

Thaw in the Climate Model

Nowhere does climate change make its presence felt more strongly than in the Arctic. The volume of sea ice there has fallen drastically in recent decades. Climate models have been far from accurate in conveying the full extent of this loss. This is set to change now – not least because **Dirk Notz** and his research group at the **Max Planck Institute for Meteorology** in Hamburg are constantly improving their understanding of the processes that influence the formation and melting of sea ice.

TEXT UTE KEHSE

Every year, when the polar night falls over the Arctic Ocean, a wafer-thin solid crust forms on the bitterly cold water. Initially, it consists merely of individual crystals that glide over the surface of the water, forming a sludgy mixture with a slush-like consistency. This mass gradually consolidates to form circular pancake-shaped structures from which meter-thick ice floes eventually form. By the end of the winter, the ice fills almost the entire Arctic Ocean, extend-

ing from Canada to Siberia, pushing through the Bering Strait and Baffin Bay and almost fully enveloping Greenland and the Spitsbergen archipelago. By the end of February, the Arctic sea ice covers an area of around 15 million square kilometers every year, an expanse equivalent to one and a half times the area of Europe. During the summer months, in contrast, the vast white expanse retreats considerably.

And it is retreating more and more: The Arctic sea ice has been shrinking rapidly for some years now. In 2012, for

the first time since satellite measurements began in 1979, the minimum area of the ice in summer was less than four million square kilometers. "The expanse and thickness of the Arctic sea ice in summer has approximately halved over the last 35 years. Three-quarters of the volume is gone," says Dirk Notz, a sea ice expert at the Max Planck Institute for Meteorology in Hamburg. The melting of the sea ice has reached dramatic proportions: the northeast passage along the Siberian coast is now navigable in most summers and the ice edge



is shifting further and further north. Most climate models now predict that the Arctic Ocean could be ice-free in summer by the middle of this century.

This has considerable consequences for the global climate. Although sea ice is only a few meters thick, it sits on the ocean like a lid, largely preventing heat from the water from reaching the atmosphere in winter. In summer, in contrast, the bright white ice radiates a large proportion of the incident sunlight back into space. Both effects cool the air in the polar regions. If the ice

disappears, the high latitudes will warm up at an even faster rate than is already the case. This would lead to a decrease in the temperature difference between the mid- and high latitudes, a development that could give rise to freak weather conditions in temperate zones.

As recently as ten years ago, many climate models came to the conclusion that ice-free summers could be expected in the Arctic at the end of the 21st century at the earliest. However, the ice has retreated considerably faster than projected by these simulations. In 2007, for

Not stranded: Dirk Notz and Thorsten Heller, a member of the ship's crew, take a sample on an ice floe. On this expedition they joined polar researcher Arved Fuchs, who was travelling on the sailing vessel "Dagmar Aaen" for nostalgic reasons.

example, the ice shrank so much that some researchers suspected a tipping point had already been reached, beyond which the ice could disappear in a matter of just a few years. However, it expanded again over the following two years – again, an unexpected development. In short, the sea ice was behaving



Cinematic experience in the sky: The Max Planck researchers enjoyed breathtaking views of the aurora borealis from the Daneborg Research Station in Greenland.

so strangely that it seemed that climate researchers couldn't get a handle on it in their models.

Since then, however, the gaps between the models and reality are far better understood and have narrowed considerably – thanks in part to Dirk Notz's work. He has been head of the Sea Ice in the Earth System research group at the Max Planck Institute in Hamburg for seven years. Notz and his colleagues devote their efforts to finding out what kind of future lies ahead for the sea ice around the North Pole and on the far side of the globe in the Antarctic.

NEW MEASURING INSTRUMENTS FOR FIELD EXPERIMENTS

The team takes a very comprehensive approach to its research: they keep an eye on the overall comings and goings of the sea ice, evaluate satellite data, and model the observed rhythms using complex computer programs. They also investigate the physics of the sea ice in detail: In their laboratory, they observe how the ice changes when it freezes or

melts. They use models to describe these physical processes, and they also develop new measuring instruments and use them in field experiments. "The way we combine research on a laboratory scale with general studies and mix different methods is our unique characteristic and the great strength of our group," says Dirk Notz. "We bring the worlds of the modelers and experimental researchers together."

