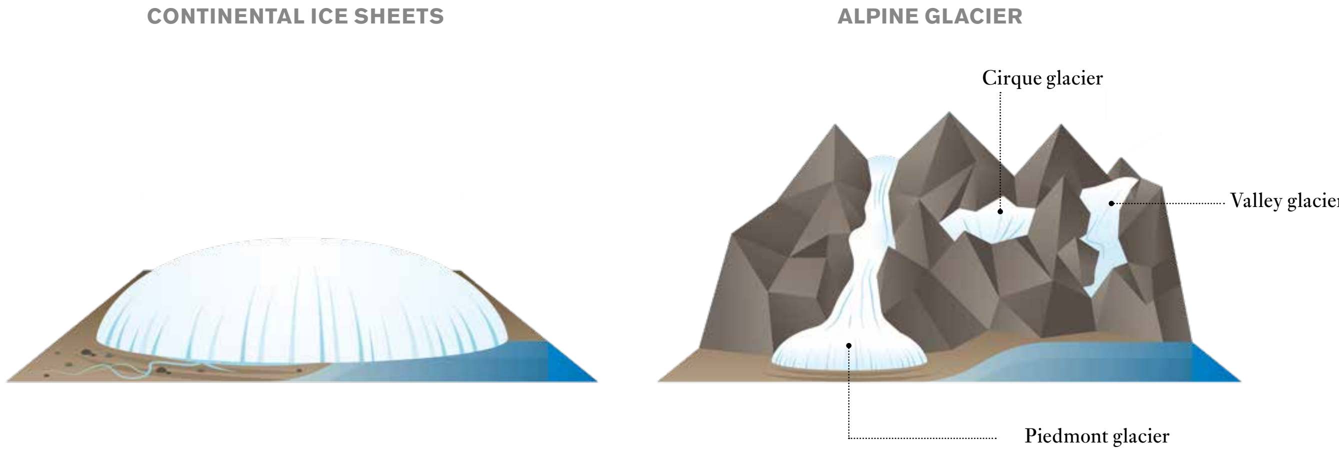
Fading splendor: The ice sheets of Greenland and Antarctica are shrinking. For example, ice is breaking from the glaciers of the Mogens Heinesen Fjord in southwestern Greenland and ending up in the ocean.

PHOTO: BENOIT LECAVALIER

THE BIG MELT

TEXT: KLAUS JACOB

Climate change is melting the ice sheets of Greenland and Antarctica and causing sea levels to rise. This could be a disaster for island states and coastal cities. How much the ice sheets shrink also depends on feedback effects between the ice sheets and the climate system. Marie-Luise Kapsch and Clemens Schannwell are studying these effects at the Max Planck Institute for Meteorology.



Types of glaciers: The ice sheets of Greenland and Antarctica together contain around 33 million cubic kilometers of ice. That is eight times more than the amount of water contained in the Mediterranean Sea and around 99 percent of the ice masses on land. In the mountains there are piedmont glaciers, which flow from a valley into the lowlands, where they spread out in a ring shape. Valley glaciers move downward through a valley. Although they account for less than one percent of the global ice mass, they include the best-known Alpine glaciers, such as the Aletsch Glacier. Cirque glaciers are found in shaded, kettle-shaped depressions and can therefore occur at lower altitudes than other glaciers.

GRAPHIC: ADOBESTOCK

So much for "eternal ice." The poles are melting and temperatures in the Arctic are rising between two and three times faster than the global average. Warmer temperatures are breaking up sea ice, allowing more and more ships to traverse the Northwest Passage, the sea lane connecting the Atlantic and Pacific through the Arctic Ocean. They're also causing the ice sheet covering Greenland to suffer considerable losses – with global consequences. When glaciers melt, the sea level rises. The severity of the situation became clear on August 14, 2021: on that day, the highest-altitude weather station in Greenland reported rain. This had never happened before, for as long as scientists have been recording weather data at that station – 3216 meters above sea level. The ice melted over the entire island. At the peak of the heatwave in 2021, the ice sheet lost about 12 billion tonnes of mass, or roughly 12.5 cubic kilometers, in a single day.

On the other side of the globe, where over half the freshwater on Earth is stored in ice, the situation looks just as precarious. Some 168 billion tonnes melted in the hot summer of 2019 alone, as indicated by the Ice Sheet Mass Balance Intercomparison Exercise (IMBIE). According to those calculations, the Antarctic and Greenland ice sheets lost a total of 7560 billion tonnes of ice between 1992 and 2020, the equivalent of a cube with sides measuring 20 kilometers. This melt caused the sea level to rise by 21 millimeters, whereby Greenland contributed to the majority of the melt, by around 13.5 millimeters. Within this period, water expansion due to warming contributed even more to rising sea levels than glacial melting – it amounted to around 35 millimeters. The ratio between the contribution of ice melt and thermal expansion to sea level rise could reverse, however.

