FOCUS

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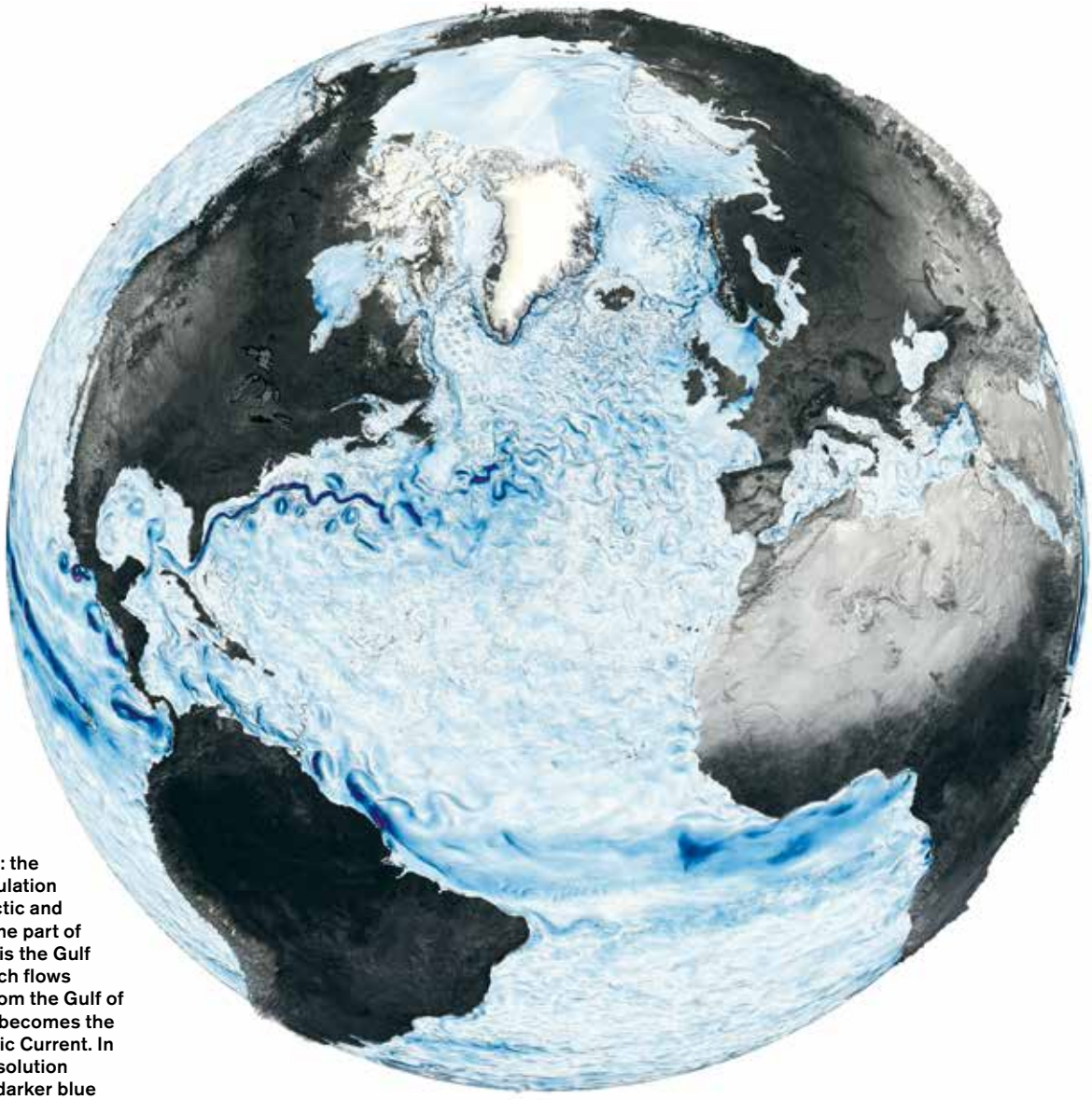


Global cycle: the Atlantic circulation links the Arctic and Antarctic. One part of this system is the Gulf Stream, which flows northeast from the Gulf of Mexico and becomes the North Atlantic Current. In this high-resolution simulation, darker blue indicates faster flow.