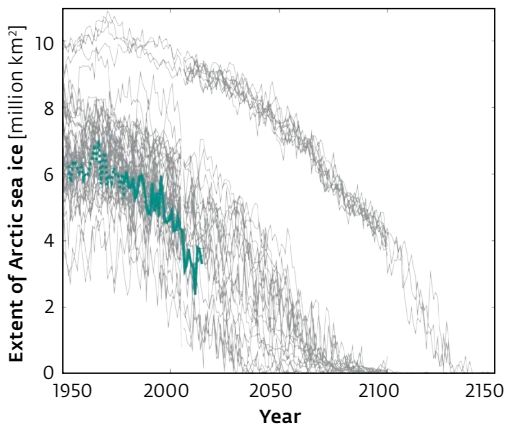
In this way, the Max Planck researchers improve the climate models' simulations of how the sea ice is changing at the global level. "Our measurements enable us to gain a better understanding of the minutiae of the processes that influence the growing and melting of sea ice in nature," explains Notz. Through this understanding, the scientists can then estimate which processes must be incorporated into the global models to obtain reliable answers to the central questions of sea ice research. "Thanks to our work, we know which questions we can reasonably answer using our models – such as why the sea ice is increasing in the Antarctic but melting in the Arctic."

The place where the group's laboratory experiments are carried out is just a short walk away from Dirk Notz's office. On the 13th floor of the neighboring building, the University of Hamburg's Geomatikum, Notz and his colleagues have set up a cold room that's not much bigger than a store-room. Most of this space is taken up by an ice tank measuring almost two meters long and one meter high. The researchers can grow and study their own sea ice here. They also test prototypes for the measuring equipment they develop themselves and later use in the field.

"In principle, the entire room is a big freezer," explains Dirk Notz. By cooling the air down to as low as minus 25 degrees Celsius, the researchers can reduce the greenish water in the tank from room temperature to negative temperatures within a period of three to four days. After another half day, enough ice accumulates on the surface for them to carry out all sorts of experiments. With the help of several pumps, they can make the water flow in steady circles or generate waves. Heating plates help them simulate thaw conditions. Snow comes from standard spray bottles, and wind from a ventilator.

HOMEMADE SENSORS

It all seems a bit improvised, but that doesn't bother Dirk Notz. "It doesn't matter if it doesn't look pretty, it just has to work," he says. The group has the same attitude to measuring equipment. Because there were no suitable sensors available for many of the parameters they wanted to measure in the ice, the team had to develop suitable measurement sensors themselves. Dirk Notz uses words like "tinkering" and "cobbling together" when he describes the work they did on developing the sensors. "We do almost all of the practical stuff ourselves – it's all



part of our work, so a bit of practical intelligence is needed," he says.

The results of this development work are internationally unique. For example, the Hamburg-based research group has a measuring device with which it can measure the salt content of sea ice at different depths. The sensor resembles a harp. The small version, which is used in the experiment tank, consists of a circuit board and a Plexiglas sheet from which eight pairs of wires protrude at intervals of one cen-

timeter. Electrical conductivity is measured between the wires, and the salt content can be extrapolated from this.

"The salt content of the sea ice is difficult to determine, but it is an extremely important parameter when it comes to characterizing the ice," explains Dirk Notz. When sea water freezes at minus 1.8 degrees Celsius, salt and other dissolved substances are not incorporated into the crystal lattice, but are left over as concentrated brine in tiny pockets and channels within the

Above The models taken into account in the latest global climate report make very different predictions regarding sea ice cover in the Arctic. The measurement data from ships and aircraft (dotted green line) and that from satellites (solid line) are located around the mean of the most reliable simulations.

