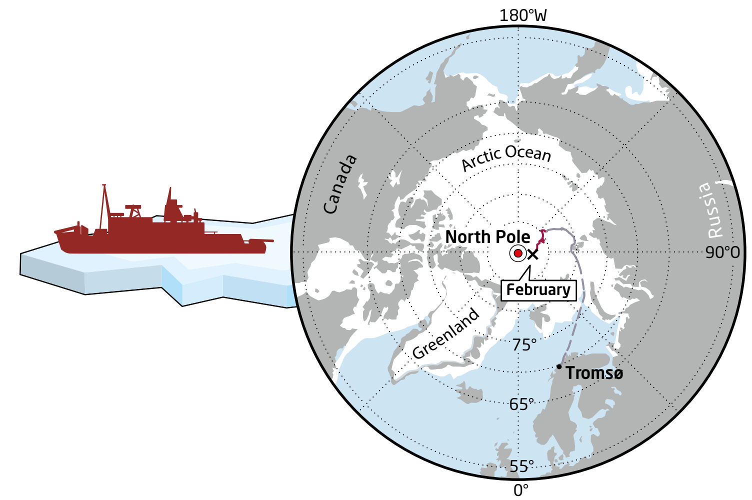
In March 2020, two clearly visible leads formed in the ice near the research icebreaker Polarstern. Their appearance was unexpected, and posed a number of logistical challenges for the expedition members, as the picture on the left shows. In response, solutions were jointly and quickly sought and found.

Luisa von Albedyll: Personally, I'm surprised by the frequency and intensity of the ice deformations we're currently seeing. Potentially, both factors could point to fundamental changes in the Central Arctic. After all, from the outset the sea ice has been thinner than expected. But it could also just mean that the winter was exceptionally stormy. The analyses haven't yet been completed. But one thing is for certain: so far we've been able to observe a range of deformation events, which has of course been of tremendous value for my research. But I can imagine that my colleagues on the ship were less enthusiastic: for them, these events often entail additional work, like when they're forced to relocate their monitoring equipment.

meereisportal.de: ***Thank you both so much.*** ■



Researchers used the AWI's remotely operated underwater vehicle (ROV) BEAST (top) to explore the underside of the sea ice, where they discovered clouds (bottom) of thin ice crystals measuring up to 15 centimetres in length, officially known as platelet ice.



DriftStory 04

Glittering clouds below the ice

The phases of Arctic sea ice growth could already be found in textbooks when AWI sea ice-physicist Christian Katlein was at university. Nevertheless, the 34-year-old made a new discovery on the MOSAiC expedition: while piloting the AWI's ROV below the ice, he observed a phenomenon previously only found in the Antarctic.

Generally speaking, it's very easy to explain how Arctic sea ice becomes thicker. You take an ocean, add a young, thin layer of sea ice on top, and then let a bitterly cold wind sweep over the ocean and ice for weeks without sunlight (the Polar Night). If you like, you can also turn down the temperature slightly on each new winter day – just like Mother Nature did in the MOSAiC winter 2019/2020, by the end of which the air temperature had dropped to -39 degrees Celsius.

Under such extreme conditions the ocean, despite being covered by a thick 'lid' of ice, emits a relatively large amount of warmth to the atmosphere. It makes its way through the uppermost water layer and surface ice, where it is released into the air. At the same time, the high-saline seawater on the underside of the sea ice grows so cold that it reaches its freezing point (-1.8 degrees Celsius). New ice crystals form and the ice cover begins to grow from below – though not uniformly.

"The interesting thing about sea ice is that it doesn't freeze homogenously, like the ice on a lake or pond," explains AWI sea-ice physicist Dr Christian Katlein. "Instead, the salt contained in the sea water in the form of brine gathers in small lenses or channels between the ice crystals. The majority of this brine seeps out into the ocean, but the rest remains in the ice, causing it to grow from below in layers. If you take a closer look at the underside of the ice, you can recognise rows of ice crystals, with these brine layers between them."

THE SPY BELOW THE ICE

'Taking a closer look' and documenting the growth of the MOSAiC floe for an entire winter, and on as broad a scale as possible, was one of the most important tasks for Christian Katlein and his team during the second leg of the Arctic expedition. Unlike all the other sea-ice experts on board the Polarstern, they didn't investigate the ice on its surface or using satellites, but instead explored a different perspective, using the AWI's ROV 'BEAST' as a high-tech spy below the ice – and sending it right into the action, where the water was constantly transforming into ice crystals.

The AWI's ROV is hardly a lightweight: it takes the muscle power of two researchers to lower it into the water through the entry hole. A tent that was erected over the hole protects the sea-ice physicists from the wind and snow.

The BEAST is an ROV (Remotely Operated underwater Vehicle) and is designed a bit like a cube-shaped flounder. All of its ice sensors and measuring instruments are located on the top and point upwards. Underwater cameras provide a clear view to the front and back, and a 300-metre-long fibre optic cable allows Christian Katlein to pilot the 130-kilogramme ROV by joystick, while also transmitting all data gathered directly to the piloting station: a small alloy hut on the ice that houses the control console, and which the ROV team painstakingly insulated so that they wouldn't become terribly cold during the long BEAST dives.

One of the most important instruments on the BEAST is the multibeam echosounder, which can scan a 25- to 30-metre-wide stripe of the ice's underside, record every nook and cranny, and measure the ice's depth, which can be used to determine the ice thickness with a high degree of certainty. For the weekly MOSAiC ice thickness measurements, Christian Katlein takes the BEAST to a depth of 20 metres and then pilots it back and forth as if he were mowing the lawn in a football stadium.

From the starting point – the ROV tent and entry hole – the BEAST proceeds straight ahead on autopilot, at a speed of one knot (ca. 1.85 km/h), to the edge of the circular measuring field. Once there, Katlein turns the autopilot off, turns the ROV about, and turns it back on until it reaches the end of the next sweep. This is repeated stripe for stripe, and takes between six and seven hours to complete.

"These measurements produce a complete, high-resolution spatial map of the ice thickness, which offers an excellent complement to our thickness measurements taken on the surface and shows very clearly how the ice thickness increases," Katlein explains. During the MOSAiC winter, the ice thickness grew by six to eight centimetres every week. Back in October 2019, the younger, thin part of the MOSAiC floe was only 20 to 30 centimetres thick; by early March 2020, the BEAST recorded thicknesses of ca. 130 centimetres. In the older part of the floe, composed of multi-year ice, it even reached two metres.

A SURPRISE ON THE LAST DAY OF THE YEAR

On the last day of 2019, Christian Katlein learned first-hand just how important it can be to explore the Arctic sea ice from below. As the BEAST slowly drew closer to the underside of the ice, on the display he suddenly saw collections of delicate ice platelets, which seemed to hang like cirrus clouds under the ice and glittered in the ROV's spotlights. The first thought that crossed Katlein's mind was that it reminded him of a snow-covered forest in winter, glittering in the sun. "Until that day, we had only ever seen platelet ice in the Antarctic. Finding it in large quantities below the MOSAiC floe in winter came as a complete surprise to us," the physicist recalls.

A subsequent review of the literature revealed that practically no other polar researcher had ever found platelet ice in the Arctic, carefully examined it and reported on it in a book or journal. The very few references to be found were largely anecdotal.

DR CHRISTIAN KATLEIN

is a sea-ice physicist at the Alfred Wegener Institute. He spearheaded the development of the AWI's ROV BEAST and oversaw its use during the winter leg of the MOSAiC expedition, from December 2019 to March 2020.

Accordingly, Katlein and his colleague, the AWI oceanographer Dr Benjamin Rabe, began investigating the phenomenon in more detail. They found a first clue in the temperature readings from the ocean buoys deployed in the vicinity of the MOSAiC floe. They all indicated that the top five metres of the water column had become supercooled during the winter, i.e., the temperature was ca. 0.01 degrees Celsius below the actual freezing point for the seawater. So why didn't it freeze?

"The Arctic seawater is so calm, and especially so clean, that it contains virtually no crystallisation nuclei like dust particles, algae or other tiny impurities. But these are necessary for the formation of ice crystals," says Katlein. It is only when the supercooled water below the underside of the sea ice collides with crystallisation nuclei that the often platelet-like ice crystals are formed. The experts observe the same effect when they lower cables or metal measuring rods into the supercooled water below the surface; after just a short time, they are covered with crystals.

Inspired by the discovery underneath the MOSAiC floe, the researchers then expanded their temperature analyses to include oceanographic time series from beyond the context of the expedition – and found frequent references to supercooling in surface water covered by sea ice. "But the temperature differences were so small that they were most likely written off as a measuring error, so no one took the time to investigate," says Katlein. "But we can now show that in our case, it definitely wasn't a measuring error. The biggest surprise was realising that there is a process underway in many parts of the Arctic that no one had ever truly noticed before."

The sea-ice physicists weren't the only ones on the MOSAiC expedition to collect ice cores. Here, biogeochemists drill into a freshly collected core to measure its temperature.

Platelet ice in the Arctic clearly differs from that in the Antarctic: for one thing, it doesn't form metre-thick layers; for another, it forms in the supercooled water on the underside of sea ice – and not at great depths below ice shelves.

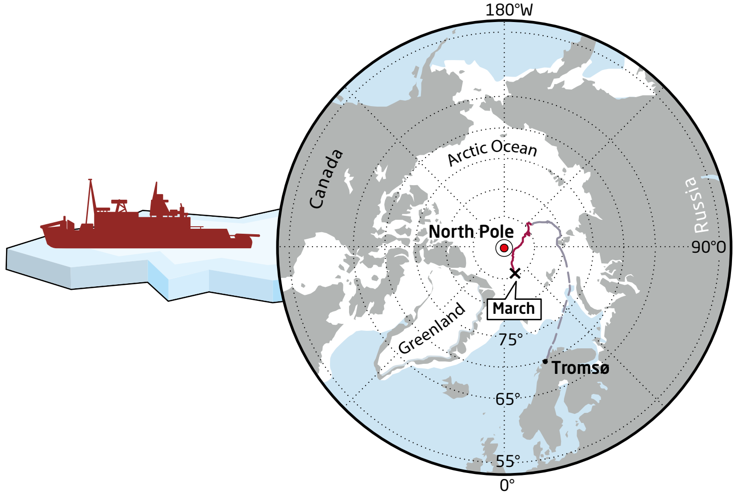
In the Antarctic, platelet ice forms under the **ice shelves**, is pulled away from them by rising water masses and ultimately collects in five- to ten-metre-thick layers below the sea ice. Since some of the wafer-thin platelets grow into the underside of the sea ice, when researchers conduct crystallisation tests on Antarctic floes, they can recognise the platelet ice in the sea ice's structure. However, in the ice samples taken from the MOSAiC floe, Christian Katlein and his colleagues found no trace of the platelets; even tests run in the on-board laboratory didn't yield any clear evidence.

An ice shelf is the part of an ice sheet or glacier that floats on the ocean – i.e., that part that does not lie on either the land or seafloor. These ice tongues can vary in thickness, from 50 to 1500 metres.

"That's most likely because the conditions for platelet ice formation differ considerably between the Arctic and Antarctic," says Katlein. In the Arctic, the ice platelets are formed in the supercooled water layer directly below the sea ice and grow on its underside, not in the water. Further, the 'clouds' of Arctic platelet ice are only 10 to 20 centimetres thick. "And since the normal sea ice grows rapidly in winter, we believe it also quickly expands through the platelet ice layer, essentially absorbing the individual platelets in the process."

But the AWI team doesn't need any further proof that the extraordinary crystal clouds are real: the BEAST caught the 'glittering winter forest' under the Arctic sea ice, and even the formation of the crystals, on video. Christian Katlein and his colleagues are now preparing an article, in which they will report on their observations and findings. It looks like the textbooks on sea ice might soon need to be rewritten. ■

Premiere in the Arctic: Snowcat driver Hannes Laubach had levelled the runway at the German Antarctic research station Neumayer III plenty of times, but even for him, ploughing on the surface of Arctic sea ice was a new experience.



DriftStory 05

One hot strip of ice

How thick does sea ice have to be for aeroplanes to safely land on it – and how do you patch cracks in the landing strip? These and other questions confronted AWI sea-ice expert Christian Haas and his team when they began constructing a landing strip on the MOSAiC floe, in total darkness. They successfully completed the task – and were the first German polar researchers to ever do so. But the project also showed them that building a runway on the ice is a science of its own.

Throughout his career, AWI geophysicist and sea-ice expert Prof Christian Haas has landed on Arctic sea ice plenty of times: to the north of Ellesmere Island (Canada) on board the AWI research aeroplane Polar 5 and with Twin Otter planes on skis; or as a passenger on a Russian Antonov cargo plane resupplying an ice camp near the North Pole. But, until the launch of the MOSAiC expedition, the 53-year-old could never have imagined that these personal travel experiences would one day help make him the first German polar researcher to lead the construction of a landing strip on the Arctic Ocean. But extraordinary expeditions call for extraordinary solutions! And that's how, at the start of MOSAiC's second leg, expedition leader Christian Haas, RV Polarstern's captain Stefan Schwarze, and logistics specialist Hannes Laubach found themselves faced with the challenge of creating a 400-metre-long and 25-metre-wide landing strip on the ice, in perpetual darkness. Safety considerations are what made it necessary to create a landing strip at short notice. At the time, Polarstern was over 1,000 kilometres from civilisation. If there had been a medical emergency, evacuation by air would have been the only option. Canadian Twin Otter planes could have been used to fly out patients.

However, the strip's planned long-term use was for logistics purposes. During the aerial surveys planned for the spring, the AWI's research aeroplanes could have landed near the Polarstern to refuel. This would have allowed them to penetrate far deeper into the Central Arctic than without refuelling. In addition, a crew transfer by plane was planned for April 2020: a Russian Antonov would have brought the new researchers to the RV Polarstern and flown the winter crew back to land. To make this feasible, the strip's length was to be extended to 1,000 meters. As we all know, the corona pandemic put an end to all these plans, though Christian Haas and his colleagues had no way of knowing it back in December 2019. They got down to work, and began by addressing a number of key questions.

QUESTION 1: HOW THICK DOES THE ICE HAVE TO BE FOR A PLANE TO LAND ON IT?

The team found the answer in the professional literature on the bending stiffness and breaking strength of sea ice. "Using the equations and formulas we found, we determined

Mission accomplished! Participants in the second leg of the MOSAiC expedition inspect the freshly cleared runway – to the extent possible in the dark.

that the ice had to be at least 80 centimetres thick for a 2.6-metric-ton Twin Otter to safely land on it – a thickness that many parts of the MOSAiC floe had already reached by late December," explains Christian Haas.

But the much bigger problem for him and his colleagues was the fact that, by its nature, sea ice isn't smooth, but coarse. "The surface was full of pressure ridges and snowdrifts, so we couldn't just look for a nice, smooth spot for planes to land on," says the expert. Accordingly, the team would have to use Polarstern's on-board snowcat to clear away these obstacles, plus plenty of snow. But back then no one knew what size of ridges the snowcat could handle; they'd just have to use trial and error.

But first they had to find a suitable area to clear. To do so, the team relied on ice-thickness and surface data that the ship's on-board helicopters had gathered with a laser scanning system during surveying flights in the Polar Night. To be allowed to fly at night, the pilots had completed special training prior to the expedition, plus the helicopters had a host of new technical systems on board. A hefty investment, but it immediately paid off. Using the high-relief ice charts produced, the researchers identified two suitable areas: one a stone's throw from the ship, and another roughly two kilometres away.