The aforementioned changes affect around 300 million people worldwide living in regions that lie less than one meter above sea level. Cities with over a million inhabitants, such as New York, Jakarta, or Amsterdam are in danger. Adding even further to the danger, climate change is making storms more violent and driving waves deeper inland, so that every centimeter of sea level rise may effectively be doubled. It is therefore crucial to develop reliable forecasts of how the sea levels will change in the coming decades and centuries and how large ice sheets respond to climatic changes. To this day, however, many questions remain. First and foremost, the rate at which the ice sheets melt can only be predicted to a low degree of certainty, in part due to a lack of long-term data from the Earth's cold zones. In its Sixth Assessment Report, the Intergovernmental Panel on Climate Change (IPCC) predicts that by 2100, the sea

SUMMARY

The ice sheets of Greenland and Antarctica are shrinking due to progressive climate change. As a result, the sea level will likely rise as much as one meter by 2100, according to the *Sixth Assessment Report* of the IPCC. Conventional climate models do not yet account for slow changes in the ice sheets. Researchers at the Max Planck Institute for Meteorology have developed a model that can calculate the long-term dynamics of ice sheets and their interactions with the climate system. The interplay of climate and ice sheets can lead to instabilities beyond which an ice sheet melts away irreversibly. These tipping points are still being investigated, but one such threshold may have already been exceeded in West Antarctica.

level will probably rise between half a meter and a meter compared to 1900, depending on how greenhouse gas emissions develop. However, the predictions do not factor in feedback effects between ice sheets and the climate system, and so the true scope of the situation is not yet fully understood.

A team at the Max Planck Institute for Meteorology, including researcher Marie-Luise Kapsch, has expanded a climate model to factor in changes in the ice sheets in both the past and future – which they use to describe and understand the changes in the climate and ice sheets during the last glacial cycle.

To understand how ice sheets and climate interact, it is helpful to examine the last glacial period, commonly referred to as the last Ice Age. It started around 115,000 years ago and ended around 11,500 years ago. During the peak of the last Ice Age, a phenomenon occurred that caused significant fluctuations in sea level: ice sheets became unstable and led to abrupt changes in the climate. Hartmut Heinrich, a marine geologist and climatologist from Germany, found the first evidence of such events early in his career. While studying sediments from the floor of the Atlantic in 1988, he stumbled across deposits that clearly came from North America. He could find only one rational explanation: icebergs had drifted across the Atlantic and melted, shedding the rock material trapped inside them. A peculiar aspect of these findings was that that the sediments did not trickle down continuously throughout the last glacial period, but had been deposited in spurts. Evidently, large quantities of ice from the Laurentide ice sheet, which covered much of North America during the last glacial period, had repeatedly slid into the Atlantic over a short period of time. Such periods are now termed Heinrich events. These events also affected the climate in neighboring regions: the freshwater that was added to the oceans through the melting of icebergs modified ocean currents and thereby the transfer of heat around the globe. These events show that, even before humans interfered with the climate, thresholds existed beyond which massive changes to the climate would occur. The ice sheets could become unstable in the future as well. Instabilities like these have become known to the public as tipping points. It remains unclear whether such tipping points might be reached in the near future, and if so, what part of the Earth system might be involved, e.g., the Amazon rainforest, the Siberian permafrost, or the ice sheets. The possible effects of exceeding them is still a subject of research among climatologists (see the interview on p. 74).

Compromise in the climate model

When seeking to determine the future climate, scientists rely on computer models, which are depicting more and more aspects of reality. It stands to reason that changes in the ice sheets would factor into the equations used within the models. But this is where computers reach their limits. The problem is that although the climate changes relatively quickly, ice sheets move slowly and often require several millennia to respond to external changes. Running complex climate models over such long periods even exceeds the capabilities of today's supercomputers. Furthermore, changes in the ice sheets and the consequences that result in response to changes in ice sheets are hard to incorporate into conventional climate models. For that reason, researchers have thus far been forced to represent the shape of the ice sheets as constant within models. That seemed like a good approximation, because noticeable changes take anywhere

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A team led by Jason E. Box of the Geological Survey of Denmark and Greenland has projected how much ice will disappear in Greenland alone by the turn of the century and how much the sea level will rise as a result if the melting continues at the rate it has in the past two decades. The researchers calculated it at around 27 centimeters, nine centimeters more than the upper limit designated by the IPCC. If the projection is based on the summer of 2012, which set a record for melting, the result is as high as 78 centimeters – from Greenland alone. The forecasts do not yet account for progressive warming, which may soon make the record-setting summer of 2012 look like just another year.

