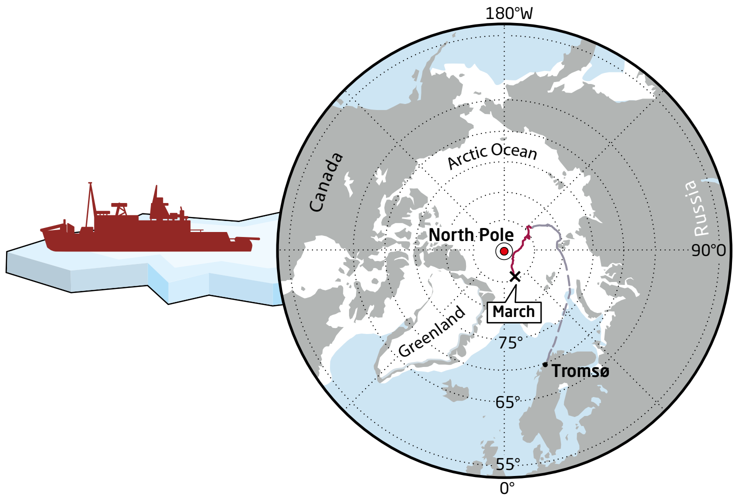
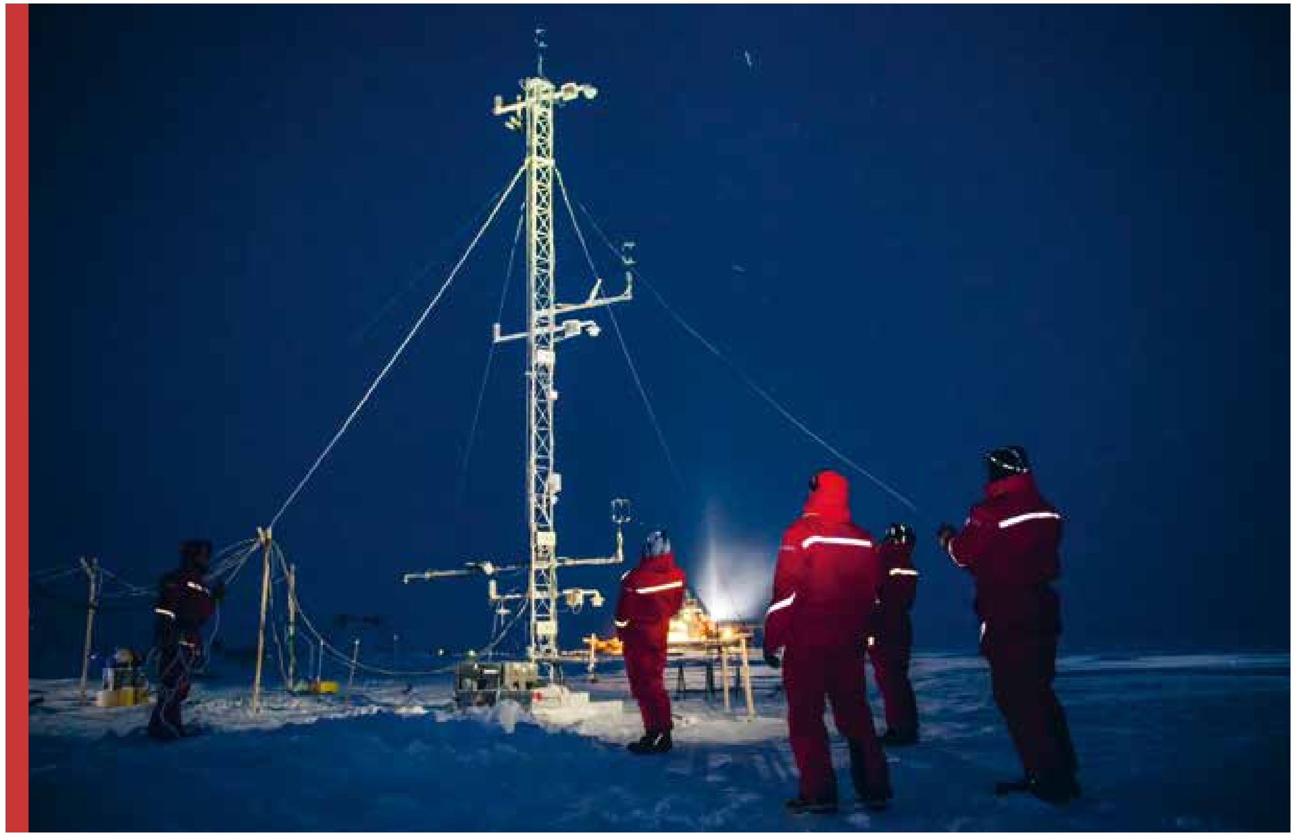
Miss Piggy is the name that the AWI's atmospheric researchers have given to this orange tethered balloon, which can rise to heights of up to two kilometres. On the ice floe, it was used to measure the temperature in the lower air layers.