"We opted for the area closer to the ship, even though it consisted of very young ice that had only formed a few weeks earlier. Nevertheless, it was sufficiently thick throughout, and offered us a number of advantages," the expedition leader explains. For one, having the landing strip closer would allow the team to avoid countless long and difficult treks across the ice; for another, all of the clearing and smoothing work required to make the strip could be done with the support of Polarstern's searchlights. Choosing the other site would have meant working in complete darkness, making every movement on the ice that much riskier.

PROF CHRISTIAN HAAS
heads the Alfred Wegener Institutes Sea Ice Physics Section and, as Leg Expedition Leader, coordinated all research activities during the second phase of the MOSAiC expedition (December 2019 – March 2020).

QUESTION 2: JUST HOW POWERFUL IS THE SNOWCAT?

The next question concerned the 16-ton snowcat. Would the sea ice be able to support it? "As long as the vehicle is in motion, the ice below it only gives slightly. But when it stays in the same spot for several hours or days, then it gets problematic," says Christian Haas. In this case, the snowcat would gradually sink as the ice around it gave way. Eventually, cracks would form in the ice, until the massive vehicle fell through. Accordingly, it was parked at a different location after every shift.

The snowcat was put to the test before it even reached the area where the landing strip was to be built: on the way from the ship to its destination, massive pressure ridges blocked its way, meaning the snowcat would have to clear a path to proceed. How easy this was came as a surprise to the expedition leader and logistics experts alike. As Christian Haas recalls: "With sheer brute force, the snowcat levelled a one-metre-tall pressure ridge effortlessly." This was chiefly due to the ice's age: "The pressure ridges consisted of young ice. In other words, they were basically loosely stacked piles of ice blocks, which fortunately for us hadn't yet become frozen together." If the ridges had already survived a summer, the blocks would have already condensed into a compact mass that wouldn't have been so yielding.

In this aerial thermal image (r.) the runway appears as a 'hot' strip. The other brighter areas are leads in the ice, patches of thinner ice, and the RV Polarstern. Because of the coronavirus pandemic, ultimately aircraft only landed on the runway once (l.).

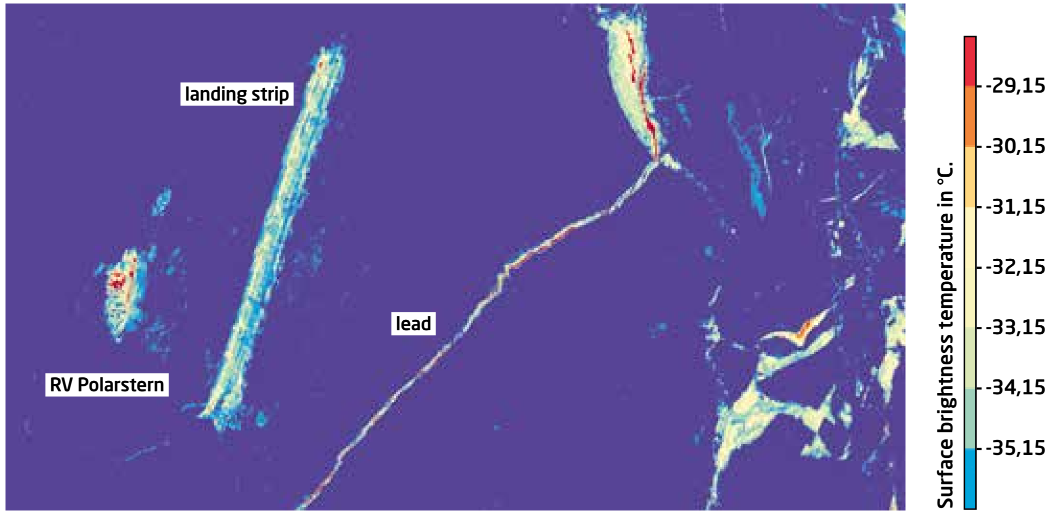
QUESTION 3: HOW CAN WE PATCH CRACKS IN THE LANDING STRIP?

While the snowcat was clearing the path to the construction site, the researchers were busy staking out a straight line for the future landing strip with flags. Not an easy task in the dark. With the aid of positioning lights, which they used like small lighthouses for orientation, the team was able to ensure that the 'straight and narrow' would ultimately live up to its name. After that, the actual task of clearing and levelling the strip with the snowcat only took a day – mission accomplished, right?

"In February we noticed the first cracks in the landing strip. This immediately raised the question of how we could patch them, how close the snowcat could safely get to them without breaking through the ice, and how wide they could be for the snowcat to even be able to repair them," Christian Haas recalls.

Back then, the ice was still more than a metre thick, easily thick enough for the snowcat to drive to the ice edge. According to the available literature, the cat shouldn't be used to repair cracks with a width exceeding one-third of the vehicle's length – so no more than one to three metres wide. And the cracks could be filled with snow and blocks of ice. "The advantage of snow is that it's the same temperature as the air, making it far colder than the ice. If you pack snow into a crack and then seal it, the snow mass almost immediately freezes into a cement-like mortar, and the crack is patched. So it was really quite simple; after all, we had snow to spare," the expedition leader reports.

At the same time, during helicopter flights over the MOSAiC floe, the researchers had made an interesting discovery: in thermal imagery of the floe, the snow free landing strip glowed a brilliant colour, indicating it was a 'hot strip'. But why? According to Christian Haas: "The rest of the ice was so well insulated by snow cover that hardly any heat was released from the ocean into the atmosphere. But on the landing strip, that insulating layer had been removed." For the same reason, the ice below the landing strip (snow free – no insulating effect, heat loss from the ocean, more freezing) grows significantly faster than the surrounding ice (snow-covered – insulating effect produced by the snow, less heat loss, less freezing).



QUESTION 4: WHAT DO WE DO WITH ALL THE SNOW?

Driven by their own success, in February 2020 the team decided to expand the strip, originally meant to accommodate Twin Otter aircraft, to suitable dimensions for an Antonov (1,000 metres long, 60 metres wide). But where could they put all the snow?

One-metre-tall walls of snow had already piled up on the sides of the landing strip – and, as if by magic, were steadily growing thicker. "On sea ice, anything that projects above the surface is an obstacle, and the drifting snow accumulates behind it. That's why the snow shouldn't really be piled up, but instead scattered over a broad area," Christian Haas explains. Plus there's the weight of the snow masses to consider: "If you plough the snow into a pile, all the weight is concentrated at one point, pushing down on the sea ice. And that can lead the ice to crack or break, or the area can flood if the weight of the snow pushes the ice below water level and seawater begins rising through the porous spaces and cracks."

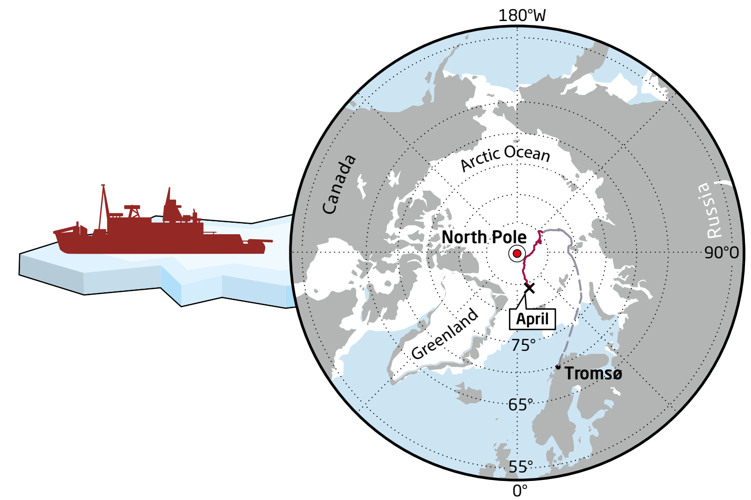
In contrast, wherever snow is removed, the weight of the snow layer is lost. As a result, the snow-free ice rises somewhat, which can produce further cracks and reduced stability.

After the corona pandemic had turned virtually all expedition planning on its head, instead of the originally planned Antonov aircraft, two Canadian Twin Otter planes landed at the MOSAiC Ice Camp on 22 April 2020.

As you can see, constructing a landing strip on the Arctic sea ice is a science in its own right, and far more complex than one would imagine. But in retrospect, for Christian Haas it was one of the most exciting sea-ice projects at the MOSAiC Ice Camp, even though he wasn't there in person when the two Twin Otter planes landed there in April 2020. By that time, the team for Leg 3 had commenced operations in the Central Arctic, and Christian Haas was – like the majority of AWI staff – doing home office to keep safe from corona. ■

After the outbreak of the coronavirus pandemic had made the planned personnel changeover impossible, on 22 April 2020 two Canadian Twin Otter aircraft – instead of the massive Antonov planes originally envisioned – landed near the MOSAiC Ice Camp to fly out selected researchers. Widely considered to be virtually indestructible all-rounders, the turboprop planes are frequently used for flights in the polar regions.

In the Central Arctic, snowfall is comparatively rare. The snow that does fall is often blown by the wind, chiefly accumulating on the lee side of obstacles like pressure ridges.



DriftStory 06

Snow, the great unknown

The number of winter days on which snow falls in the Central Arctic can be counted on one hand. Nevertheless, the amount of snow on the Arctic sea ice is a key factor influencing how quickly the ice grows, and when it begins melting in the spring. But until recently, little has been known about this enigmatic white substance. AWI sea-ice physicists have developed and implemented a unique snow research programme, the first findings of which have attracted considerable interest.

Freshly fallen snow is one of nature's miracles; no other natural product on our planet reflects as much sunlight as it does. And no other natural covering provides as much insulation against the cold as a blanket made up of millions and millions of tiny snow crystals. When the Arctic is covered in its snow-white winter cloak, it reflects up to 90 percent of the sunlight back into space, keeping the region from warming – an effect known as

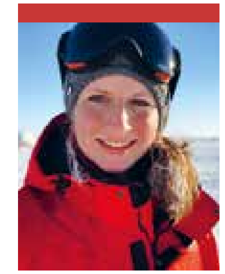
albedo. At the same time, the layer of snow on land protects plants and animals from freezing. While air near the ground can, under certain circumstances, reach temperatures as low as minus 40 degrees Celsius, beneath the snow layer it remains tolerably mild. There – depending on how high the snow has piled up – temperatures reach ca. zero degrees Celsius. This difference makes it possible for small animals like ermines to survive.
However, from a sea-ice researcher's perspective, the white snow layer first and foremost raises questions. To date no one knows precisely how much snow falls over the Arctic Ocean, how much of it remains on the sea ice, or how it is distributed on the ice. This is all the more important because snow is a decisive factor in determining the fate of the sea ice. In winter, the insulating layer prevents the ice from cooling to any great extent and growing more quickly. In spring, on the other hand, it reflects sunlight and delays the onset of melting – but only until the snow itself melts. When meltwater collects on the ice, puddles are formed, known as meltwater pools. These pools absorb heat from the sun, accelerating sea-ice melting. As such, the relationship between ice and snow is extremely complex and variable.
However, the extent to which the amount and depth of snow make a difference in that relationship, and which physical and chemical processes are at work in the snow layer

The researchers have placed a SnowMicroPen on the snow (l.) in order to obtain a high-definition density profile of the snow cover. The measuring rod is inserted vertically into the snow, where a small sensor on its tip measures the resistance. When storms blow, they all ask themselves: is it really snowing, or is the wind just kicking up loose crystals? (top).

over the course of the year, has remained unchartered scientific territory. Which is why the AWI's sea-ice physicists have made snow a major focus of their MOSAiC research and developed an extensive measuring programme. Since October 2019 they have been investigating sea-ice cover at all temporal and spatial scales, on a daily to weekly basis.
This fieldwork is fundamental research in its purest form – from the tiny snow crystals and their metamorphosis into snow grains; to the formation of different snow layers and their density, microstructure, thermal conductivity, temperature, and water and salt content; and finally to the distribution of snow over the entire MOSAiC floe. This has resulted in one of the most valuable MOSAiC datasets, the preliminary results of which are already attracting considerable interest. Actually, it snows far more rarely in the northern polar region than you might think. According to simulations, between 10 and 40 litres of precipitation per square metre of sea ice fall in the Central Arctic, more than 60 percent of it in the form of snow. That means the monthly average precipitation in the North Pole region is exactly the same as that in the Sahara Desert.

GONE WITH THE WIND

"On our leg of the expedition, we could have counted the days on which we were consciously aware of snowfall on one hand," reports AWI sea-ice physicist Dr Stefanie Arndt, who led the snow programme on the third leg of MOSAiC (from March to May). If



DR STEFANIE ARNDT
is a sea-ice physicist at the Alfred Wegener Institute in Bremerhaven, where for the past several years, she has been investigating the role of snow in polar regions. Her work has led her to explore the remote past, especially of the Antarctic.
But for MOSAiC, the 31-year-old headed back to the High North.

DR MARCEL NICOLAUS
coordinates the AWI Sea Ice Physics Section's Arctic snow buoy programme. In the course of several expeditions to the Arctic and Antarctic, he has especially investigated the transfer of heat, light and energy through the sea ice and the snow cover atop it.

snowflakes are swirling through the air, there's usually a strong wind blowing. "At times like this, it was hard to tell whether fresh snow was actually falling, or whether the wind was just stirring up snow crystals that had already fallen," Arndt explains.

That's why, at the end of her stay at the MOSAiC Ice Camp, the researcher drew the same initial conclusions as her AWI colleagues Daniela Krampe and Dr Marcel Nicolaus had before her on the first two legs: when it comes to local snow accumulation on the Arctic sea ice, snow drifts appear to play a far more important role than total precipitation. "Because of the strong winds, fresh snow doesn't simply stay where it fell. It is transported and accumulates in large mounds on the ice surface, for example in the lee of pressure ridges," says Daniela Krampe.

The AWI researchers' observations have since been confirmed by data from the 14 snow buoys that the team had installed on level ice at the beginning of the expedition. While the snow layer on the level ice increased only gradually, and was still nowhere near the 30-centimetre mark by the end of the winter, behind the ridges the researchers soon found themselves hip-deep in snow.

"Observing the distribution of the snow throughout the winter and being able to measure it to within a centimetre was a unique opportunity," says AWI sea-ice physicist Marcel Nicolaus. Prior to MOSAiC, he had taken part in several past Polarstern expeditions to the Arctic. On these summer voyages, the ship usually didn't reach the Central Arctic until late May or early June. "By then, the snow drifts that had been formed by the wind had largely melted, so that we had little idea what sizes they reached in winter," the 44-year-old explains.

NEW COMPONENTS FOR SEA-ICE MODELS

The wealth of new data gathered on the snow depth and distribution is now being evaluated. The next task for the AWI researchers will be to integrate the new information into current ice models. "Up to now, in our models the snow has mostly been evenly spread over the ice surface. That means they lack a vital component that we need in order to correctly calculate the energy flows and energy balance, so that we can more accurately predict the future development of Arctic sea ice," says Marcel Nicolaus. A few years ago, he conducted a study investigating the influence of snow on the energy balance in the sea ice / ocean system. What he found: if the snow cover melts just 14 days earlier in the year, the sea ice melts so rapidly that, over the summer, the ocean absorbs up to 50 percent more energy than if the snow had melted later. A real eye-opener, and one that led the AWI sea-ice researchers to closely follow the spring snow melt.