PHOTO: TOM PINGEL FOR MPG

from decades to centuries to occur. However, observations in recent years have shown that even small changes in ice sheets can have substantial effects, particularly on the local climate.

Meteorologist Marie-Luise Kapsch, who studies the role of ice sheets in the climate system at the Max Planck Institute for Meteorology in Hamburg, has therefore developed a model with her colleagues that accounts for changes in the ice sheets. Its resolution is lower than that of standard climate models in terms of both space and time – "A compromise," Kapsch concedes. Nevertheless, the model can be used to compute several millennia. Similar difficulties confront researchers investigating possible tipping points in the Earth system.

Global warming releases ice brakes

No one can predict the future without first examining the past. After all, a model's ability to reflect reality must be tested over a time period for which abrupt climate events are reasonably well known. The Max-Planck model has even managed to simulate/reproduce Heinrich events – that is, the collapse of ice sheets. However, the initial situation during the last Ice Age was different than today. An ice sheet several kilometers thick covered North America and North Eurasia, and the sea level was more than 100 meters lower than today. A collapse consistently occurred when the burden of the ice became too large – when the ice buckled under its own weight, so to speak. The thick ice caused the underside of the glacier to melt, which acted as a lubricant, setting gigantic ice flows in motion. The large quantities of freshwater that reached the Atlantic as a result cooled the North Atlantic and adjacent regions. The Atlantic circulation came to a halt, precipitation fields changed, and the jet stream took a different path.

Ice losses similar to Heinrich events are possible today, says Kapsch, but on a much smaller scale. Other factors currently play the leading role when it comes to ice sheets. It seems as though climate change is loosening the brakes that so far have inhibited the glaciers of Antarctica from flowing into the sea. For example, ice shelves, which are the floating extension of ice sheets and form when land ice reaches the ocean, are thinning in many places. While this does not cause the sea level to rise, it does reduce the force that is holding the ice sheet back. As a result, glaciers flow faster into the ocean. The undulating seabed can provide additional stability to the ice sheet and act as a brake if it comes into contact with the floating ice shelves. In Antarctica, around 700 such undulations are present along the periphery of the ice sheet. Kapsch's colleague Clemens Schannwell has studied several. One particularly interesting finding: these brakes, too, are becoming less efficient. The glaciers are becoming thinner and lighter as they melt. As a result, they lose contact with the seabed sooner and float over the undulations.

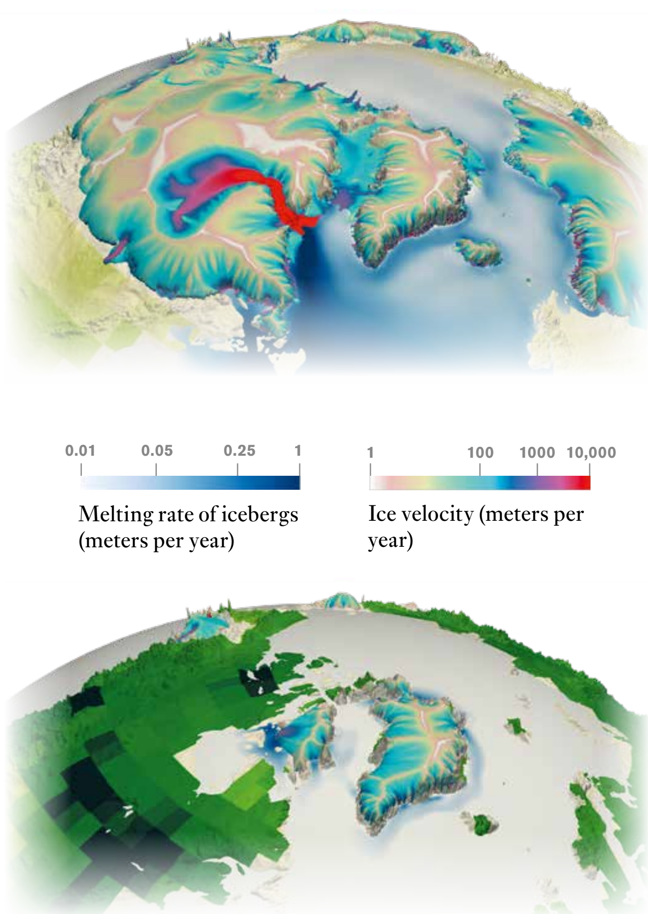
At the same time, the sea level is rising, which amplifies the effect of losing contact with the seabed further inland. And to top it all off, because the heavy ice compresses the Earth's crust, the seabed slopes inland in many areas. As a result, the ocean now gnaws away at the glaciers from underneath. Lately this has caused more and more meltwater and ice to reach the ocean, which raises the sea level, causing even more ice to be lost. "The process is susceptible to a positive feedback loop," says Schannwell. Once the melting process exceeds a threshold value, it may no longer be possible to stop it. "In West Antarctica, we may have already passed the critical point," explains Schannwell. However, the simulation also showed that it will take hundreds or thousands of years before West Antarctica is free of ice. And it has shown that the change occurs in spurts rather than as a continuous process.