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.



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.

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.

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.

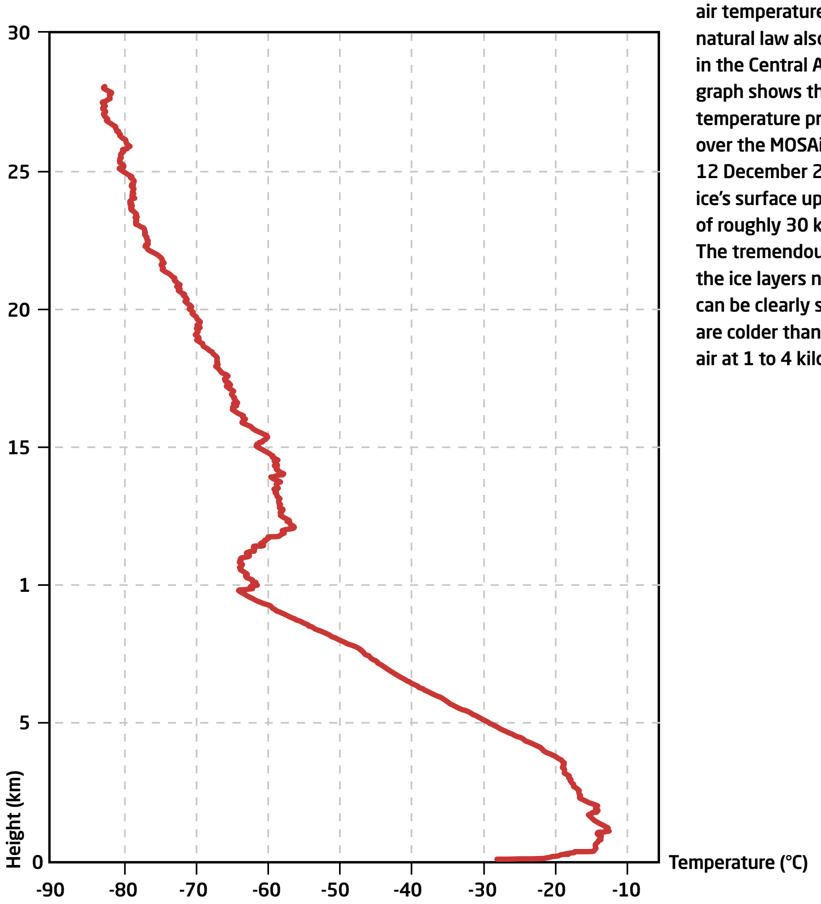
When it comes to sea ice, however, the temperature curve at high altitudes is not particularly relevant. In the context of ice, what's important in terms of the atmosphere is what happens at its surface; in other words, in the atmospheric boundary layer near the ground. This layer ranges from a few dozen 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

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.