The drifts on the lee side of pressure ridges are the only parts of the floe where the researchers find themselves up to their thighs in snow; everywhere else, the snow cover is less than 30 centimetres by the end of the winter.

In the summer, all the snow melts away. The resulting meltwater creates pools on the ice, with dark surfaces that reflect far less sunlight. Instead, they largely absorb the solar radiation, causing the water to grow warmer and accelerate the melting of the ice.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Range of Methods Used

What more can you ask for

During the MOSAiC expedition, virtually every type of sea-ice measuring device was used – including proven technologies and newly developed ones alike. In the following, we'll briefly introduce some of the most important methods and tools employed, sorted by where they were used or from which perspective. The experts left no stone unturned when it came to investigating the sea ice from every angle imaginable.

MEASUREMENTS FROM THE AIR AND SPACE

Research airplane Polar 6

Ice-thickness sensor EM-Bird

A research aeroplane was used for large-scale measurements of the ice thickness. It towed below it the ice-thickness sensor EM-Bird, suspended 15 metres above the ice.

Satellites

Sentinel-2

CryoSat-2

Today, there are more than 20 satellites circling the Earth to observe its sea ice; the majority at an altitude of 600 to 800 kilometres. Two of the most important ones are CryoSat-2 (ice thickness) and Sentinel-2 (structure of the ice's surface).

Quadrocopters

Sometimes the bird's-eye view can provide the best overview: that's why the researchers also used drones to take aerial photographs and measurements of the ice's surface characteristics.

Helicopter

Hyperspectral camera

Laser scanner

EM-Bird

Radiation-measuring device

Equipped with night-flying instruments, the icebreaker Polarstern's on-board helicopter can also take to the air in the dark, and was used for various ice measurements.

MEASUREMENTS ON AND IN THE ICE

Ice corers

Whether biologists, physicists or chemists: virtually all of the researchers on board needed ice cores for their work. The cores were extracted using an ice corer.

Remote sensing sites

In order to check how accurately satellites can measure the sea ice, the experts set up ten instruments with similar sensors on the ice.

Ice mass balance buoys

This buoy measures the snow height, ice thickness, and temperature to monitor how the snow cover and ice cover wax and wane.

Thermistor-chain buoys

These five-metre-long chains, dotted with temperature sensors, extend from the surface of the floe into the ocean and measure the temperature of the snow, ice and water.

Research Vessel Polarstern

Panoramic camera

Ice radar

Ice lab container with various instruments

Mission headquarters: on board the RV Polarstern, researchers had access to the ice lab container, which was home to micro-CT scanners and various other special-purpose instruments.

Flux stations

How much heat does the ocean release through the ice and into the air? To answer that question, the researchers measured energy fluxes with the aid of flux stations and sledges.

Ice thickness sensors

To take ice-thickness readings from the surface of the floe, electromagnetic sensors were hauled over the ice on a sledge – usually on previously defined routes.

Measuring the mechanical properties of the sea ice

When ice floes collide, tremendous forces can be released, and have crushed entire ships in the past. In order to gauge how stable the ice was, and what forces were currently at play, the experts used the following tools:

Stress or pressure sensors

Seismometer and tilt sensors

Laser extensometer

Used to measure ice pressure, strength and stability of the ice

Light measurements

Radiation station

Light harp

Radiation buoy

Sunlight is an essential parameter for the sea ice: the experts used a variety of methods to measure how much was absorbed or reflected.

MEASURING THE SNOW

Stakes and hotwires

Both were used to take ice-thickness readings on a spot-check basis. The difference between the two tools: the stakes froze in place, whereas the hotwires could be moved again after heating.

Snow pits

The researchers used snow pits to measure and take samples from the snow cover. To do so, they needed e.g.: a shovel, trowel, yardstick, sample containers and a clipboard for taking notes.

MagnaProbe

The experts used the MagnaProbe to measure the height of the snow. To do so, they simply inserted the rod into the snow vertically; at the touch of a button, the coordinates and recorded data were saved.

SnowMicroPen

The SnowMicroPen allowed the experts to create density profiles of the snow cover. The measuring rod is inserted vertically into the snow, where a sensor on its tip measures the resistance.

Terrestrial laser scanner

The laser scanner surveys the surface of the ice and generates a detailed elevation profile, making it possible to detect e.g. snowdrifts.

MEASURING BELOW THE ICE

Acoustic Doppler current profiler

An acoustic Doppler current profiler (ADCP) uses sound waves to measure the flow speed of water masses.

AWI underwater vehicle BEAST

Cameras

Sonar systems

Light sensor

CTD sonde

Oxygen sensor

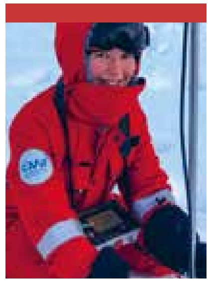
The underwater vehicle BEAST is remotely piloted via cable and can be equipped with mission-specific sensors prior to dives below the ice.

CTD sonde and water sampler

The CTD sonde measures the electrical conductivity and temperature of the water at a given depth (Conductivity, Temperature, Depth = CTD). The water sampler does just what its name implies.

Microstructure sonde

This sonde is specially designed for use with eddies, and measures the turbulent mixing of the water at extremely high resolution.



DANIELA KRAMPE
a doctoral candidate, is researching the carbon particle content of snow cover on Arctic sea ice. The second leg of the MOSAiC expedition offered her a unique opportunity to collect snow in the immediate vicinity of the North Pole.

The temporary shutdown of the MOSAiC Ice Camp due to the corona pandemic meant that, from mid-May to mid-June, observations were only possible via satellite. Thankfully, the snow buoys on the ice floe continued to faithfully transmit data on the snow thickness. The data showed, among other things, that in May, just four days with an air temperature of less than one degree Celsius above zero were enough to cut the snow depth in half – from 20 to 10 centimetres. In the future, sea-ice and climate models with snow components will have to measure up to this and various other types of new snow data gathered during MOSAiC. Until now, no one else has succeeded in gathering data – especially not such consistent and reliable data – on the snow on Arctic sea ice over an entire winter and beyond.

LITTLE SNOW IS LOST IN ICE LEADS

Based on what was learned during the MOSAiC winter, we also need to rethink our answer to the question of how much snow is lost when leads form in the ice, or when ice floes drift apart and the snow falls into the sea. "Previously, we assumed that ice leads contributed substantially to snow loss. But at the MOSAiC Ice Camp, time and time again we saw newly formed ice leads freeze over within a matter of hours, due to the frigid air temperatures," reports Stefanie Arndt. That means that the snow didn't disappear into the sea for long, but instead soon began collecting on the new ice, where it was then potentially redistributed by the wind.

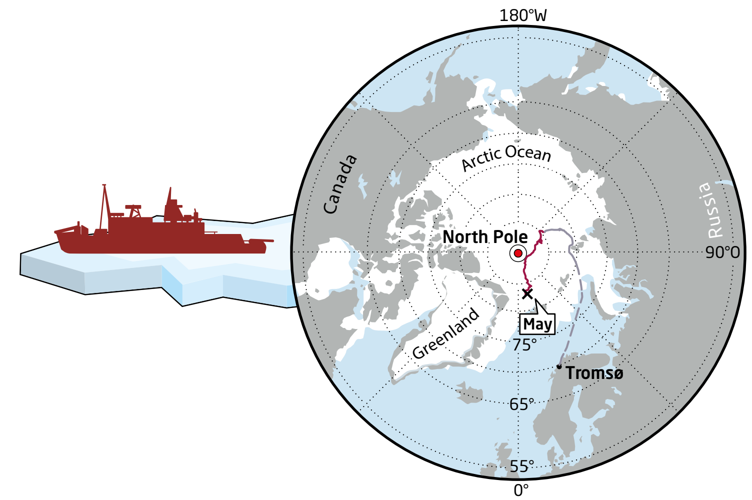
PAW PRINTS IN THE SNOW

While working on the ice, Stefanie Arndt also observed a second phenomenon: since relatively little snow fell during the winter months, tracks made in the snow were often preserved for several months – including those left by four-legged visitors. "In April 2020, during one of our measurement campaigns, we could still clearly see the tracks of a polar bear that had most likely visited the MOSAiC Ice Camp in December 2019, since there hadn't been any new polar bear sightings during our expedition leg since January," the 31-year-old sea ice physicist explains.
Together with her AWI sea-ice colleagues, Arndt is now eagerly awaiting the end of the expedition and Polarstern's return to Bremerhaven, because the ship's refrigerated cargo hold contains countless snow samples collected at regular intervals and at various sites throughout the Ice Camp. These samples will provide insights into e.g. the number of carbon particles deposited on the snow, or how much microplastic from the Arctic air the snow contains. In addition, investigations of the water isotopes are planned.
The findings of these investigations will shed new light on where the precipitation originated before falling on the Arctic sea ice as snow, and on how the snow itself has changed during its time on the ice. Furthermore, based on the water isotopes from the snow and ice, the sea-ice physicists can identify precisely which portions of the ice were formed from snow rather than from seawater. In this regard it's important to know that the snow layer on the sea ice can, under certain circumstances, become so thick that its weight

forces the sea ice under the water's surface. When this happens, water permeates the ice – e.g. by rising up through pores or cracks. When the water subsequently refreezes, snow-ice is formed, and the ice floe grows from above.
Snow is a topic that the AWI's sea-ice experts will be investigating long after the MOSAiC expedition comes to an end. Given the vast number of snow samples and the wealth of new datasets collected, we can expect to see exciting new findings. ■

Throughout the expedition, polar bears frequently approached the ship. Fortunately, there were no encounters between humans and bears that were remotely dangerous.

On 30 June 2020, meltwater ponds nearly as long as the research vessel Polarstern covered the MOSAiC ice floe – though the snow began melting weeks earlier.



DriftStory 07

The importance of the first snowball

In spring, along with the sun, warmer temperatures return to the Central Arctic. However, precisely how this changes the snow layer and how it ultimately affects the sea ice are still not completely understood. Accordingly, throughout the MOSAiC expedition, AWI sea-ice physicists have closely observed the changes in the snow cover, and used a surprisingly simple trick to do so.

Satellites, robots, high-tech cameras: on no other polar expedition has the Arctic sea ice been monitored using so much modern technology as on MOSAiC. However, sometimes the sea-ice physicists still use quite simple tricks – like the snowball test. "Trying to make a snowball gives us a fairly good indication of whether or not the snow has started to melt and the percentage of liquid water has increased. Under normal winter conditions, the snow on the Arctic sea ice is far too cold and dry to be made into a ball," explains AWI sea-ice physicist and snow expert Dr Stefanie Arndt.

That's why she regularly used the snowball test as part of her research at the MOSAiC Ice Camp. Arndt took part in the 3rd leg of the expedition, and arrived at the floe at precisely the point when, for the first time after the long Polar Night, there was once again twilight and the sun announced its return. Spring was just around the corner, bringing with it crucial research questions: when, and above all how would the sunlight and rising air temperatures alter the snow cover on the Arctic sea ice?

But each time, before trying the test, the researcher first let two handfuls of snow run through her fingers – even in the first two weeks of April, when the sun shone round the clock. "An undisturbed area of snow is highly reflective – or has what we call high albedo. It reflects up to 90 percent of the sun's rays. If at the same time the air temperature is below freezing, the solar energy can't melt either the snow or the sea ice below it. That means the physical properties of the snow barely change and it doesn't stick together," Arndt explains.

June 2020: a sheet of wood offers the researchers a makeshift bridge over a stream of meltwater running between the ship and camp.

A FIRST TASTE OF SPRING

The turning point came on 19 April in the form of a brief but massive inflow of warm air into the Central Arctic. Within the space of a day, the air temperature at the snow's surface in the Ice Camp rose from minus 7.4 degrees to minus 0.2 degrees Celsius. The warm spell only lasted 24 hours, but it was enough to make a lasting change in the snow layer. "The warm air at the snow's surface immediately brought the top third of the snow layer up to the melting point," reports the scientist. Afterwards the entire snow layer froze again. But by that point, the warmth had already left its mark on the snow. "We assume that, in this brief warm phase, the first of many large snow crystals began to melt, changing their shape and becoming smaller, even though we couldn't yet see these changes in detail in the overall snow cover," says Arndt. The only thing that could be seen with the naked eye was a clearly recognisable glazed layer. "From above, the snow looked as if the entire area was starting to melt. But in fact, following the inflow of warm air, the surface refroze and became reflective like a mirror," the researcher reports.

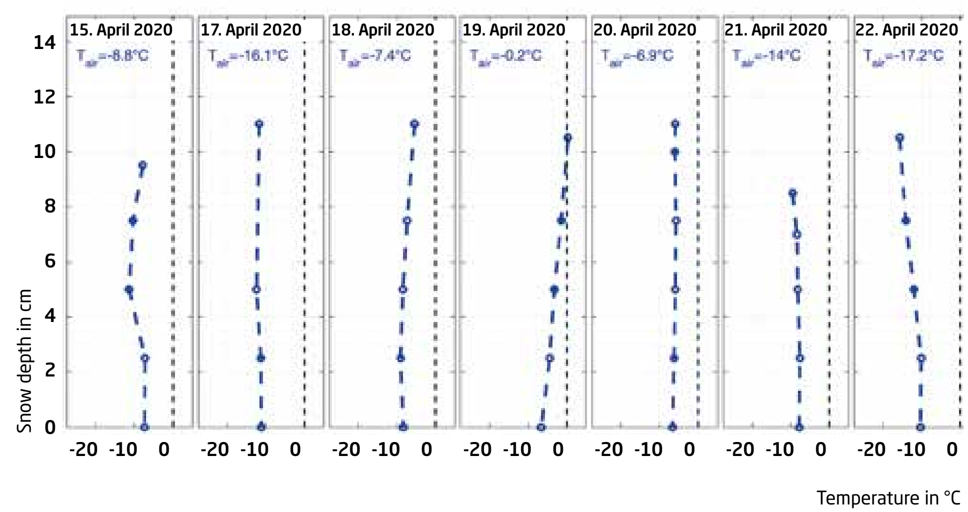
The opportunity to personally experience such a warm spell in the Central Arctic was the highlight of the spring for Stefanie Arndt and the other researchers. All the research groups intensified their measurements in order to document the effects of this event at all levels – from the atmosphere to the ocean. But it soon became clear: it would take more than just a brief influx of warmth to set off the melting season in the Central Arctic. It would take a special event – which occurred almost four weeks later, on 12 May.