IMAGE: DKRZ – MICHAEL BOETTINGER

Inspecting Europe's Central Heating System

Text:
Denise Müller-Dum and Peter Hergersberg

It could be thought of as Europe's central heating system: the Atlantic meridional overturning circulation carries heat to the continent's coasts, keeping winters there relatively mild. However, as a result of climate change, this system could weaken severely. A team led by Jochem Marotzke, Director at the Max Planck Institute for Meteorology in Hamburg, is investigating whether the ocean current has already weakened, how much it could weaken further in future, and what consequences this would have for Europe's climate.

Reports on some studies of present-day climate change can seem paradoxical. According to these studies, climate change is expected to bring about a cooling trend in Europe in the future – in spite of the fact that the planet is heating up noticeably in almost every region. The reason: the Atlantic meridional overturning circulation (AMOC) could weaken severely or even shut down entirely, according to the reports. This would lead to falling temperatures across swaths of Europe. The evidence from available studies, however, is far from conclusive. How realistic, then, is the scenario in which the Atlantic current system collapses and Europe's central heating system fails?

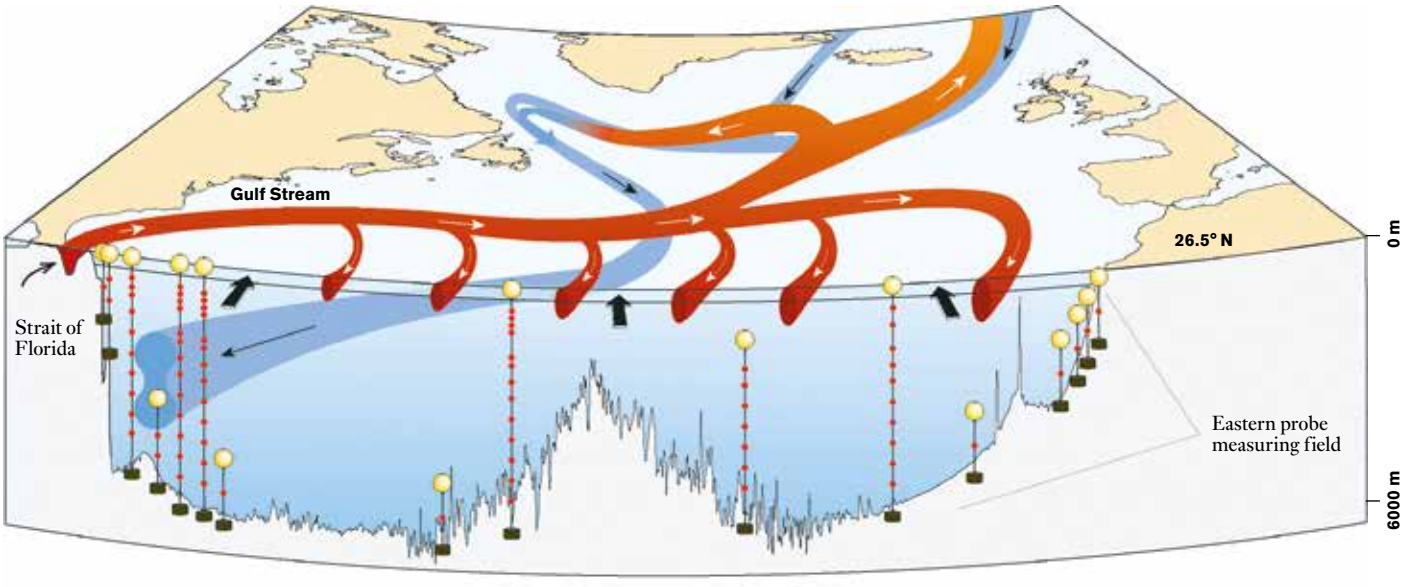
The AMOC is a global system of ocean currents stretching from the Arctic to the Antarctic. One part of this system is the Gulf Stream, which flows northeast from the Gulf of Mexico along the US coast. As it continues toward Europe, it becomes the North Atlantic Current. This current carries warm surface water northward, where its heat is released into the air and ferried onward through the atmosphere to Europe.