Temperature curve of the Arctic atmosphere

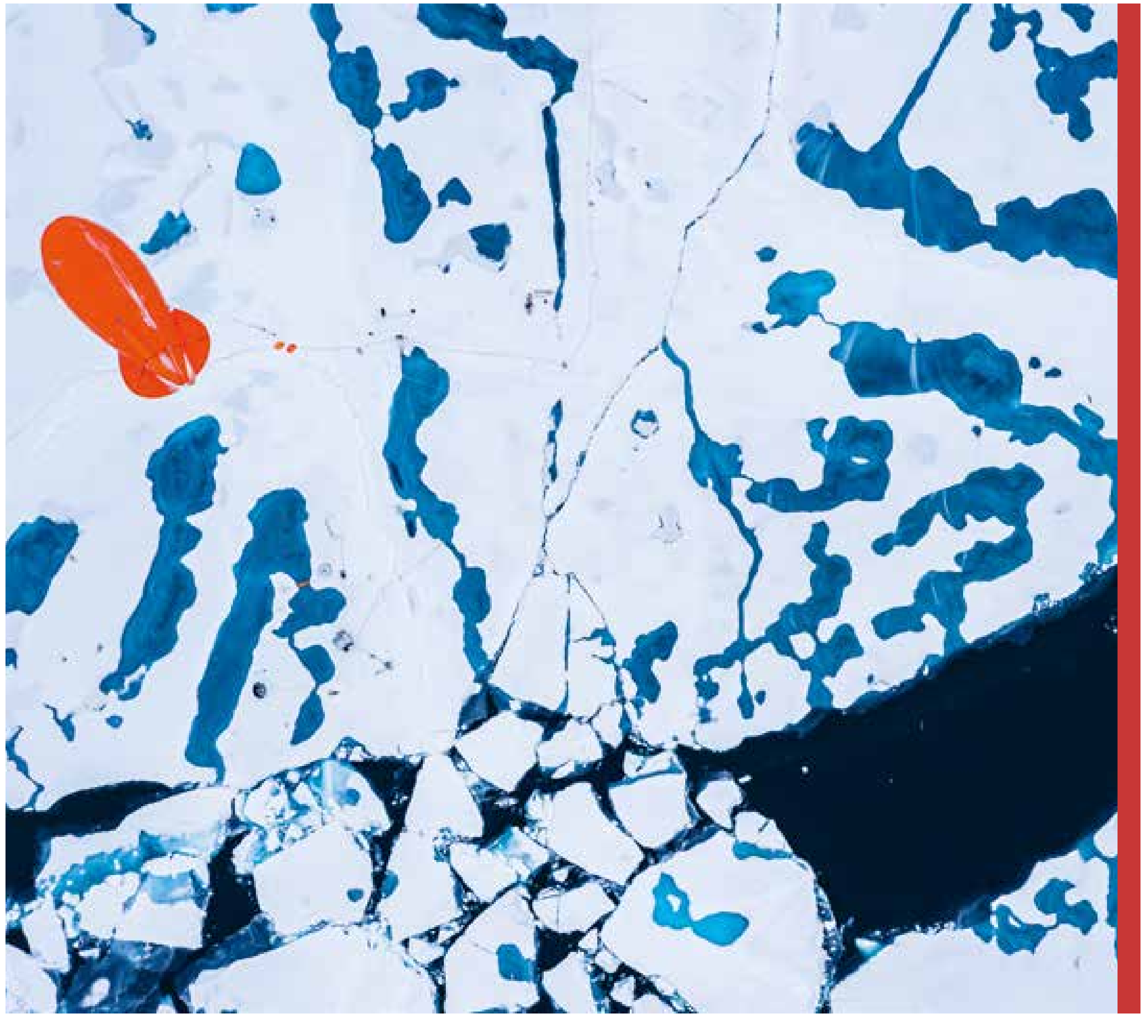


At increasing altitudes, the air temperature sinks. This natural law also applies in the Central Arctic. This graph shows the vertical temperature progression over the MOSAiC floe on 12 December 2019, from the ice's surface up to an altitude of roughly 30 kilometres. The tremendous cooling in the ice 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'.