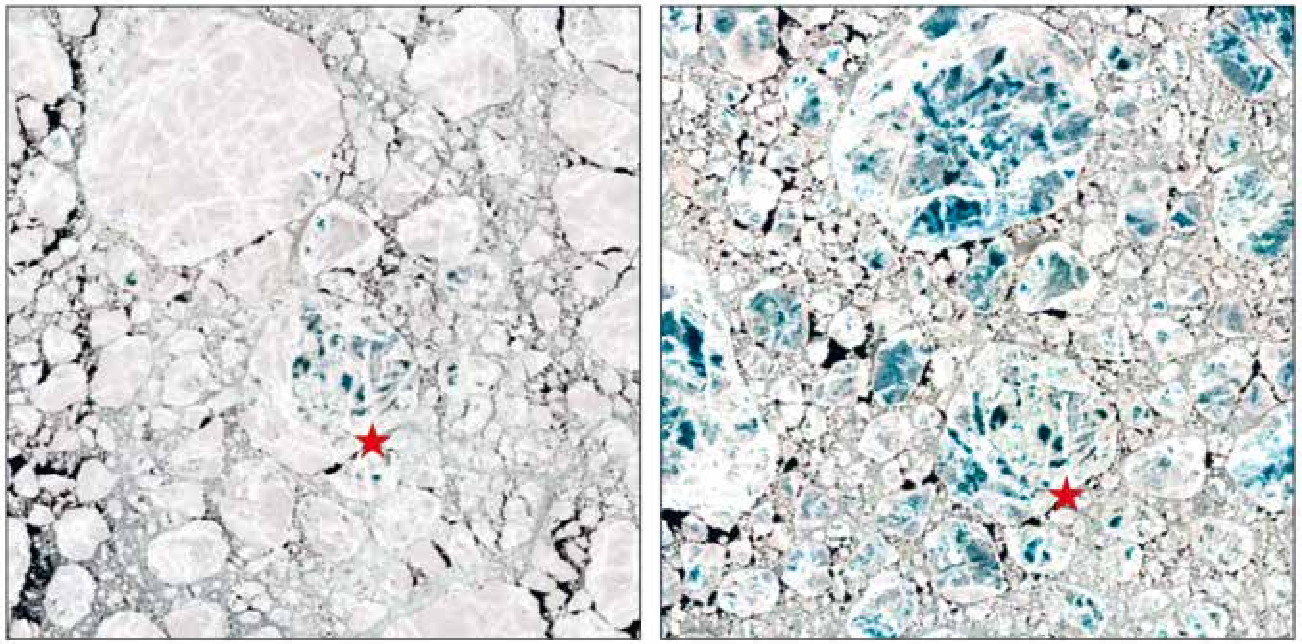
DR STEFANIE ARNDT

In the course of the MOSAiC expedition, Dr Stefanie Arndt frequently made snowballs for research purposes – provided the snow had the right qualities for doing so.

When the atmosphere warms the snow

When the air masses over the MOSAiC floe suddenly warmed between 18 April and 19 April 2020, the temperature profile of the snow layer on the ice rapidly changed, as this data clearly shows. Above all, the upper third of the snow layer nearly reached the melting point. Afterwards, however, the snow cooled again just as quickly.





These two satellite images of the ice near the MOSAiC floe (red star) were taken nine days apart. On 21 June 2020 the first meltwater pond formed (l.); by 30 June 2020 they covered large expanses of the ice (r.).

The North Cape is a promontory extending into the Arctic Ocean from the island of Magerøya, which lies off the northern coast of Norway. Since 1999 it has been dubbed the northernmost point in Europe that can be reached by road from the mainland.

On that day a storm front from the North Cape with wind speeds of 7 to 10 on the Beaufort scale swept through the Central Arctic and replaced the cold winter air at the MOSAiC Ice Camp with warmer air from the south. Once again, the air temperature at the snow's surface soared – from minus 10.9 to minus 0.2 degrees Celsius. But this time the warmth was here to stay, and finished what it had started in April.

WHEN THE FLOES TURN GREY

Freshly fallen snow crystals possess a multitude of tiny surfaces and edges. These reflect the sunlight so that to observers the snow layer appears white. But when the snow becomes warmer, the heat causes the various microstructures to melt into each other. The edges become rounder and the crystals clump together, creating sticky snow that can be formed into snowballs.

"If this process continues for two to three days, the previously white snow turns grey, since the altered optical properties mean that it no longer reflects the entire spectrum of the sun's rays. Instead, it absorbs more and more sunlight, causing the snow to become warmer and to melt further from within. It collapses and becomes wetter, turning into grey slush, and forming the first puddles of meltwater in depressions on the sea ice," explains Stefanie Arndt.

The onset of melting on the sea ice in spring also marks the end of the AWI ice-thickness measurements using the CryoSat satellite. When the snow is wet, the satellite's radar signal is no longer reflected clearly enough. The researchers then have difficulty determining on the basis of the measurement data whether the signal has been reflected by a snow-and-ice layer, or by open water. They therefore discontinue the measurements during the summer.

Unfortunately, in the third and fourth weeks of May, Stefanie Arndt was only able to observe the beginning of the snow melting from on board Polarstern. Due to the coronavirus pandemic, during this key phase for the sea-ice physicists the ship was on her way to Svalbard for a personnel rotation. By the time the ship returned to the MOSAiC floe, it was already mid-June.

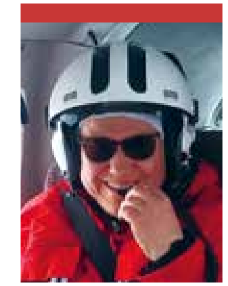
A PATCHWORK OF MELTWATER PONDS

AWI climate researcher Dr Gerit Birnbaum was one of the first participants in the fourth leg of the expedition to actually see the floe. During her laser measurements of the ice with Polarstern's on-board helicopter, she flew over it and its neighbouring floes, and documented the condition of the ice surface: "On our first flyover, on 16 June, the first ponds had already formed on the ice floes in the vicinity of the MOSAiC floe, mainly along the pressure ridges. Meltwater ponds in the flatter, undeformed areas of the floes were still relatively rare. Instead, here we saw regular grey patterns or areas that indicated melting snow, while the pressure ridges looked like white bands stretching across the floes," she reports from on board Polarstern.

Two weeks later, there was water in many areas of the floes. "By the end of June, the area covered by ponds had increased rapidly; the snow melting was in full swing. But as temperatures varied, there were several cycles of melting and refreezing in the top layer of water in the ponds. We could clearly see newly formed, thin layers of ice on their surfaces," Birnbaum recalls. On the young ice, which was just one winter old, the grey slush had disappeared and the resulting meltwater had formed a patchwork of interconnected ponds and puddles. The pressure ridges could still be seen as lighter bands crisscrossing the floes.

The effects of changes on the surface of the ice reach down to the ocean, as the AWI sea-ice physicists' radiation measurements show. In those areas where meltwater ponds form on the ice, less sunlight is reflected. The light warms the water in the ponds and increasingly penetrates the thinning ice into the upper layers of the ocean, where it signals algae to start growing.

Astonishingly, this transparency doesn't decrease again until the meltwater ponds penetrate the ice from above, allowing most of their water to flow into the ocean. At this point the areas of exposed ice at the edges of the former ponds start reflecting more sunlight, and the AWI's MOSAiC sensors beneath the ice record a substantial reduction in light intensity – an important finding in terms of the energy balance and heat fluxes in the sea ice / ocean system.



DR GERIT BIRNBAUM

is a meteorologist in the Sea Ice Physics Section at the Alfred Wegener Institute in Bremerhaven. The role of meltwater ponds in interactions between the sea ice and atmosphere is one of her main research topics.

Radiation sensors measure the amount of incoming or reflected light, and were used both on the ice and below it during the MOSAiC expedition. The underwater measurements focused e.g. on the question of at what point the algae within and below the ice receive enough light to start reproducing.

ACCURATE TO THE NEAREST SQUARE METRE

"By the first few days of July, above all the water in the large, deep ponds on the two-year-old ice had drained out – that means, their water surface or extent had shrunk again. On the one-year-old ice, the melting was so far advanced that in some parts, the area covered by shimmering blue ponds was larger than that still covered by snow, which could only be found at points that were topographically elevated," says Gerit Birnbaum. In technical jargon, these patches of grey and white are also known as the 'scattering layer', since what remains can't really be considered snow.

Gerit Birnbaum and her team were able to document the waxing and waning of the meltwater ponds down to the nearest square metre, since during the helicopter survey flights over the ice, cameras recorded the size and shape of the individual ponds. Furthermore, based on the camera data, the researchers were able to determine the size distribution of the meltwater ponds, whether the ponds were interconnected, and how deep each one was. The average albedo of the sea ice was also measured, while a laser scanner mapped its surface topography.

Knowing how early in the year the first ponds form, how large they become, and when they drain is essential in terms of predicting when in the summer the Arctic is likely to be ice-free for the first time. As a dark, sunlight-absorbing area, the network of meltwater ponds is a major factor in the Arctic sea ice melting more rapidly and extensively in summer than it has in the past.

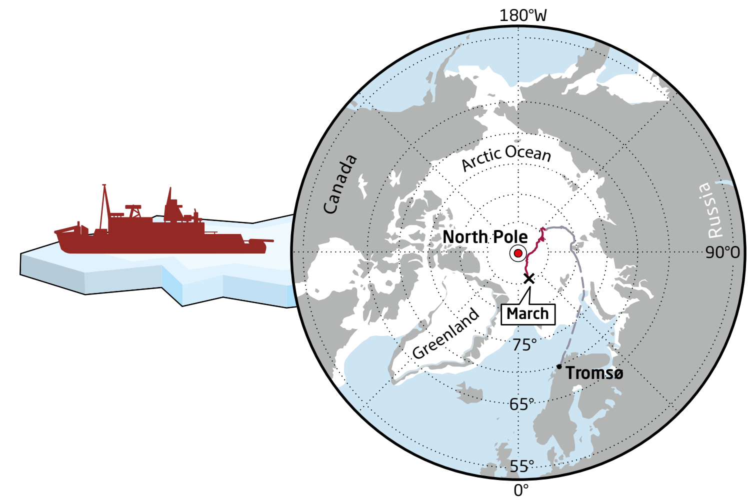
The heat's handiwork: the areas of grey snow tell the researchers in which parts of the ice floe the snow has already started to melt. This aerial shot was taken on 24 May 2020.

Consequently, Birnbaum's meltwater pond data gathered during MOSAiC will be used to support numerous scientific analyses. Some researchers are investigating whether the ponds on the MOSAiC floe and in its immediate vicinity are representative of the sea ice in the Central Arctic. At the same time, others are using data from the helicopter flyovers to assess how accurately the various satellite-based measuring systems capture the Arctic's meltwater ponds.

One of these systems is MODIS, the Moderate Resolution Imaging Spectroradiometer, aboard the United States' Terra and Aqua satellites. This summer, AWI sea-ice physicists plan to use MODIS data to painstakingly monitor sea-ice melting across the Arctic. To do so, they will use the satellite system to record where and when sea ice was present, in which areas it was covered with meltwater ponds, and where areas of open water formed. So in the end, Gerit Birnbaum's countless helicopter flights over the slowly melting MOSAiC floe will pay off in a variety of ways. ■

Just over eight weeks later, on 29 June 2020, the experts dismantled their research camp. At this point, much of the floe was already covered with water, and just one day later, it broke into several pieces.

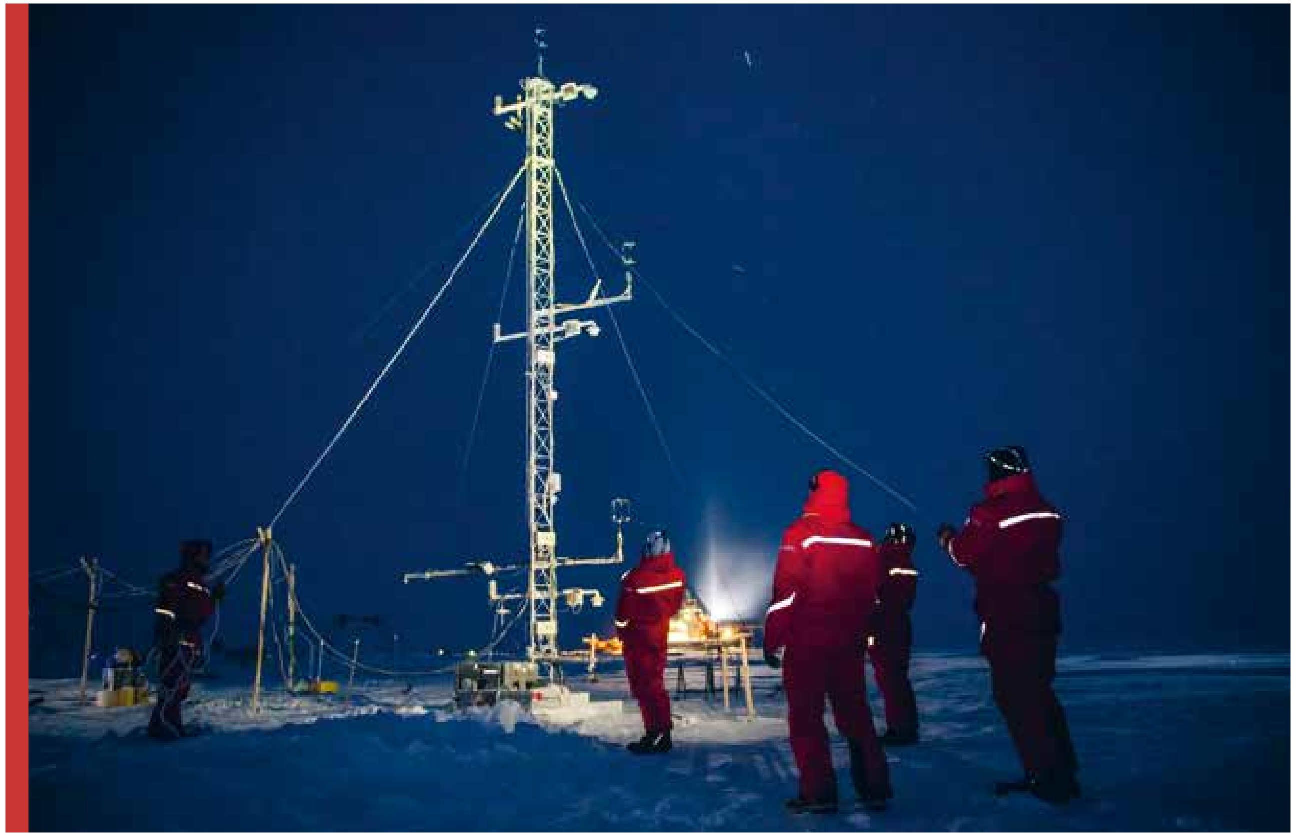
Miss Piggy is the name that the AWI's atmospheric researchers have given to this orange tethered balloon, which can rise to heights of up to two kilometres. On the ice floe, it was used to measure the temperature in the lower air layers.



DriftStory 08

The many faces of cold

In response to the question: "How cold does it get in the Arctic?" polar researchers will give you very different answers – depending on whether their work focuses on the **atmosphere, snow** and **sea ice**, or the **ocean**. As part of the MOSAiC expedition, scientists recorded temperature trends in all three contexts and analysed how they influence one another. One of their findings: even on the coldest winter day, there were temperature differences of up to 60 degrees Celsius! We asked the AWI experts how this was possible and what it means for the sea ice. Here are their replies. Combining these various scientific aspects helps us to arrive at a better overall understanding of the entire system.