Below In the laboratory in Hamburg, Dirk Notz (left) takes an ice core, while Niels Fuchs measures the temperature of the ice's surface.





Left Leif Riemenschneider (left) and a member of the team install a measuring instrument they use to determine the salt content of the ice by measuring its conductivity as it grows. They are wearing survival suits in case they fall through the ice.

Right To be able to carry out experiments in the youngest sea ice possible, the researchers move around a fjord in northeast Greenland in a hovercraft that can travel over ice and through water.

ice. Thus, sea ice is a mixture of solid freshwater ice and liquid brine. Because this brine has a higher density than sea water, some of it drains out of the ice and into the sea water over time. The researchers deduce from the salt content of the sea ice how much brine remains in the ice. This, in turn, enables them to draw conclusions about almost all of the other physical properties, such as the heat conductivity and mechanical strength of the sea ice, which have to be included in the simulations of global sea ice development.

The brine that drains from the sea ice also plays an important role in the global circulation of the oceans, a process known as thermohaline circulation. Again and again, the heavy liquid increases the density of the surface water in some locations in the polar zones so much that it sinks to the bottom and provides the deep sea with cool, oxy-

gen-rich water. The draining of the brine from the sea ice is thus an important driver of this cycle, which also keeps the ocean currents on the surface in movement.

HOW DOES THE SALT CONTENT DEPEND ON THE AGE OF THE ICE?

So there are plenty of reasons for wanting to gain a better understanding of the complicated processes that influence the salt content of the sea ice and the volume of brine that flows out of it. For example, it was long unclear how the salt content depended on the age or thickness of the ice. To explore these and other correlations, Dirk Notz and Philipp Griewank, his former doctoral student, not only studied the salt content in experiments, they also developed a complex one-dimensional model for describing it. They included all of

the physical processes that can change the salt content in their calculations. The structure of the ice, and thus its salt content, develop not only during growth and thawing, but also when it snows or rains or when the sun shines on the surface. The model they developed enabled Griewank and Notz to gain a clear understanding of the measured salt content of sea ice.

Another gap in the research has been closed by meteorologist Ann Kristin Naumann. For her master's thesis, she studied how sea ice freezes in the experiment tank when the water is stirred up by waves or kept in motion by wind and currents. Little was previously known about these processes. Naumann first had to find a suitable method for measuring the solid part of the slushy ice that forms in the agitated water. As she observed, even if the overall mass of ice in the tank increas-



es, the solid proportion of the slushy ice doesn't increase with time. As long as slushy ice is present, only one quarter of it consists of solid ice crystals. This finding is important for understanding the large-scale behavior of sea ice and can now be incorporated into climate models.

Over the course of the last few years, Dirk Notz and his colleagues have examined numerous other sea ice processes in detail in their experiments, such as the thawing and other developments that arise at the boundary between ice and water. They have also focused on the interaction between snow and sea ice. For example, they examined exactly what happens when a layer of snow pushes the sea ice so far down that the floe is flooded with sea water. The water freezes and forms snow ice, which accounts for up to 40 percent of the volume of sea ice in some parts of the Southern Ocean. Another topic of interest to the scientists is the influence of sea ice on the exchange of CO₂ between the ocean and atmosphere. This is a question of global relevance, as the world's seas and oceans have absorbed

around a quarter of the anthropogenic CO₂ emissions to date.