In the process, the water doesn't just cool: it also becomes saltier as a result of evaporation. The water becomes denser and sinks, then flows southward at depth. Near Antarctica, it rises again and begins moving northward, completing the cycle. It carries roughly 50 times as much water as the Amazon River discharges into the ocean. But the engine driving this circulation could stall as a result of human-induced climate change, which is altering the ocean's temperature and salinity. As Greenland's glaciers melt, they release large amounts of freshwater into the ocean, lowering its salinity. This makes it harder for the water masses to sink. The consequences could be far-reaching, especially for Europe. As a rule of thumb, the AMOC raises average temperatures in northwestern Europe by two to three degrees Celsius. For comparison: in central England, 1740 was the coldest year since temperature records began almost 400 years ago. Temperatures that year were 2.4 degrees Celsius below average, and it came at the height of the Little Ice Age, when the Thames repeatedly froze over. What remains unclear, however, is what a weakening of the AMOC would mean for Europe in a warming world. Some scien-

"This discrepancy with the more direct current measurements needs to be addressed."

Jochem Marotzke

Measurements in the Atlantic: in 2004, within the context of the Rapid array project, researchers moored 15 measuring probes to the seafloor along the 26th parallel. At different depths, the probes measure temperature, salinity, pressure, and current speed. This allows researchers to determine the strength of the Atlantic circulation. The number of probes has since been reduced.



Probe measuring field on the Atlantic Ridge

GRAPHIC: STUART A. CUNNINGHAM, NATIONAL OCEANOGRAPHY CENTRE, UK, CHURCH (2007) SCIENCE 317, 908–909

tific papers raise the specter of icy winters in Europe, with such scenarios often dominating media coverage. Any cooling expected from a weaker AMOC, however, would be countered by human-induced warming. In Europe, temperatures are currently rising at twice the global average rate. To outline what scientists currently know about what Europe may actually face, it helps to begin with the AMOC's present state: just how much warm water flows north? And have there already been changes in recent decades, as climate change has become increasingly noticeable? "This is where things get messy," says Jochem Marotzke, Director at the Max Planck Institute for Meteorology. For more than 40 years, he has studied the AMOC's role in the climate system, and how it is changing as the planet warms.

When it comes to the volume of water being transported, a comparison can help illustrate the problem: for a river, the amount of water flowing past a given point is relatively easy to calculate from the river's cross section and the speed of the current. This calculation is much harder for an ocean current, however, because there are no clearly defined boundaries below or to the sides. Nor is it a laminar current flowing smoothly along a fixed path. Winds drive it; obstacles slow it down. Sometimes, the current fans out. Eddies also move with the current, creating the impression of flow in the opposite direction. Measuring the current only at isolated points would not produce a complete picture, but merely a patchwork of individual readings. On the basis of the cost alone, it would never be feasible to deploy a sufficient number of current meters to capture every part of the AMOC. Precisely measuring the overall circulation is therefore extremely difficult.

One might say that Marotzke has made this challenge his life's work, right from his doctoral thesis, whose subject was the stability of the AMOC. His idea, which he developed in detail around the turn of the millennium: building on a theory formulated by the polar explorer Fridtjof Nansen and widely accepted in climate science, Marotzke drew an analogy with weather patterns. There are areas of high and low pressure in the atmosphere; because of the difference in pressure, wind blows from the area of high pressure to the area of low pressure. The Coriolis force then deflects the flow to the right, such that it runs parallel to lines of equal pressure. It's much the same in the ocean. In this analogy, differences in density correspond to high-pressure and low-pressure areas, while current speed corresponds to wind strength. The aim, then, is in effect to produce a weather map for the ocean and use it to infer the current.

In 2004, Marotzke and a team at the National Oceanography Centre Southampton had the chance to put this idea into practice. The researchers moored an array of instruments along the 26th parallel to measure temperature, salinity, pressure, and current speed at different depths. The weather-map analogy allowed them to work with a relatively small number of moorings. This network of instruments, known as the Rapid array, stretches from the Bahamas in the west to the African coast at the latitude of the Canary Islands in the east. The Rapid array provided the first continuous direct measurements of the AMOC and is still used by many researchers today. One reason the team chose the 26th parallel was because heat transport is greatest at this point. Another was that a separate measuring installation already existed at this latitude, supplying additional data. Since 1982, researchers have relied on an old telephone cable that runs along the seafloor between the Bahamas and Florida. As seawater flows through Earth's magnetic field, it induces an electrical voltage in the wire, providing a measure of the Gulf Stream's strength.