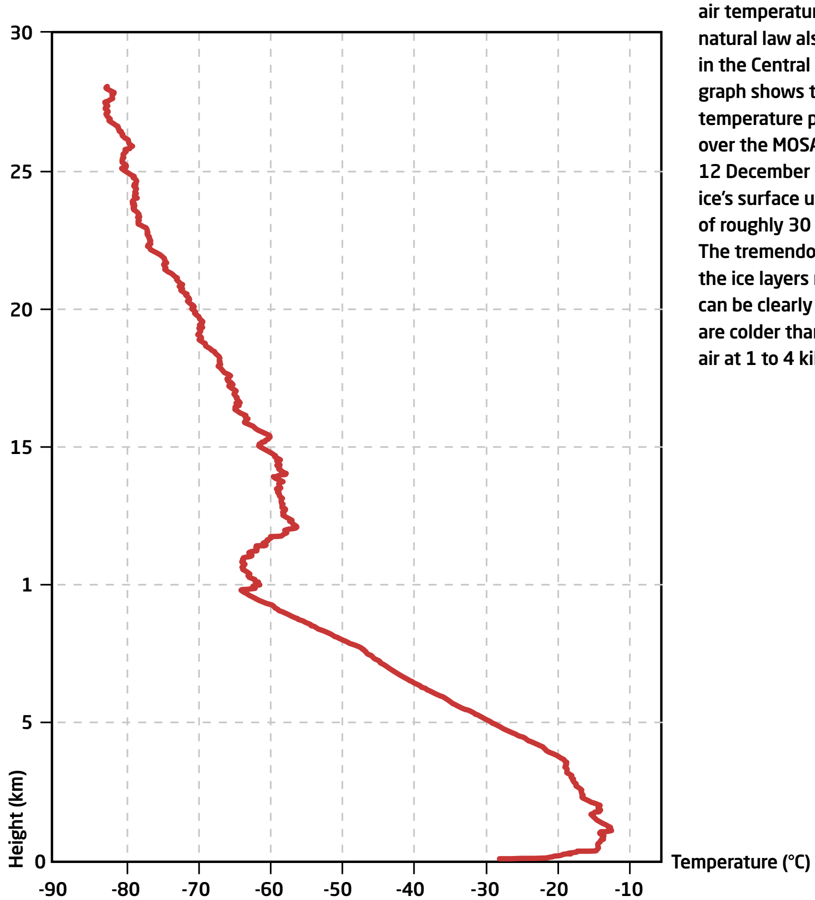
At the beginning of the drift experiment, US researchers erected a weather mast (l.) on the ice floe in order to measure the energy and heat flows in the air layers directly above the ice. In contrast, AWI expert Dr Anja Sommerfeld (top) focused on taking readings up to an altitude of roughly 30 kilometres.

DR SANDRO DAHLKE
is an atmospheric researcher at the Alfred Wegener Institute in Potsdam. He took part in two legs of the MOSAiC expedition – the first and last.

THE ATMOSPHERE:
CLOUDS OR NO CLOUDS – THAT IS THE QUESTION

When meteorologists talk about air temperature in weather forecasts, they mean the temperature of the air two metres above the ground. For us as atmospheric researchers, this value is just one of many, since with our radiosondes we investigate the temperature profile of the air column up to a dizzying altitude of 35 kilometres. To do so, throughout the MOSAiC winter, we released a weather balloon into the Arctic sky from the research icebreaker Polarstern's helicopter four times a day, and with the help of a small sensor continuously measured the air temperature, humidity and atmospheric pressure. In addition, the sonde's GPS data allowed us to measure the wind strength.
At first glance, the temperature profiles obtained showed a similar pattern: in the wintery Arctic, the air temperature drops with increasing altitudes. If, for example, at an altitude of two kilometres our sensors recorded a temperature of -20 degrees Celsius, at ca. ten kilometres it was -60 degrees Celsius, and at an altitude of over 25 kilometres it even fell below -80 degrees Celsius in places. In other words, there was a temperature difference of up to 60 degrees Celsius between the lower air layers and the stratosphere.
The phenomenon of air temperature falling with increasing altitudes, not just in the Arctic, but everywhere in the world, is referred to as adiabatic temperature drop, and can be explained simply: at ground level the atmospheric pressure is high, since here the weight of the entire atmosphere or the entire air column is pushing down. High atmospheric pressure, in turn, means high air density and more air molecules per volume of air. This increases the likelihood of molecules colliding – and these collisions produce heat. However, the higher our weather balloons rise, the less atmospheric mass there is theoretically pushing down on them. Consequently the atmospheric pressure, air density and the likelihood of molecules colliding decrease, and the air temperature drops.
When it comes to sea ice, however, the temperature curve at high altitudes is not particularly relevant. In the context of ice, what's important in terms of the atmosphere is what happens at its surface; in other words, in the atmospheric boundary layer near the ground. This layer ranges from a few dozen to hundreds of metres thick, and on many days in the Arctic winter it is significantly colder than the air masses above it. What causes this? First of all, the Polar Night dominates the Arctic winter. The sun doesn't rise above the horizon and therefore cannot provide any radiant energy. But at the same time, the Earth, sea and ice naturally emit heat.
If there are clouds over the water vapour rich air above the ice, they absorb a portion of the outgoing thermal energy, warming as a result, and then radiate the energy back towards the surface. In this way, the lower air layers become warmer. Clouds really make

Temperature curve of the Arctic atmosphere

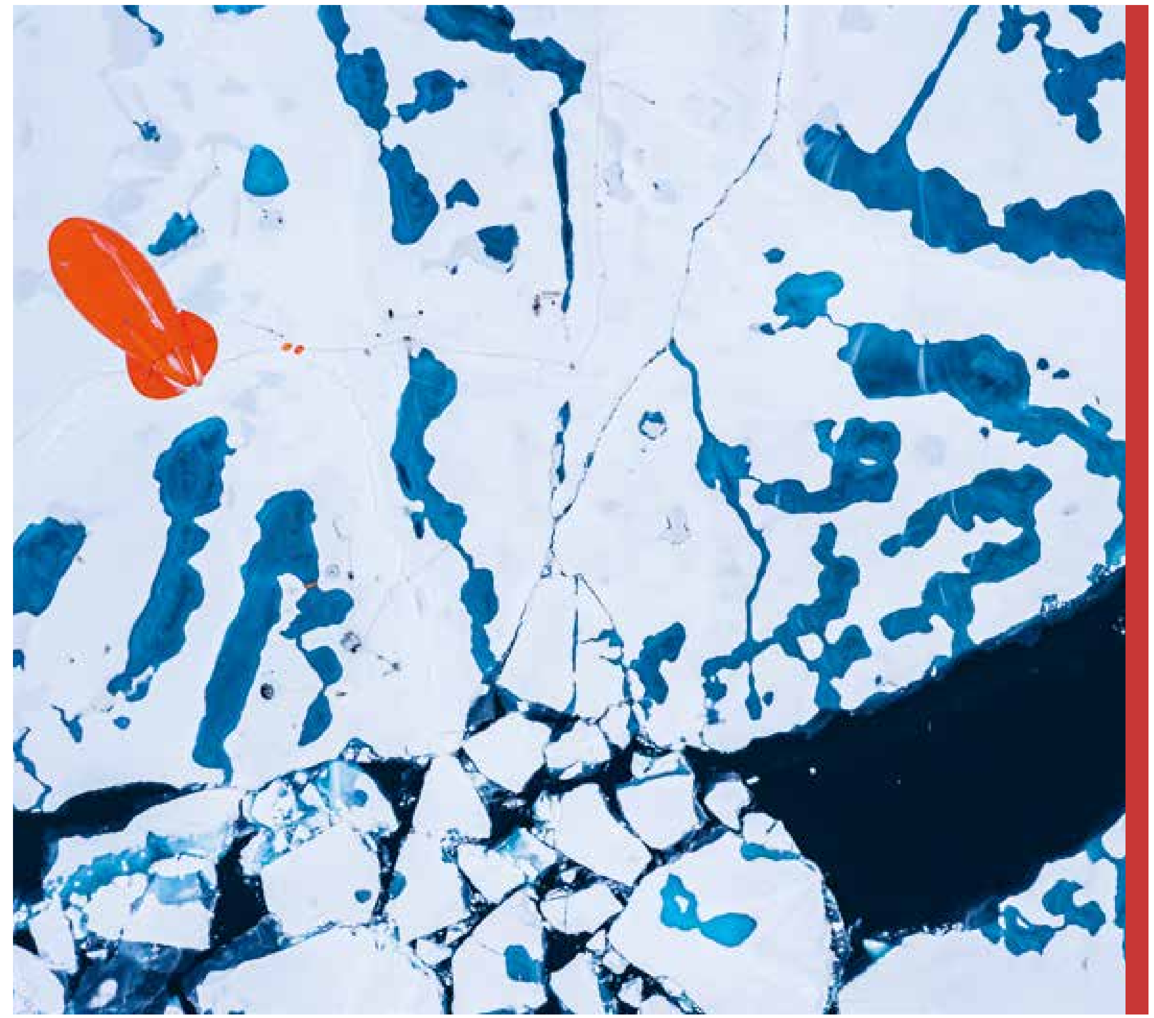


At increasing altitudes, the air temperature sinks. This natural law also applies in the Central Arctic. This graph shows the vertical temperature progression over the MOSAiC floe on 12 December 2019, from the ice's surface up to an altitude of roughly 30 kilometres. The tremendous cooling in the ice layers near the surface can be clearly seen; they are colder than the overlying air at 1 to 4 kilometres.

a difference here! When the sky was overcast in the MOSAiC winter, the air temperature on the ice was generally about -15 degrees Celsius. On cloudless days, in extreme cases the temperature fell to -38 degrees Celsius, since the radiated heat was able to escape unhindered towards outer space. Under these conditions, the temperature of the air layers close to the ground plummets. This means that it's significantly colder on the surface of the ice than at two, ten or 20 metres above it. Meteorologists call this cooling phenomenon 'inversion'.

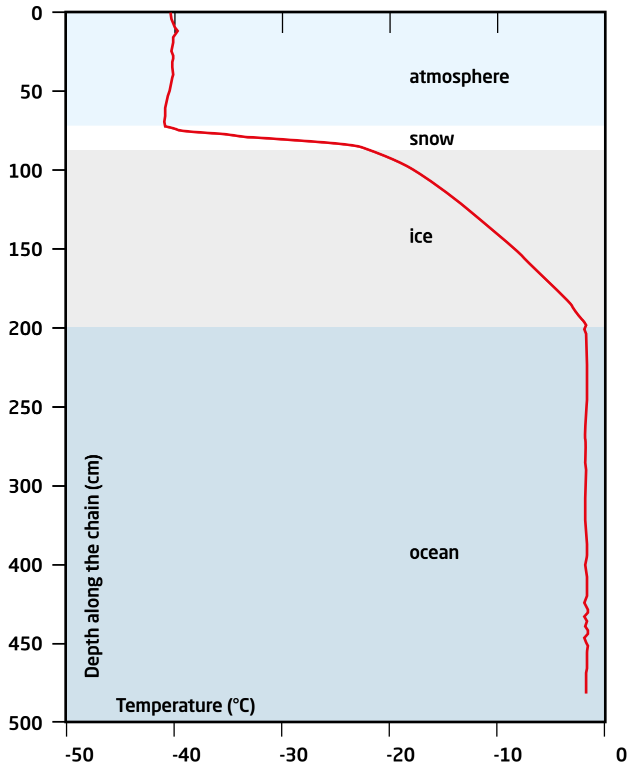
On the coldest winter days, while taking measurements on the MOSAiC floe we recorded temperature differences of up to four degrees Celsius between the air at the ice's surface and the air layer at 30 metres. This finding was not just relevant for sea-ice formation; for us researchers it also had a highly practical significance: it meant that on cloudless days, we always had to subtract a few degrees Celsius from the temperatures in our ship's weather report if we wanted to know how cold it actually was on the ice. The RV Polarstern meteorologist based his forecasts on measurements from the onboard weather station, which is attached to the ship's mast – at a height of roughly 30 metres.

Dr Anja Sommerfeld and Dr Sandro Dahlke
atmospheric researchers at the Alfred Wegener Institute in Potsdam



The tethered balloon 'Miss Piggy' floats high above the sea ice of the Central Arctic, taking meteorological readings. If you look closely, at the end of the tether you can see a sledge on the ice, which AWI atmospheric researcher Sandro Dahlke and a colleague used to launch the balloon.

Temperature curve of the snow and ice



In the course of the MOSAiC expedition, the sea-ice physicists used more than 30 digital thermistor chains to monitor temperature changes in the snow and ice. The resultant curves show how much the temperature changed at the respective interfaces. In this curve the first spike indicates the air-snow interface; the second, the snow-ice interface; and the third, the interface between ice and ocean.

Swiss researcher Dr Martin Schneebeli and a colleague digging a snow pit to assess the snow cover on the ice. The snow insulates so effectively that the temperature on its underside is ca. 20 degrees Celsius warmer than on its surface.

SNOW AND SEA ICE:
PUTTING THE BRAKES ON COLD

For us sea-ice physicists, one of the coldest days of the MOSAiC expedition was 3 March 2020. On that day, our thermistor chains recorded an air temperature of -43 degrees Celsius directly above the snow layer on the ice. These thermistor chains are ca. five metres long and reach from the surface of the ice floe, through the snow and ice and into the sea. They look a bit like a string of LED lights. But instead of lights, there are small temperature sensors attached at two-centimetre intervals. They measure the temperature in the snow, ice and the top layer of the water, and help us understand how thermal energy passes from one level to another – or how the snow slows down cooling and, with it, the growth of sea ice. On that bitterly cold March day, the sensors in the uppermost snow layer recorded -42 degrees Celsius. 30 centimetres deeper, at the snow-ice boundary, the temperature was a mere -8 degrees Celsius. This means that in just a 30-centimetre-thick layer of snow, we observed a temperature difference of more than 30 degrees Celsius. That's truly impressive and shows just how effectively snow insulates. In the sea ice beneath, the drop in temperature between the top and the underside wasn't quite as steep, since ice contains significantly less air than snow and therefore conducts heat better. This thermal conductivity is measured in watts per metre Kelvin. The lower the thermal conductivity of a material, the better it insulates. Snow, for instance, has a thermal conductivity of between 0.1 and 0.4 watts per metre Kelvin; for sea ice, the number is 2. That means that snow insulates five to 20 times better than sea ice.

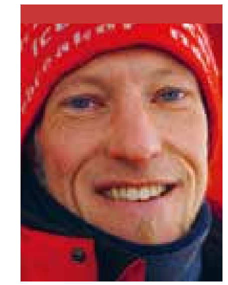
A look at the ice temperature profile from 3 March reveals that deeper down, the floe grew progressively warmer. When the temperature at the ice's surface was -8 degrees Celsius, the temperature on the underside was -1.8 degrees Celsius, which is equivalent to the freezing point of seawater. In principle, in winter the temperature change in the sea ice was so simple that we were able to draw most of the profiles with a ruler. You just needed to know the ice thickness and the initial temperature at the snow-ice boundary. If you knew both of these, you could place the ruler at the initial temperature and draw a straight line to the freezing point of seawater at -1.8 degrees Celsius. However, this only works in

Sea-ice physicist Jakob Belter installs a snow buoy on the MOSAiC floe. It uses four downward-pointing ultrasound sensors to measure the distance to the snow or the surface of the ice.

winter. In spring, when the air and water temperatures increase, the sea ice warms from above and below simultaneously, with the centre initially remaining cold. The temperature profile is then no longer a straight line, and instead resembles the shape of a banana.
Heat is a good catchword, since it can significantly alter the snow's thermal conductivity, as we observed live in the field for the first time on the MOSAiC expedition. Well into April, the snow cover, especially the snow deeper down, was made up of particularly large snow crystals. This left plenty of room for air, which only warms up slowly and as a result conducts heat poorly. When, in April, there was an inflow of warm air, and within a few hours the air temperature over the MOSAiC floe rose dramatically, we could observe how the heat penetrated the snow layer from above, changing its structure. The large snow crystals became smaller, and the room for air pockets decreased. Almost simultaneously, the heat flows between the atmosphere, ice and ocean changed. As a result, it took e.g. a week for the heat signal from the air to completely penetrate the snow and sea ice. Thanks to this and other observations, we now have a much clearer idea of the scales at which these processes, which are so important for our sea-ice research, take place. Moreover, we also have a better understanding of how the individual components of this complex system fit together – findings that would have been impossible to arrive at without MOSAiC.