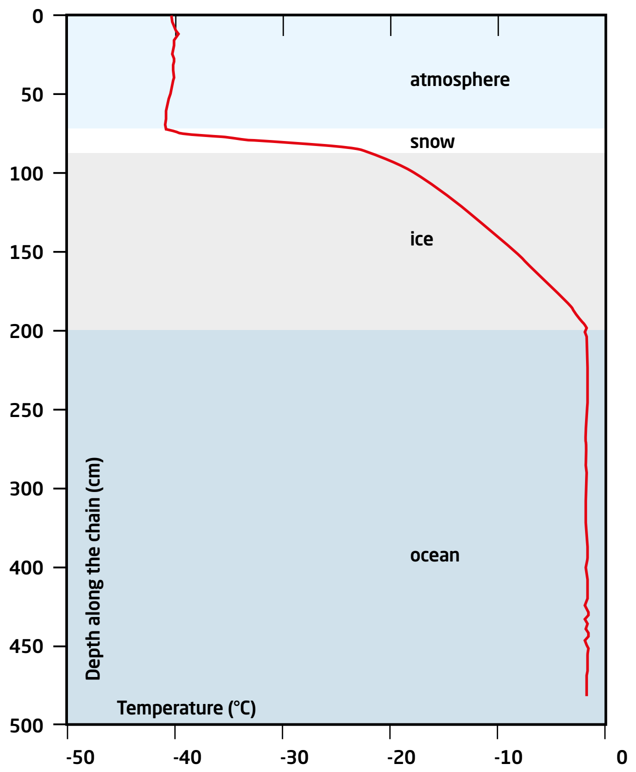
On the coldest winter days, while taking measurements on the MOSAiC floe we recorded temperature differences of up to four degrees Celsius between the air at the ice's surface and the air layer at 30 metres. This finding was not just relevant for sea-ice formation; for us researchers it also had a highly 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.

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.

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.

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.

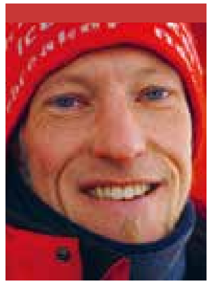
Dr Stefanie Arndt, Dr Christian Katlein and Daniela Krampe
sea-ice physicists at the Alfred Wegener Institute in Bremerhaven.

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.

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



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.

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.

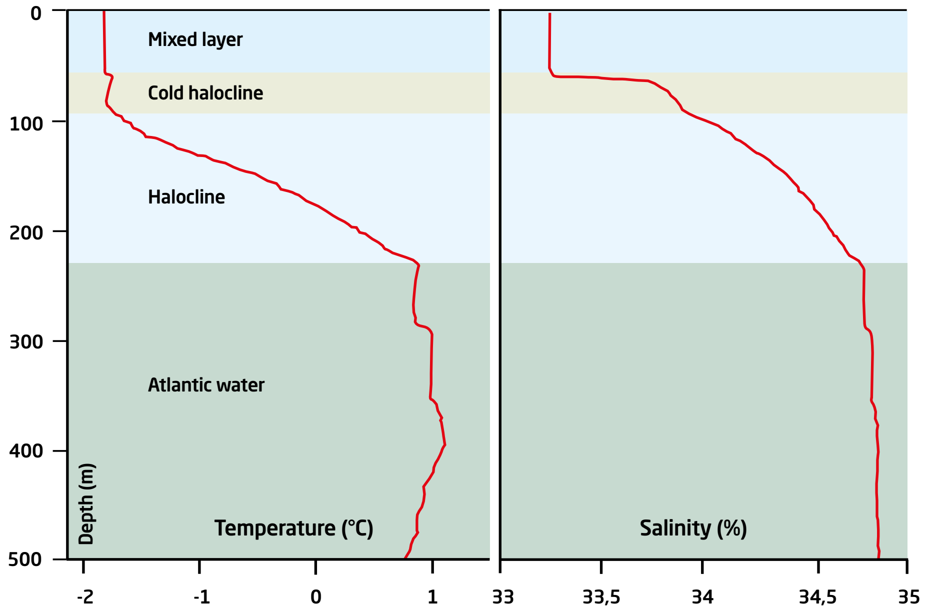
Brine is produced when seawater freezes: instead of becoming trapped in the latticework of ice crystals, the salt contained in the water initially accumulates, in the form of brine, in tiny pores and channels in the sea ice. It subsequently trickles from the underside of the ice, and into the ocean.