Summary

There is currently no decisive evidence that human-induced climate change has already weakened the AMOC. Direct measurements of the Atlantic circulation over the past 20 years show only a slight decline, the cause of which remains unclear.

There is a consensus among climate researchers that the AMOC will weaken by the end of the century. What remains unclear is how much it will weaken, and what consequences this would have for Europe's climate. Studies using high-resolution models are designed to help answer these questions.

It's already clear that a weakened AMOC would further fuel global climate change. Economically, the resulting global damage from extreme weather events would outweigh any benefit Europe might gain from reduced warming if the AMOC weakens.

A Flickering Measurement Curve

Analyses of the Rapid measurements showed that the volume of water flowing north has decreased by about 10 percent over the past two decades, from roughly 18 to 16 sverdrups. (One sverdrup equals 1 million cubic meters per second.) Marotzke considers the measurements "very reliable" and the "gold standard," because they capture the Atlantic circulation as directly as possible. Yet the same measurements, now coordinated by British researchers, have also shown that the AMOC fluctuates dramatically: from 3 to 35 sverdrups within ten days. "The thing jumps all over the place," Marotzke says of the measurement curve. The reason, he says, is the wind, which churns up the water. Marotzke is therefore cautious in interpreting the results: it remains unclear, he says, whether the weakening measured since the turn of the millennium is due to climate change or to natural causes. The measurement record, he believes, is too short to allow for definite conclusions.

In addition to direct measurements, researchers can also infer the strength of the AMOC indirectly. Here, climate researchers use what they call "proxies" – essentially, substitute data. These include, for example, sediments that settle on the ocean floor. The weaker the current, the finer the deposits. Without a current, even the finest particles reach the seafloor. Surface water temperature, which has been measured for centuries, is also used as an indicator. In addition, dead cold-water corals preserve a record of the water's properties. These, too, provide clues, because water carried by currents is usually richer in oxygen and lower in nutrients. Ice cores and dripstones also provide important evidence because they can be used to identify temperature changes that are, in turn, linked to the AMOC. While direct measurements of the AMOC have

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PHOTO: SEAN GALLUP/GETTY IMAGES

A weaker driving force: meltwater from Greenland's glaciers lowers salinity in the North Atlantic, making it harder for water to sink. Researchers are now investigating how much this weakens the Atlantic circulation.

been possible only for a few decades, proxy data reaches much further back in time. Some of this proxy data suggests that the AMOC has already weakened substantially. Marotzke thinks searching for meaningful proxies is the right approach. He does not think, however, that researchers are justified in treating proxy data as a straightforward picture of reality. For the industrial era at least, the findings are inconsistent, and they can only be used to infer the Atlantic circulation indirectly. "This discrepancy with the more direct current measurements needs to be addressed," says Marotzke.

Such measurements are meaningful only when several different proxies point in the same direction. This is the case for the last ice age, during which evidence suggests the AMOC probably came to a standstill several times. Temperatures in the north fell during these episodes and rose quickly when the circulation resumed. That suggests there is a tipping point at which the circulation inevitably shifts from one state to another. Scientists from institutions including the Potsdam Institute for Climate Impact Research and the Royal Netherlands Meteorological Institute see signs in today's climate change that the AMOC might be heading for collapse in the future.

"It is considered all but certain that the AMOC will weaken."

Jochem Marotzke

Marotzke points out, however, that conditions during the ice age were very different from those today. Most significantly, vast areas of the Atlantic were covered by ice. As a result, the water in the north could no longer sink. Looking ahead is even harder than looking into the past because, naturally enough, there is no measurement data available from the future. Researchers use models to make projections, but these models cannot capture reality in full. Models do, however, allow researchers to test how the AMOC could respond, for example, to an increased influx of meltwater. One commonly used type of virtual experiment is known as a hosing experiment: in these simulations, freshwater is added to the North Atlantic to test how lower salinity affects the AMOC. For example, in a 2006 study, Marotzke and colleagues assumed that the Greenland ice sheet would melt completely within 1000 years – a relatively short time frame. The study found that glacial melt does affect the Atlantic circulation, but not substantially. By contrast, other simulations do show a collapse of the AMOC; however, these rely on unrealistic conditions. For example, in a study published in early 2024, a team led by Utrecht University scientist René van Westen stalled the current in their simulation by dumping three times more freshwater into the North Atlantic than is locked up in Greenland's glaciers. In the model, northern Europe all the way to Great Britain also cooled significantly more than a complete shutdown of the AMOC's heating effect would suggest. "That was because, in the simulation, sea ice expanded all the way to the coast of Great Britain," Marotzke explains. "However, climate change will put an end to sea ice."