Dr Stefanie Arndt, Dr Christian Katlein and Daniela Krampe
sea-ice physicists at the Alfred Wegener Institute in Bremerhaven.

This tent was dubbed 'Ocean City' because it was where the oceanographers most often did their work. Using a hole in the ice and the tent's wooden floor, the researchers lower their most important instrument, the CTD sampler, into the water.



DR MARIO HOPPMANN
is a researcher at the Alfred Wegener Institute's Physical Oceanography Section. He gathered oceanographic readings on two legs of the MOSAiC expedition and was jointly responsible for installing buoys and autonomous monitoring systems.

OCEAN:
HOW LONG CAN THE PROTECTIVE LAYER OF COLD ENDURE?

We oceanographers don't generally encounter temperature differences like those measured by the sea-ice physicists and atmospheric researchers in the Arctic winter, because sea ice and snow effectively protect the Arctic Ocean from the atmosphere. In addition, in its liquid form, our element, water, can't become much colder than its freezing point – which in the Central Arctic is -1.8 degrees Celsius. The only exception is so-called supercooled, or undercooled water, the temperature of which can drop to 0.01 degrees Celsius below the freezing point of sea water. It doesn't freeze immediately, due to the lack of what are known as ice nuclei on which the first ice crystals could form.
For us oceanographers, the extreme cold over the MOSAiC floe could above all be seen in the fact that the sea ice grew more rapidly – at its fastest by up to eight centimetres per week. That meant that more and more water froze on its underside: a process in which large amounts of brine flows out of the ice into the surface water, increasing its salinity. Water with an increasing salt content, in turn, becomes heavier and slowly sinks. In this way, sea ice creates a protective layer of cold water for itself. This lies like a lid atop the

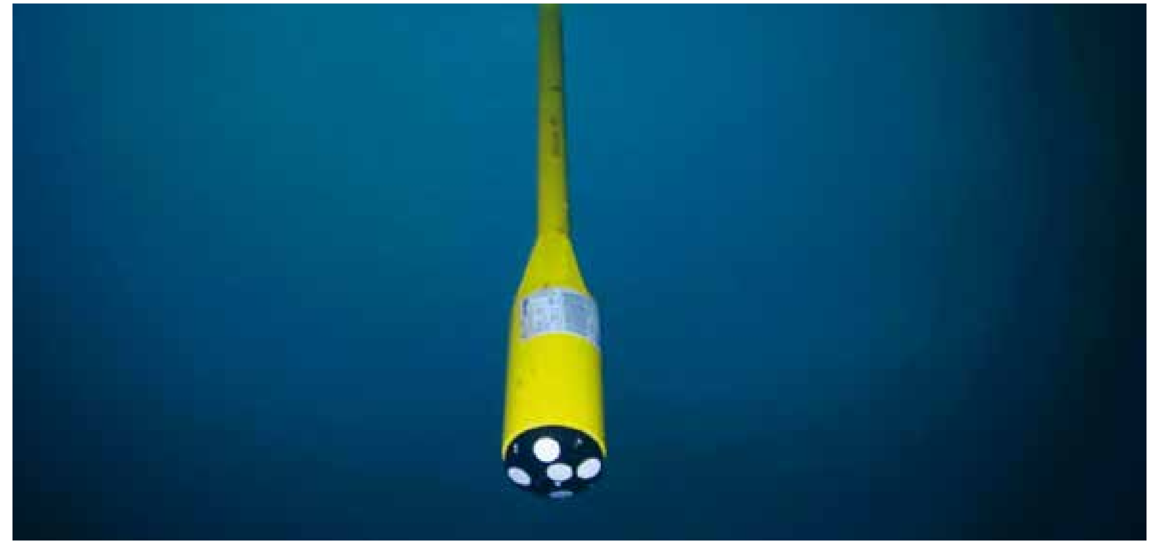
Brine is produced when seawater freezes: instead of becoming trapped in the latticework of ice crystals, the salt contained in the water initially accumulates, in the form of brine, in tiny pores and channels in the sea ice. It subsequently trickles from the underside of the ice, and into the ocean.

warmer, saltrich – and therefore heavier – water masses below. Due to its warmth, this deeper water, which flows into the Arctic Ocean from the North Atlantic, can pose a threat to the sea ice – if it manages to reach the ocean's surface.

If we examine the protective layer under the sea ice more closely, we can see there are in fact two water masses that interact there. Above is the so-called mixed or surface layer, which is fed freshwater from the numerous rivers that flow into the Arctic Ocean. As a result, at the beginning of winter the water in the mixed layer is very light and lies at the surface. Only after ice has formed and the **brine** 'settles' does it become heavier, and over the winter the layer gradually becomes thicker. We were able to observe this during the MOSAiC expedition. The mixed layer beneath the MOSAiC floe was roughly 20 metres thick at the start of our drift, and by May 2020, it had reached a depth of 120 metres.

Directly below the mixed layer is the second protective layer – referred to as the cold halocline. The term 'halocline' comes from the Greek and describes a transition zone between water masses with different salinities. That means that the halocline water masses become more saltrich with increasing depth – until, at roughly 200 metres, the water is just as salty as the warmer Atlantic water below. Salinity stratification of water masses like this can be found in many of the world's ocean regions.

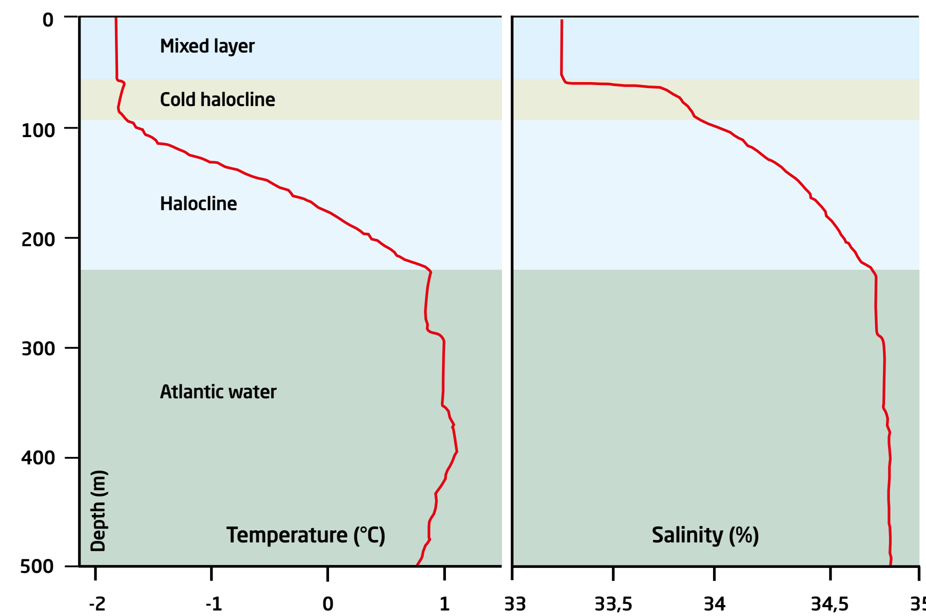
When a lead formed in the sea ice on the morning of 23 January 2020, oceanographers Dr Volker Mohrholz and Dr Benjamin Rabe got out a fishing pole and lowered a microturbulence probe into the water. The probe measures the temperature, saline and oxygen content, and eddies in the water.



This acoustic Doppler current profiler was one of the many oceanographic measuring devices deployed under the MOSAiC floe.

Light layers rise, heavy ones sink

The temperature and salinity of a given water layer determine how heavy the water is and to what depth it sinks. This combined temperature and salinity profile shows how clearly the individual water masses below the MOSAiC floe differed from one another.



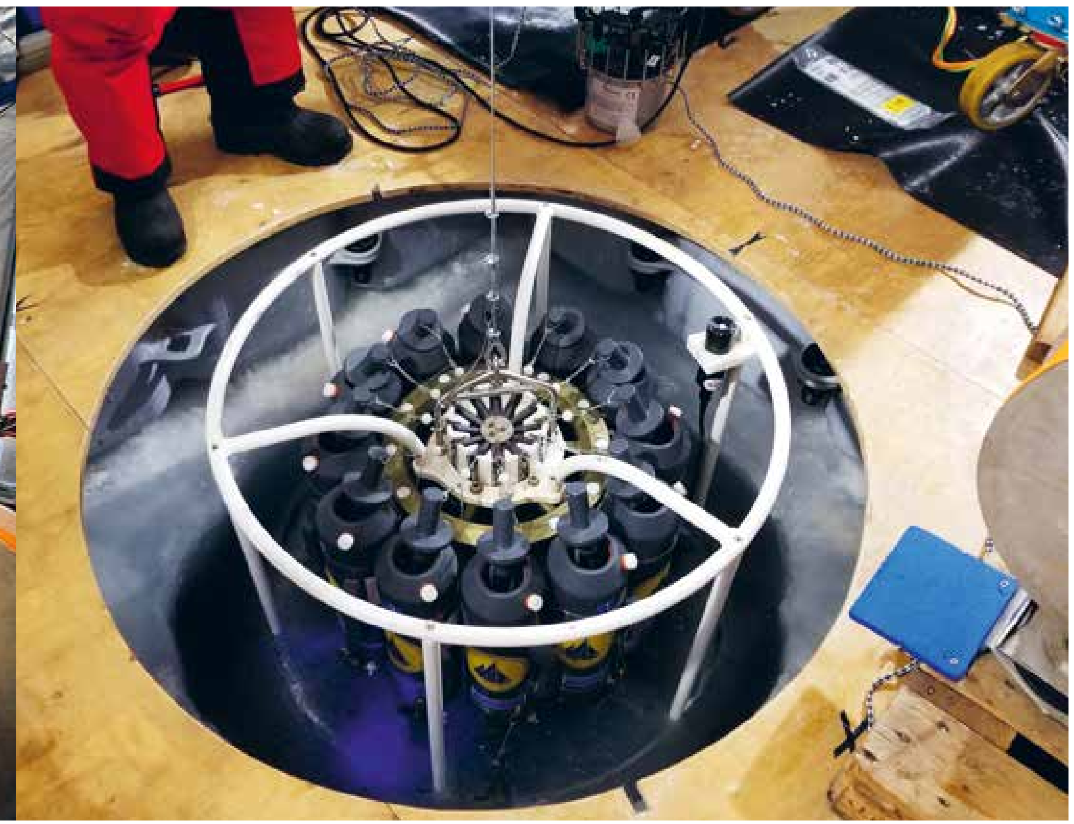
However, what makes the Arctic Ocean special is the fact that, although salinity increases with increasing depth in the cold halocline, the water temperature remains close to the **freezing point** – despite the Atlantic water in the layer below it being roughly one degree Celsius and as such significantly warmer. Theoretically, it has been assumed that the large amounts of brine from the sea ice increase the stratification of the water masses in the central Arctic Ocean – and that they do so to such an extent that there are hardly any gyres or turbulences strong enough to transport appreciable amounts of warmer Atlantic water from the deep to the ocean's surface.

Since seawater contains salt, it doesn't freeze at the same temperature as freshwater (0 degrees Celsius), but at the considerably colder -1.8 degrees Celsius.

But in our current era of climate change and sea-ice retreat, does this assumption still hold true, or does warm water from the depths somehow manage to reach the underside of the ice? One possible way for this to happen, for example, would be kilometre-wide gyres like those found in the Southern Ocean. Scientists believe they play an important part in thermaltransfer between the upper and lower water layers. To find out whether there are similar gyres in the Central Arctic, the MOSAiC expedition's Ocean Team carried out an extensive measuring programme. This involved deploying not only our CTD rosette water sampler to measure the water temperature, water pressure and conductivity (salinity), but also current profilers and microstructure sondes. The latter provide high-definition measurements of the turbulent mixing of the water. This measuring programme was supplemented by dozens of independent measuring devices that were installed on buoys in a radius of 30 kilometres on the main floe at the start of the expedition to allow us to investigate the size and speed of these gyres. The large volumes of data now have to be analysed. Once the analyses are complete, we will be able to say in detail whether our theory on the interaction between water masses in the Arctic Ocean continues to reflect the reality, and whether the cold from above is still enough to protect the sea ice from the warm waters below.

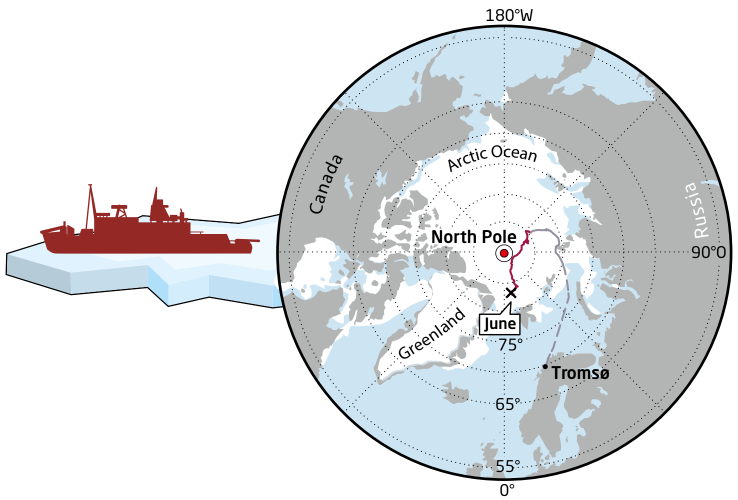
Dr Mario Hoppmann and Dr Janin Schaffer
oceanographers at the Alfred Wegener Institute in Bremerhaven

AWI oceanographer Dr Janin Schaffer (r.) and her colleagues position the CTD rosette water sampler over the entry hole in preparation for taking readings.



The rosette sampler can measure the water temperature to the nearest ten-thousandth of a degree. The bottles on the sampler can be closed at the push of a button, and at multiple depths.

In spring, a variety of algal blooms colour the waters of the Arctic Chukchi Sea. The inflow of cold, nutrient-rich water from the Bering Sea provides the phytoplankton with idea conditions for forming large blooms.



DriftStory 09

Algae in the Arctic: Apparently, anything is possible

For algae, life in the central Arctic Ocean presents two significant challenges: firstly, the sun disappears for more than 100 days per year; and secondly, the pronounced stratification of the water masses slows the transport of nutrients from the depths. How can phytoplankton survive the long periods of darkness and spring to life again once the sun returns? AWI biologist Clara Hoppe and the ECO Team explored these questions during the MOSAiC expedition and discovered some of the remarkable survival strategies of the tiny, green organisms.

STORIES FROM MEEREISPORTAL.DE

If there were a competition for filtering water, AWI biologist Dr Clara Hoppe would stand a good chance of winning. As a marine biologist focusing on phytoplankton in the Arctic Ocean, she 'trained' in this discipline almost every day of the expedition. The reason: especially in winter, the number of algae (phytoplankton) floating in the water is so small that the researcher had to pass roughly 40 litres of water through a gravity filter in order to concentrate the algal community into a few millilitres before she could start her investigations.