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.



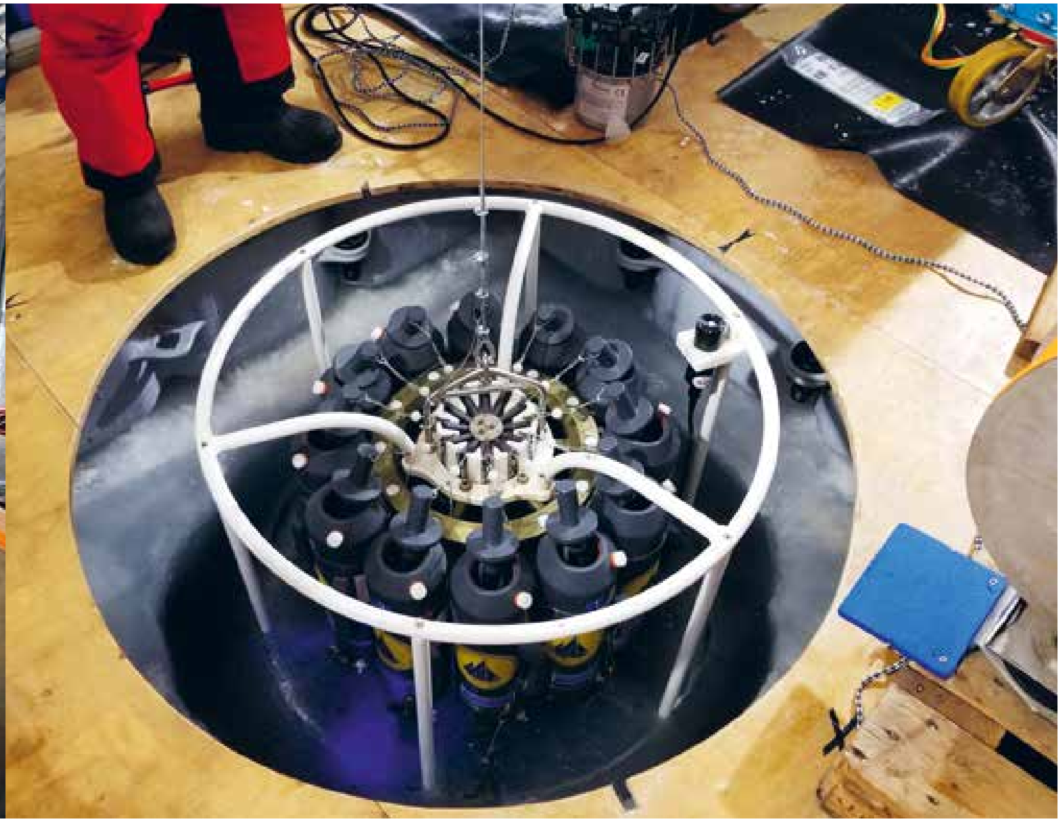
Since seawater contains salt, it doesn’t freeze at the same temperature as freshwater (0 degrees Celsius), but at the considerably colder -1.8 degrees Celsius.

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.

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.