These unrealistic assumptions make scientific sense: they allow researchers to test how the Atlantic circulation behaves under different conditions. "Basic research can learn a great deal from studies like these," Marotzke says. What does leave him somewhat aghast, however, is seeing the results of such simulations presented to the public as realistic future scenarios. "It is important to clearly distinguish here and to be clear in public communication," the climate researcher says.

Fraser Goldsworth, a researcher in Marotzke's department, recently examined how such simulations could be made more realistic. "The processes vary with season and region," the oceanographer says. "Hosing experiments that do not account for this seasonality may overestimate the proportion of freshwater entering the AMOC, and consequently overestimate the AMOC's sensitivity to freshwater input, for example, due to meltwater from the Greenland ice sheet." Hosing experiments are important for research, but they are not climate projections. These are

based on plausible assumptions, such as those regarding future greenhouse gas emissions. The models then calculate interactions among the atmosphere, ocean, sea ice, and other components, making projections possible. For the AMOC, these projections provide a clear picture on only one point: "It is considered all but certain that the AMOC will weaken," Marotzke says. However, the various models do not agree on the extent to which it will weaken or the resulting consequences.

A recent study by a team led by Valentin Portmann, a scientist at the French National Centre for Scientific Research (CNRS), made headlines, claiming that the Atlantic circulation could weaken by roughly 50 percent by the end of the century. The researchers reached this conclusion because, among the many different model simulations available, they gave greater weight to those that predict a higher salinity at the surface of the South Atlantic. "That advances our understanding," Marotzke says. Observations show that the higher salinity is more realistic. The relevant models consistently show a stronger weakening of the Atlantic circulation. Marotzke, however, does not yet consider the projected degree of weakening to be reliable, because all models currently used for forecasting have a fundamental shortcoming: with resolutions ranging from a few tens to a hundred kilometers, they lack detail. "For example, they leave out processes that occur on scales of barely more than a kilometer, but that could be important for the AMOC's behavior," Marotzke says. Models with a grid spacing of just a few kilometers are designed to resolve these details. The Max Planck Institute for Meteorology has been developing such a model with partner institutions for more than 20 years. Specifically, the researchers are using model simulations with a grid spacing of about two kilometers to tease out the roles that eddies and boundary currents play as water sinks in the North Atlantic. In another project, they are simulating how the AMOC develops over a longer period, using a somewhat coarser grid that is still fine-meshed compared with conventional models. Their aim is to make more robust projections of how the ocean current will change as the climate warms. Once this is resolved, however, there still remains the largely unexplored question of how a weakening AMOC will affect Europe's climate. Researchers from the University of Hamburg and the Max Planck Institute for Meteorology are also currently trying to answer this question. One thing is already clear: from an economic standpoint, there would be no cause for relief if a weakening Atlantic circulation eased some of the costly effects of global warming in Europe. That's because a weaker AMOC would also draw less CO_2 from the atmosphere. This, in turn, would further intensify climate change worldwide, leading, among other things, to more devastating and costly droughts, and heavy rainfall across the globe.

Glossary

ATLANTIC MERIDIONAL OVERTURNING CIRCULATION (AMOC)
The global ocean circulation that spans from Antarctica to the Arctic and transports heat to Europe.

HOSING EXPERIMENT
A computer simulation in which large amounts of freshwater are added to the North Atlantic, reducing its salinity, to test how the AMOC responds.

TIPPING POINT
The threshold at which a process becomes inevitable and irreversible. The Amazon rainforest, the AMOC, and the Greenland ice sheet are among the climate system's possible tipping elements; in the case of the Greenland ice sheet, that threshold may already have been crossed.

www.mpg.de/podcasts/ozeane *(in German)*

A life's work with the AMOC: Jochem Marotzke has studied the Atlantic circulation for about 40 years and is also investigating how it will change as the climate warms.

PHOTO: DAVID AUSSERHOFER