The minute water samples there are teeming with members of a truly die-hard group of organisms. Arctic algae lead a life of extremes: sunlight, which they need for photosynthesis and growth, isn't available for more than 100 days per year. And when the sun does peek over the horizon, the sea ice covers the ocean like a blind so that, at least initially, only a small amount of light reaches the water column. In addition, the algae's supply of vital nutrients, such as nitrate and silicates, is limited. These substances are dissolved in the seawater, but at different depths and in varying concentrations, depending on the water layer. Due to the pronounced temperature and salinity-based stratification of the

Clara Hoppe first began investigating the survival strategies of Arctic phytoplankton six years ago, in the research village Ny-Ålesund on Svalbard. There, she could take water samples directly from the harbour.

water masses in the Arctic Ocean, the nutrient-poor surface water and the nutrient-rich water deeper below rarely mix. That means: once the nutrient supply in the surface water has been exhausted, it is seldom replenished from further down.

BARELY VISIBLE TO THE NAKED EYE

Despite these adversities, several hundred algal species survive the winter in the Central Arctic – and several are able to grow and divide even before the sun climbs above the horizon. Precisely how the algae survive the darkness and where they get the energy for cell division at the end of the long Polar Night is still not completely understood, and the reason why Clara Hoppe absolutely wanted to take part in the MOSAiC expedition. "We have been studying the algal community in Kongsfjord, in the Svalbard region of the Arctic Ocean, for several years, and so we know that the algae in the water column only need tiny amounts of light to activate their metabolism. Here we're talking about changes in light so small that they are barely perceptible for us humans," the researcher explains. Many of the algal species investigated are even active throughout the winter. How they manage this, and whether the sea ice plays a role, are just two of the numerous open questions.

However, since there is barely any sea ice remaining in the area around Svalbard, Clara Hoppe wasn't able to comprehensively investigate its impact on the algae's chances of survival. Furthermore, when it comes to collecting water samples in Svalbard, she couldn't be sure whether the algae investigated actually spent the entire winter in the Arctic, because off the west coast of Spitsbergen flows the West Spitsbergen Current, which transports relatively warm water from the North Atlantic northwards. Consequently, it was quite possible that part of the algal community in Kongsfjord originated in the North Atlantic and didn't experience the full extent of the Polar Night. During the MOSAiC expedition, however, these possibilities were almost completely ruled out. The drift offered the marine biologist the unique opportunity to observe the overwintering and revival of the Arctic phytoplankton over several months using methods and additional measurements that wouldn't have been possible without the interdisciplinary research team on board the icebreaker Polarstern.

THREE HYPOTHESES – BUT WHICH IS CORRECT?

The question of how Arctic algae survive the cold and dark has occupied polar biologists for more than a century. As socalled primary producers, algae form the basis of the food web in the Arctic Ocean. Without phytoplankton, neither copipods nor Arctic cod, ringed seals or polar bears would be able to find food. To date, three different explanations have been proposed:

At first, researchers long assumed that it was not only the well-known ice algae that allowed themselves to become frozen in the sea ice, where they overwinter, but the entire algal community, including those algae that are mainly found in the water column. According to this hypothesis, in spring, when the air and water temperatures rise, the algae are released from the melting ice, colonise the water column and begin forming large algal blooms. "This seedbank hypothesis is now considered outdated, since the range of species in the water column differs significantly from the algal community in the sea ice. While there are certainly species that are found in both habitats, they represent only a small proportion," comments Clara Hoppe.

The second hypothesis assumes that the algae in the water survive the winter thanks to special preventive measures. "Before the onset of the Polar Night, many Arctic **diatoms** form extremely thick, hard shells to protect them from being eaten by copipods and other zooplankton," explains the marine biologist. In the coastal waters, the tiny organisms sink to the seafloor, where they spend the winter before rising up through the water column when the light returns once again. "We know from other deep ocean regions that the algae that are prepared for the winter accumulate in the thermocline; in other words, at a depth where the density differences are particularly great. As a result of winter and spring storms they are then carried back up towards the ocean's surface." However, as yet no evidence of algal accumulations in the Central Arctic has been found. "I hoped that we would be able to gather relevant samples during MOSAiC. But in our investigations we were unable to find any such layer beneath our floe," she says.

Diatoms are microscopic, single-celled algae, whose cell wall predominantly consists of silicon dioxide. There are ca. 6,000 known species.

Does that mean that the third explanation is more likely? It has found a host of new supporters in recent years, and posits that algae are not pure plants that solely survive on photosynthesis. Instead, like animals, they take up organic material, by (in some cases very actively) eating bacteria or respiring organic compounds dissolved in the water. "We see this survival strategy, known as mixotrophy, in all groups. Whatever algae we look at, they are all able to do it. So it appears that among the Arctic algae there are scarcely any pure plants, which rely solely on photosynthesis," says Clara Hoppe.

HOW MANY ALGAE DO COPIPODS AND CO. ACTUALLY EAT?

To avoid overlooking any clues when it comes to searching for new insights, the team of biologists pushed themselves to their limits on the MOSAiC floe. According to Clara Hoppe: "We measured an unbelievable number of parameters – from nutrients and carbonates to chlorophyll content, pigment composition, primary and bacterial production, biodiversity, and DNA and RNA analyses, to name just a few. Added to this were the microscope work, experiments on board, food-web studies ranging from zooplankton to fish, and sampling numerous chemical parameters. Just keeping track of it all was a real challenge."

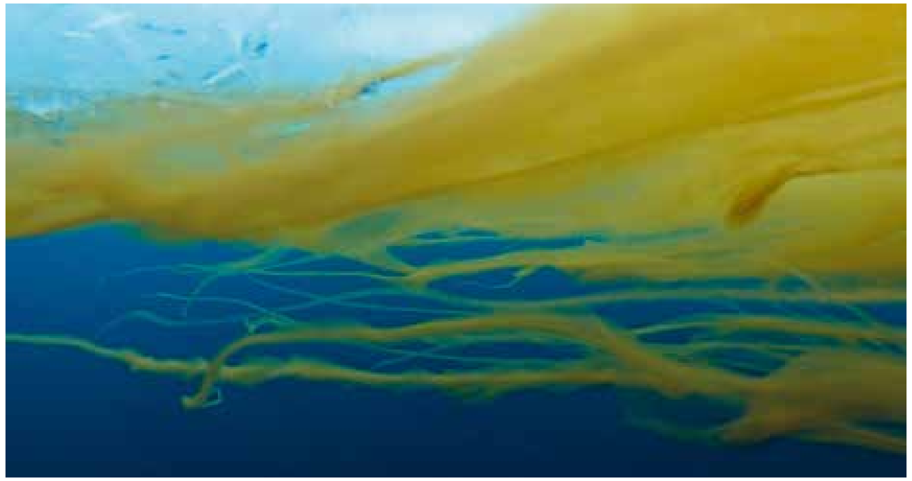
For example, to discover the extent to which hungry copipods decimate the numbers of algae, the researchers placed a handful of carefully selected crustaceans in bottles filled with water and algae and then counted how many phytoplankton were left after a day. In a second experiment, they filled bottles with sea ice and water from the ocean's surface

Clara Hoppe reconstructed the testing array used at the research lab on Svalbard (l.) on board the research icebreaker Polarstern. But before their various algae experiments could begin ...

... the marine biologist (r.) and her colleague Dr Anders Torstensson (l.) had to first bore a hole in the ice, feed a tube through the hole, and pump copious amounts of surface water and algae into their sample canisters.

and from greater depths, exposed them to increasing amounts of light over a period of weeks, and observed which life forms developed. "Sometimes it took up to two and a half months before we saw an actual bloom. But in all the samples there were enough organisms that can be found in a typical spring bloom. That tells us that sea ice as well as surface and deep water are all possible sources of algal blooms in the water column. Which one actually creates blooms probably depends on a wide variety of parameters," the scientist explains.

The MOSAiC team used a so-called light harp, developed by Hamburg-based sea-ice expert Dirk Notz, to take high-resolution measurements of the light spectrum in the sea ice. When the researchers combined this data with the below-ice light measurements taken by the AWI underwater robot and the rosette water sampler, they were able to determine how the light fields beneath the MOSAiC ice floe changed over time. "I'll compare the various light data with my primary production data – in the hope that in the end I'll be able to say whether the algae realy did grow as strongly as they could have done at the respective light level, or not. If the answer is no, it could be due, for example, to



An expedition member carefully inserts the newly developed light harp (l.) in a hole bored in an older section of the MOSAiC floe. The instrument, which measures the amount of light in the ice, will yield data that helps marine biologists like Clara Hoppe understand how much light is available to algae living within and below the ice at a given time. The Arctic diatom Melosira arctica (top) can be seen with the naked eye, since the single-celled organisms, measuring just 30 micrometres, form several-metre-long chains and algal mats, which float like curtains beneath the sea ice.

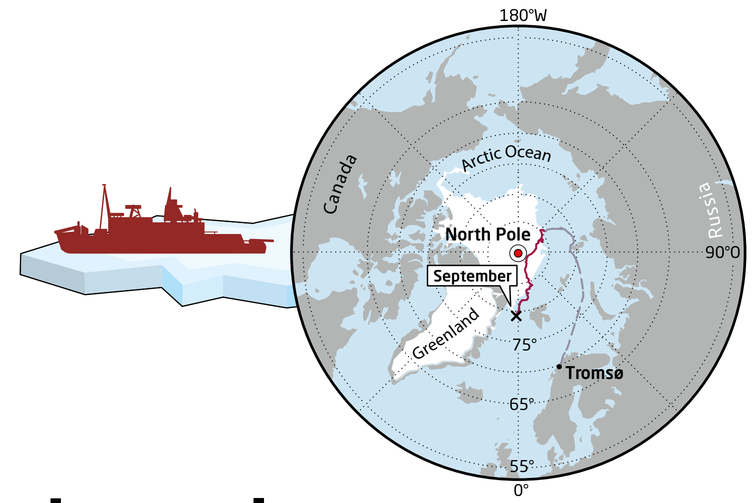
zooplankton," says the marine biologist, adding: "I now believe that the algae in the water column don't have a real survival strategy in winter. They are simply there and because it's cold and dark, their chlorophyll doesn't suffer any damage. If the algae somehow manage not to get eaten, at the end of the Polar Night, they're still there and ready for the new season."

What do these new insights mean for the big question concerning the productivity of Arctic algae? According to Clara Hoppe: "My conclusion is that, in our analyses and computations, we have to take the grazing on algae by zooplankton, as well as the recycling of nutrients, much more into account." Detailed knowledge and an accurate understanding of the processes are important, not just when it comes to clearly visible parameters like spring blooms, but also at a much earlier point in time. "In science, there has long been a debate about what can be defined as an algal bloom and when their formation starts. Personally, I consider it to be an algal bloom when I see a constant increase in biomass, even when the total percentage of algae is still incredibly small. It can definitely be relevant for the food web and nutrient cycle in the Arctic Ocean," she explains.

This approach doesn't necessarily make her research easier, especially since the chlorophyll sensors on satellites, on buoys and on ARGO gliders (autonomous buoys used to measure temperature, salinity, currents and increasingly also chemical and biological components) are not yet able to detect algal blooms that are just beginning to form. As Clara Hoppe concludes: "That's why, every day we went back and started filtering the water again – litre after litre after litre!"

Zooplankton are all fauna that drift freely in the ocean. Some of the best-known representatives are foraminifera, conches, rotifers, fish larvae, radiolarians, ciliates and bryozoans, as well as various tiny crustaceans like copepods, krill, amphipods and many others.

The two research aeroplanes POLAR 5 and POLAR 6 on standby at Svalbard Airport near Longyearbyen, ready to support MOSAiC. POLAR 6, in the background, has the sea-ice thickness sensor EM-Bird mounted in a cradle on its underside.



DriftStory 10

A reunion at the outlet of the Arctic

The AWI sea-ice physicists Thomas Krumpen and Jakob Belter were two of the first researchers to scout the vicinity of the MOSAiC floe in late autumn 2019. Back then, the floe was just beginning its journey through the Central Arctic. Eleven months later, the experts returned to survey the floe again – but this time from an aeroplane and off the coast of northern Greenland, at the other end of the transpolar drift.

How alike the two pictures are: as AWI sea-ice physicist Dr Thomas Krumpen flies over the scattered remains of what was once the MOSAiC floe and many of its neighbouring floes on 2 September 2020, he can't help but recall his first encounter with this particular stretch of sea ice, back in October 2019. Once again, the first cold autumn nights have frozen the ocean's surface; once again, a layer of new ice covers the countless meltwater ponds. And once again, those areas characterised by instable ice, weakened by the summer sun, are covered in a blanket of snow, making the ice look much more intact than it truly is.

On ice-measuring survey flights the aircraft makes low flyovers, offering the pilot and crew an optimal view of the sea ice. While in the cockpit there's still enough time for a quick glance at the ocean (l.), researchers Thomas Krumpen, Jakob Belter and Cristina Sans i Coll (top, l. to r.) watch closely via camera to ensure that the EM-Bird properly separated from its mounting bracket and is now floating freely over the sea ice.

POLAR 6 is one of two Basler BT-67 aeroplanes used for German polar research. The turboprop plane is used in the Arctic and Antarctic alike, and is equipped with special-purpose research instruments for each mission.

If Thomas Krumpen didn't know exactly in what part of the Arctic he and his colleague Jakob Belter were, he might think the MOSAiC floe had survived after all. But the location alone dispels any such notion. Today the research aeroplane **POLAR 6** is flying over Fram Strait, an area of ocean between Svalbard and eastern Greenland, and one widely considered to be the largest outlet for the Arctic Ocean. In the winter months (October to April), year after year ca. 1,600 cubic kilometres of Arctic sea ice pass through Fram Strait to the North Atlantic and their certain doom. Just for the sake of comparison: the meltwater produced by this quantity of sea ice would be enough to fill Lake Constance 35 times over.

As such, Fram Strait also marks the end of the transpolar drift: the name given to the wind and ocean-current-powered drift of sea ice from Russia's marginal seas of the Arctic Ocean across the North Pole and ending off of Greenland's eastern coast. It took the MOSAiC floe roughly 610 days to complete its lifecycle, covering more than 5,200 kilometres. On the second-to-last day of July 2020, it finally broke up into several fragments. Ever since, the remains of the ice that once formed the extended vicinity of MOSAiC have been trapped off the eastern coast of Greenland – wedged in a hodgepodge of icebergs and markedly thick floes that most likely hail from the extreme north of Greenland.

A PROGRAMME CALLED ICEBIRD

Yet the majority of the ice in Fram Strait hails from the Laptev Sea and East Siberian Sea, offering researchers valuable insights into the climate system in the Arctic. Accordingly, Thomas Krumpen and his colleagues at the AWI's Sea Ice Physics section have returned to the northern Fram Strait at regular intervals for nearly 20 years, to measure the thickness of the sea ice between the 80th and 86th N parallels, and to document its surface characteristics.

The ice-thickness measurements are taken with an electromagnetic sensor called the EM-Bird, which works a bit like a metal detector: the device generates an electromagnetic field, and can distinguish between various layers below it on the basis of their electrical conductivity. For example, saltwater is highly conductive, while sea ice is barely conductive at all. The sea-ice physicists use this contrast to determine how high above the underside of the ice the EM-Bird is.