"In West Antarctica, we may have already passed the critical point."

CLEMENS SCHANNWELL

Another organization studying changes in the ice sheets is the Potsdam Institute for Climate Impact Research (PIK). It, too, uses an ice model. Researchers at PIK have examined the last interglacial periods, periods that had climate similar to that of today. According to researcher Torsten Albrecht, if the average global temperature rises another 0.5 degrees, the ice masses in West Antarctica may collapse. Albrecht is part of a working group led by Ricarda Winkelmann, who was recently appointed as founding Director at the Max Planck Institute of Geoanthropology in Jena. However, findings like these are beset with serious uncertainties. Small changes to the initial conditions lead to significant differences in the long term. Furthermore, the speed of the changes clearly played a role in the past. There is therefore hope, in Albrecht's opinion, that West Antarctica will remain stable despite exceeding a temperature threshold linked with an expected tipping point – provided humans take countermeasures quickly enough.

Greenland's ice sheet is even more important to Europe than Antarctica's. It, too, could become unstable and vanish. It is hard to determine if and when this tipping point could be reached.



Cold and warm periods compared: At the height of the last glacial period around 21,000 years ago, ice sheets covered large parts of North America and northern Europe (top graphic). Heinrich events, during which large amounts of ice flowed from the North American ice sheet into the sea, can be identified from the high flow velocity of the ice (red). This meant a lot of melt water also flowed into the sea (dark blue). The bottom graphic shows the ice sheets in around 1850, so before human-induced climate change.

GRAPHIC: CLEMENS SCHANNWELL / MPI FOR METEOROLOGY

It would be risky to let it come to that, however. After all, the North Atlantic contains a motor that drives the North Atlantic Current, which is fed by the Gulf Stream. The current is our central heating system, carrying heat from lower to higher latitudes, from south to north, from the Equator to the Pole. Large quantities of freshwater, which flow from the Greenland ice sheet to the North Atlantic, reduce its salinity and density. However, the relatively high density of the North Atlantic seawater is a prerequisite for keeping the North Atlantic Current flowing. If it were to weaken or stop altogether, the climate would change fundamentally, especially in Europe. The average temperature here could fall several degrees in the long term if heat were no longer supplied from the West Atlantic. Measurements by a team from the PIK and other research institutes indicate that the overturning circulation in the Atlantic has already slowed. However, it appears very unlikely that the North Atlantic Current will stop, even as climate change advances.

By contrast, at high latitudes today one can already observe several striking feedback effects that are amplifying climate change and ice loss. One of these feedback mechanisms is the connection between loss of sea ice and temperature increase. Without ice, the Sun's energy is no longer reflected back into space. Instead, it warms the water. The result: temperatures in the far north are rising between two and three times faster than the global average. Another mechanism depends on the height of the ice sheets. The highlands are colder than the valley, as every mountain climber knows. When ice melts, however, its surface gets lower and lower, where higher temperatures are present. This intensifies the melting process itself.

Anyone who studies ice sheets has to contend with all these complex connections and dependencies within the climate system. Sea ice and temperature, ice loss and rising sea levels – the gears are interlocked. Feedback effects and tipping points pose major threats to the stability of our climate. Researchers from the Potsdam Institute for Climate Impact Research and other institutes have studied how the individual tipping points interact – with worrying results. They warn of a domino effect, in which one irreversible change triggers the next. A cascade of tipping points like that could start with the ice sheets on Greenland and West Antarctica. The currents in the Atlantic would be the next to change, which in turn would affect the Amazon rainforest, and finally the climate of the entire world. A study by a team led by Ricarda Winkelmann shows that the risk of this happening increases dramatically even when the temperature rises between 1.5 and 2 degrees Celsius, the upper limit designated by the Paris Climate Accords. And the more global warming advances, the more likely such a scenario becomes. Humanity should do everything it can to prevent it.

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GLOSSARY

HEINRICH EVENT
is the term for the episodic and rapid loss of large masses of ice from the North American ice sheet during the last glacial period/ Ice Age.

TIPPING POINT
is a threshold value such as temperature that, when exceeded, leads to irreversible changes in the climate system.