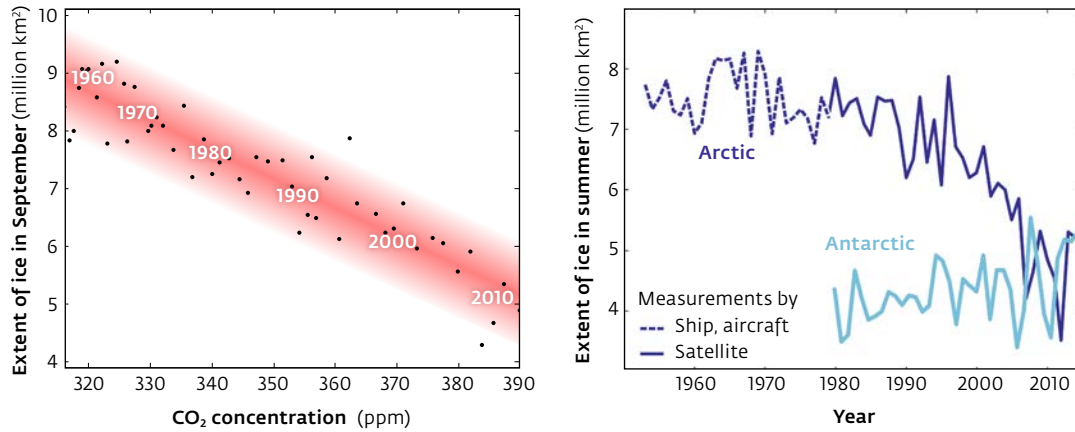
The scientists would also soon like to study some of these processes in field experiments. To do this, they have built a bigger version of the salt measuring device that is buried in the sea ice and transmits data via a satellite connection. An initial test carried out in Greenland in 2013 came to a premature end after just two weeks, but it already provided a lot of valuable data. "We now want to extend the monitoring period and observe for the first time how the salinity in sea ice develops over time," explains Notz. The only information previously available about the salt content of sea ice came from individual measurements taken from ice cores.

To this end, the researchers plan to transport the salt measuring device to a fjord in Spitsbergen as soon as possible, and put it to practical use there for an extended period of time. The team also aims to insert additional sensors into the ice to measure the light conditions, pH value, and oxygen and carbon dioxide concentrations at different depths.

In this way, the researchers in Hamburg are collating many important details that help them obtain a better understanding of the peculiarities of the sea ice – and thus ultimately enable them to provide better simulations of its large-scale behavior. Dirk Notz has already achieved some success in this area, too. "By examining apparent contradictions between observations and model simulations, we were able to fill several major gaps in the understanding of sea ice in recent years," he reports.

AN EXPLANATION FOR THE INCREASE IN ANTARCTIC ICE

Together with his colleagues Hauke Schmidt and Alexander Haumann, Dirk Notz discovered, for example, why a slight increase in the extent of the sea ice in the Antarctic is currently being observed – a puzzling effect that is often not apparent in climate models. The study's findings were published in *GEOPHYSICAL RESEARCH LETTERS* in 2014: Winds blowing from the land have intensified on the Ross Sea, an ocean region on the Pacific side of Antarctica,



Above There is a linear correlation between the retreat of the Arctic sea ice and the increase in CO₂ concentrations in the atmosphere (left). Dirk Notz and his colleagues were able to eliminate all other possible causes for the retreat. While sea ice in the Arctic has retreated over the last 50 years, it is expanding slightly in the Antarctic (right).

Right Dirk Olonscheck, Dirk Notz and Niels Fuchs (from left) discuss the latest measurement data and consider further experiments.

and are driving the ice away from the coast. “The ice is being blown to the north and the ocean south of it freezes over again,” explains Notz. As a result, sea ice cover in the Antarctic, particularly the Pacific sector, is increasing – despite global warming.

In another study, Dirk Notz and some colleagues from the Max Planck Institute for Meteorology discovered in 2011 that there is no tipping point beyond which the summer retreat of sea ice in the Arctic would be irreversible. Many climate researchers previously suspected that the Arctic Ocean would enter a new state of being ice-free in summer if the extent of the ice went below a certain limit for the first time. It was feared that the ice loss could accelerate by itself, since sea water absorbs more heat in summer than ice.

The climate simulation created by the Hamburg-based researchers revealed, however, that the sea ice also recovers quickly after a completely ice-free summer. In winter, the ocean quickly releases the previously absorbed heat back into the atmosphere. “Various feedback mechanisms ensure that the former state is re-established

after around three years,” explains Dirk Notz. This means that the sea ice in the Arctic adapts relatively quickly to the prevailing climate conditions – and it would remain largely stable if climate change were halted.