The sea-ice thickness sensor EM-Bird resembles a torpedo and is towed behind aircraft on a long cable (20 metres for helicopters, 80 metres for planes), at a height of ca. 15 metres above the surface.

For the first measurements, taken nearly 20 years ago, the scientists had to drag the sensor over the sea ice on a sledge. Consequently, the measured distance from the underside of the ice offered a fairly direct indication of how thick the sea ice and the snow cover atop it were. Since this approach only allowed them to cover very small distances, however, since 2004 the AWI sea-ice physicists have instead used helicopters or research aeroplanes, suspending the torpedo-like sensor on a long cable, ca. 15 metres above the ice – which explains why they call it a 'bird'. A laser range finder measures the exact distance between the sensor and the ice's surface. Afterwards, all it takes to determine the sea-ice thickness is some basic maths: the experts note the distance between the sensor and ice underside, and subtract the EM-Bird's height above the ice.

In honour of this unique measuring method, the AWI's sea-ice physicists named their entire aerial sea-ice measuring programme in the Arctic after the sensor. IceBird has since gathered data from several key regions of the Arctic Ocean and is widely considered one of the most important reference datasets on the development of Arctic sea-ice cover in the world.

TWO MAJOR LEAPS CHARACTERISE THE TRANSFORMATION

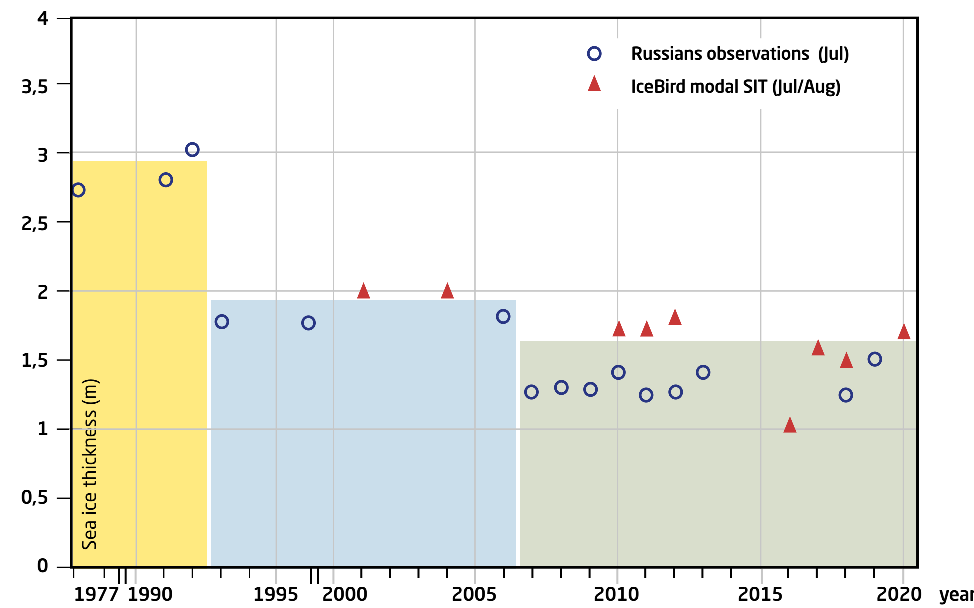
The IceBird data on the northern Fram Strait show one aspect particularly clearly – the steady decline of all parameters. For example, where the mean ice thickness was still 2.6 metres in 2001, now it's only 2 metres – a loss of 24 percent. At the same time, the most frequently measured ice thickness value (modal ice thickness) has dropped from 2 metres (2001) to 1.5 metres (2018).

"Today, every single floe has much less time to grow, because the sea ice drifts faster than it used to. Compared to 2000, today's thinner floes complete the transpolar drift in virtually half the time," explains Jakob Belter. Whereas, back at the beginning of IceBird, the sea ice was nearly three years old before being exported to the North Atlantic, today much of the ice hasn't even turned two yet when it enters the northern Fram Strait.

Interestingly, the thickness of the Arctic sea ice hasn't declined uniformly over the last five decades; rather, there were two major 'leaps', as a comparison of the IceBird data with a longer time series prepared by Russian polar researchers reveals. The first leap came in 1992/1993: back then, the mean ice thickness in the Central Arctic suddenly dropped from 3 metres to less than 2 metres. Twelve years later (2005-2007), sea-ice experts from various countries recorded the second leap, in which the ice thickness sank by

The not-so-steady decline in ice thickness

Over the past 45 years the thickness of the Arctic sea ice hasn't declined steadily, but rather in 'leaps', as this comparison of Russian and German observations shows. The three colours indicate the three phases, over the course of which the respective sea-ice thickness has remained virtually constant.



another 50 centimetres. Ever since, it has remained at a relatively constant level, between 1.3 and 1.5 metres.

"We believe both leaps were sparked by fundamental and above all lasting changes in the Arctic climate system. In the meantime, we've come to view the first event as a type of early warning, because since 2007 at the latest, it's been clear that a massive change took place in the Arctic, one that produced lasting changes to sea-ice formation, sea-ice transport and the age structure of the ice. Ever since, the ice has formed later in the year, shown less growth in winter, drifted faster and now leaves the Arctic at an average age of less than two years. There is now much less older, several-metre-thick sea ice in the Arctic than in the past," says Jakob Belter.

The aeroplane-supported ice-thickness measurements complemented the thickness measurements taken at regular intervals on the floe or in its vicinity throughout the MOSAiC expedition. For the latter, researchers dragged the sensor across the ice on a sledge (top) or suspended it on a cable for helicopter flyovers (l.).

DEADLY HEAT FROM THE DEEP

To make matters worse, there are already indications of a next leap in the ice-thickness curve: in the summer of 2016, during their aerial survey flights over the northern Fram Strait, the AWI sea-ice physicists chiefly documented ice that was barely 1 metre thick (excluding pressure ridges and deformations) – an absolute record low. In order to determine why the ice was up to 50 centimetres thinner than in previous years, the experts used a three-stage plan. In the first stage they analysed satellite data, which allowed them to retrace the ice's route back to its point of origin in the Laptev Sea. They then checked what the weather conditions had been like along the route. Could a summer heat wave have melted the ice from above? But no, the atmospheric data didn't reveal any major irregularities from 2014 to 2016.

That meant the answer had to lie in the ocean – and sure enough: from January to May 2015, researchers from the University of Fairbanks, Alaska recorded unusually high temperatures in the waters north of the Laptev Sea. This was due, as we know today, to heat rising from the depths with Atlantic water masses and slowed the young sea ice's growth in winter.

At Svalbard Airport near Longyearbyen, AWI sea-ice physicist Jakob Belter performs routine maintenance on the electromagnetic sea-ice-thickness sensor EM-Bird. Here the sensor can be seen in its specially designed cradle for take-offs and landings, which is mounted on the underside of the research aeroplane POLAR 6.

"Using the satellite data, we can prove that the ice we measured in Fram Strait in July 2016 had previously passed through exactly these unusually warm waters off the edge of Russia's continental shelf," Jakob Belter explains.

But does this finding automatically mean that the low ice thickness at the end of the transpolar drift was solely due to the warm ocean water at the drift's beginning? Couldn't the effects of the heat have faded with time? To find answers to these questions, the young researcher simulated the growth of the ice in a simple sea-ice model. The computer calculated how thick the ice should theoretically be, based on the ocean and atmospheric data supplied to it.

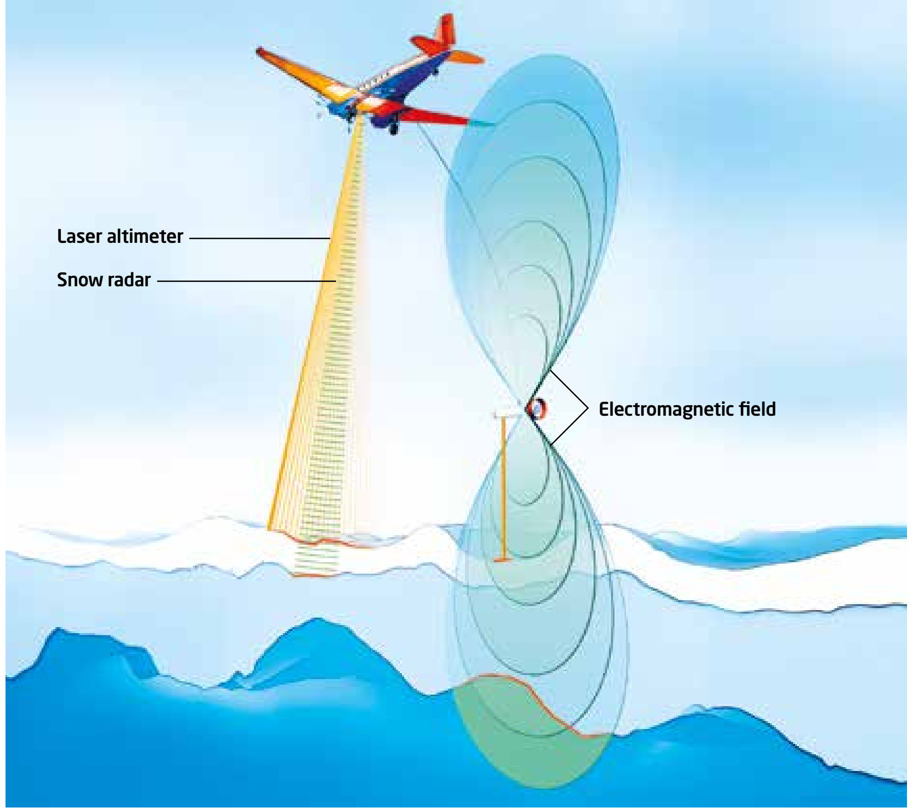
"In this model-based simulation we worked under the assumption that the heat from below, that is, from the ocean, remained constant, and that the ice only grew because of the cold atmosphere," says Belter. "But when we looked at the results, we soon realised that our model couldn't reflect the extraordinarily low ice thickness in 2016 – in other words, that the constant we'd used for the heat from below was wrong. Accordingly, the ocean must have contributed far more heat, especially at the beginning of the drift, than we initially assumed."

Just how much more heat is extremely hard to say. "In our first calculations we assumed a heat input of 2 watts per square metre of ice. We later boosted the number to 8 watts, increasing the estimated heat input more than fourfold. The results are now moving in the right direction, though they still don't match the ice-thickness values measured in the northern Fram Strait. Accordingly, we believe that the 'ocean heat wave' in the winter of 2014/2015 must have been a fairly substantial event, and that its effects on sea-ice thickness growth were too great to be fully compensated for," Belter explains.

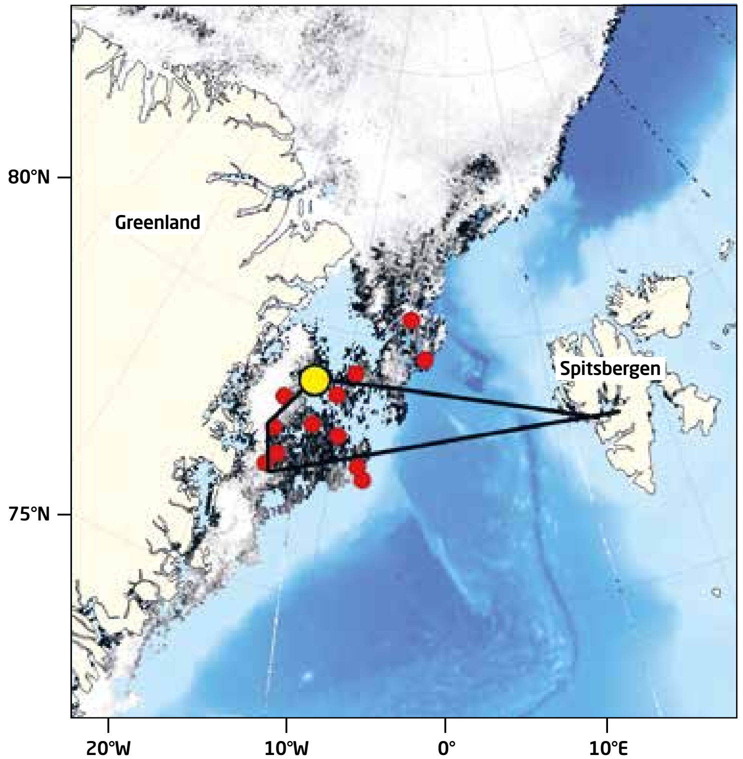
Further, this wasn't the only extreme-heat event, as the latest research findings show. In the winter of 2017/2018, the instruments of the US oceanographers in Fairbanks

Four at a go

Using its snow radar, altimeter and the EM-Bird, the research plane can combine four key parameters to determine the exact sea-ice thickness: the height of the snow cover, how high the aircraft is above the surface, and the distance between the EM-Bird and the ice's surface and underside, respectively.



Nearly at the finish line



By early September 2020 the MOSAiC floe had already broken up into several fragments and the ice from its vicinity had scattered across the Fram Strait. The red dots indicate sea-ice buoys that were deployed near the floe at the start of the expedition. The yellow dot marks the position of the Norwegian research icebreaker Kronprins Haakon, which the AWI sea-ice physicists flew over during their aerial survey flight in Fram Strait. The black line indicates POLAR 6's route during the aerial survey flight.

once again recorded rising warm-water masses in the eastern Arctic Ocean. It has since been confirmed that Atlantic water, which can be as warm as 1.5 degrees Celsius and previously circulated at depths of between 150 and 900 metres, rose to a depth of just 80 metres. Under these conditions, the thermal transfer between Arctic water masses is altered. When that happens, like it did in 2014/2015, heat rises from the depths to the ocean's surface, even in winter, and either melts the ice from below or slows its growth. The effects can still be seen a year later, as the IceBird measurements from 2016 impressively demonstrate.

Does the IceBird data from the past several years point to any further 'heat attacks' from the deep? According to Jakob Belter: "No, so far there's no indication of that. But that doesn't mean the sea ice wasn't affected by heat. Thanks to our colleagues from Alaska, we know that there were other ocean heat waves in the eastern Arctic Ocean in the past few years. But they apparently didn't affect the ice that we observed downstream in Fram Strait a year later. So far, we've only managed to capture it in 2016."

In September 2020, sea ice from the former vicinity of the MOSAiC floe drifts through the northern Fram Strait and heads to the south, where it will melt in a just a few weeks' time

THE MOSAiC FLOE: A REPRESENTATIVE ICE SHEET, RIGHT UP TO THE END

It would appear that the ice from MOSAiC's extended vicinity has also been spared contact with extreme heat from the depths of the Arctic Ocean. "Until it collapsed on 30 July 2020, the MOSAiC floe had a modal thickness of 1.7 metres. And even on our flyover in September, the remains of the great ice field were still 0.9 to 1 metre thick, which was even a bit surprising, given how late in the year it was," says Thomas Krumpen.

After learning this, everyone who participated in the MOSAiC expedition could breathe a sigh of relief. "We can now say with certainty that, up until its disintegration, the MOSAiC floe was a representative example of the sea ice in this region," say Thomas Krumpen. "In turn, this gives us confidence that the countless experiments conducted in the course of the expedition will yield representative outcomes and reflect the environmental conditions in the Central Arctic as accurately as possible. Rounding out this unparalleled expedition, that's a truly good piece of news." ■

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