ONLY THE CO₂ INCREASE CAN EXPLAIN THE SEA ICE RETREAT

However, as revealed by a 2012 study by Dirk Notz and Jochem Marotzke, Director at the Max Planck Institute in Hamburg, the increasing concentrations of greenhouse gases in the atmosphere are already having a very direct impact on sea ice. For this study, the researchers evaluated measurement data on sea ice cover since the 1950s. They concluded that the current sea ice retreat can’t be explained by natural fluctuations and must be due to an external cause. The scientists were able to rule out solar radiation, volcanic eruptions and other factors as possible explanations for this, leaving only rising CO₂ values as the cause. “The greenhouse gases increase the incident heat radiation in the Arctic, which has a direct impact on the heat balance of the

sea ice: “It melts,” explains Notz. As the two researchers have shown, anthropogenic emissions are the direct cause of the sea ice retreat.

Notz also thought about why this retreat is considerably slower in many of the climate simulations than in reality. This discrepancy is often taken as an indication that the climate models fail to realistically register important processes. However, in an article published in the British Royal Society’s journal *PHILOSOPHICAL TRANSACTIONS* in 2015, Notz concludes that the model simulations can deviate considerably from the measurement data without being fundamentally incorrect. He proves that the expansion of the sea ice is so strongly influenced by chaotic natural fluctuations that even models that realistically describe the key physical processes can deviate strongly from the way things develop in reality.

Thus, even if the climate models failed in part to predict the rapid retreat of sea ice in the Arctic and could still be improved on, this doesn’t necessarily mean that they are fundamentally incorrect. “I believe this study is



one of the most important results of our work, and it has consequences that extend far beyond sea ice,” explains Dirk Notz. The conclusion that the natural fluctuations make it difficult to accurately predict a development can also be applied to other parameters in the Earth’s climate, such as the amount of precipitation and the frequency of storms and drought.

The Hamburg-based researcher has a lot of plans for the future. He and his colleagues are now increasingly incorporating the insights gained from the group’s experiments into global Earth system models so that they can provide better predictions about the ice cover. Another focus of their current work consists in gaining a better understanding of the processes that take place at the boundary between sea ice and sea water – for instance, how the ocean transfers heat to the ice.

But their research object isn’t exactly making things easy for them at the moment: a few experiments that the team had planned to carry out in the Van Mijen Fjord on Spitsbergen in January 2016 had to be cancelled due to a lack of ice. There were several

weeks of thaw on the Arctic island in December and January – right in the middle of the polar night – and there was no trace of the sea ice that usually has the island firmly in its grasp in winter. And the National Snow and Ice

Data Center in the US has just announced that the maximum extent of the winter sea ice in the Arctic this year was the lowest ever recorded since measurements began. The great melt appears to be forging ahead. ◀

TO THE POINT

- Sea ice in the Arctic has retreated considerably since satellite measurements began in 1979. The extent of the ice there in summer today is only one-fourth of the extent recorded then. Previous climate models failed to reflect both the strong retreat of the sea ice in the Arctic and the increase in the extent of the ice in Antarctica.
- Dirk Notz and his Sea Ice in the Earth System research group are improving the simulations created for the climate models by studying all of the processes that affect the extent of the ice in the Arctic and Antarctic, both generally and in detail, using laboratory and field experiments and models. An important parameter here is the salt content of the ice, which depends on different factors.
- The researchers have established that there is no tipping point for the Arctic sea ice, beyond which the sea ice would disappear permanently in summer. They also discovered why the sea ice in the Antarctic is increasing: stronger winds from the land are driving the ice away from the coast, so that new ice is forming there.
- According to another study, due to chaotic natural fluctuations, climate simulations can deviate significantly from observations without necessarily being incorrect. This insight can also be applied to other climate parameters, such as the amount of precipitation and frequency of storms and drought.