THE HOSTILE OCEAN THAT SLOWED CLIMATE CHANGE

The waters of the Southern Ocean have delayed global warming by absorbing much of the excess heat and carbon generated by humanity.

But that might not last.

BY JEFF TOLLEFSON

Strong winds help to pull up ancient water from the ocean bottom.

Joellen Russell wasn't prepared for the 10-metre waves that pounded her research vessel during an expedition south of New Zealand. "It felt like the ship would be crushed each time we rolled into a mountain of water," recalls Russell, an ocean modeller at the University of Arizona in Tucson. At one point, she was nearly carried overboard by a rogue wave.

But what really startled her was the stream of data from sensors analysing the seawater. As the ship pitched and groaned, she realized that the ocean surface was low in oxygen, high in carbon and extremely acidic — surprising signs that nutrient-rich water typically found in the deep sea had reached the surface. As it turned out, Russell was riding waves of ancient water that had not been exposed to the atmosphere for centuries.

Although controversial when she encountered it back in 1994, this powerful upwelling is now recognized as a hallmark of the Southern Ocean, a mysterious beast that swirls around Antarctica, driven by the world's strongest sustained winds. The Southern Ocean absorbs copious amounts

COLIN MONTEATH/MINDEN/NGC

of carbon dioxide and heat from the atmosphere, which has slowed the rate of global warming. And its powerful currents drive much of the global ocean circulation.

The hostile conditions have kept oceanographers at bay for decades, but a new era of science is now under way. Researchers from around the world are converging on the region with floats, moorings, ships, gliders, satellites, computer models and even seals fitted with sensors. The goal is to plug enormous data gaps and bolster understanding of how the Southern Ocean — and the global climate — functions. Doing so could be key to improving predictions of how quickly the world will warm, how long the Antarctic ice sheet will survive and how fast sea levels will rise.

"It's been amazing to see this explosion of information," says Arnold Gordon, an oceanographer at Lamont-Doherty Earth Observatory in Palisades, New York, who led some of the early Southern Ocean surveys in the 1960s. "New technologies are allowing us access to these remote areas, and we are far less dependent on driving a ship through the sea ice."

Already, initial data from an array of ocean floats suggest that upwelling waters could be limiting how much CO_2 the Southern Ocean absorbs each year. This raises new questions about how effective these waters will be as a brake on global warming in decades to come.

"The Southern Ocean is doing us a big climate favour at the moment, but it's not necessarily the case that it will continue doing so in the future," says Michael Meredith, an oceanographer with the British Antarctic Survey in Cambridge, UK. Meredith is heading a series of expeditions over the next five years to help document the uptake of heat and carbon. "It really is the key place for studying these things."

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TRACKING CARBON

The mysteries of the Southern Ocean have beckoned explorers for centuries, but the unique geography of the region makes it a perilous place for ships. There are no landmasses to tame the winds and waves that race around the planet at 60° S. And the ice surrounding Antarctica is notorious for engulfing wayward vessels, including Ernest Shackleton's *Endurance* in 1915.

Scientists only started to realize how important the region is for controlling global climate in the 1980s, when several groups were trying to explain what had caused atmospheric CO_2 concentrations to drop by about one-third during the last ice age and then later rise. Oceanographer Jorge Sarmiento at Princeton University in New Jersey realized that changes in circulation and biology in the Southern Ocean could help to cool and warm the planet[1].

Three decades later, Sarmiento is leading an effort to gather the first real-time data on the chemical and biological processes that govern carbon in the Southern Ocean. The US$21-million Southern Ocean Carbon and Climate Observations and Modeling Project (SOCCOM) has already deployed 51 of a planned 200 robotic floats that bob up and down in the upper 2,000 metres of the Southern Ocean. Building on the global Argo array, which consists of more than 3,700 floats collecting temperature and salinity data, the SOCCOM floats also measure oxygen, carbon and nutrients.

With the new data, Sarmiento and his team can test their models and refine estimates of how CO_2 moves between the seas and the sky. Indirect evidence suggests that the Southern Ocean is a net carbon sink and has absorbed as much as 15% of the carbon emissions emitted by humanity since the industrial revolution. But at some times of year and in specific places in this region, carbon-rich surface waters release CO_2 into the atmosphere.

Now, researchers are getting some of their first glimpses in near-real time of what happens in the Southern Ocean, particularly in winter. "Right off the bat, we are seeing CO_2 fluxes into the atmosphere that are much greater than we had estimated before," Sarmiento says. "It's just revolutionary."

The unpublished analysis is based on just 13 floats that have been in the water for at least a year, so the question now is whether the higher CO_2 emissions during winter represent larger trends across the entire Southern Ocean.

"It's pretty tantalizing," says Alison Gray, a postdoctoral researcher at Princeton who is leading the study. "It would imply that potentially there is a much weaker carbon sink in the Southern Ocean than has been estimated."

Hints of something similar have been seen before. In 2007, a team led by Corinne Le Quéré, now director of the Tyndall Centre for Climate Change Research in Norwich, UK, published a study in *Science*[2] indicating that the rate of carbon uptake by the Southern Ocean decreased between 1981 and 2004. The authors blamed the changes on the winds that encircle the Antarctic continent. The speed of those winds had increased during that time, probably as a result of the hole in the stratospheric ozone layer over Antarctica and possibly because of global warming. Stronger winds are better able to pull up deep, ancient water, which releases CO_2 when it reaches the surface. That would have caused a net weakening of the carbon sink.

If that trend were to continue, atmospheric CO_2 levels would rise even faster in the future. However, a study in *Science*[3] last year found that the carbon sink started to strengthen in the early 2000s (see 'The unreliable sink').

Le Quéré says it's unclear whether that rise in CO_2 absorption is a return to normal or a deviation from the long-term weakening of the sink. Regardless, she says, it's now clear that the Southern Ocean might be much more fickle than scientists thought.

SOCCOM floats will probably help researchers to answer these questions, but it could be years before they can say anything concrete about trends. Nor is Le Quéré convinced that the new network of floats will provide enough detail. In a paper published in July[4], she found that models of carbon uptake by the Southern Ocean depend strongly on assumptions about the structure of the food web there. She says that climate scientists need to improve their understanding of the type and timing of phytoplankton and zooplankton blooms if they are going to get their climate projections right. "In my view, that's the next frontier," she says.

WARMING WATERS

Carbon is only part of the story in the Southern Ocean. Scientists are also beginning to pin down what happens to all the heat that gets absorbed there.

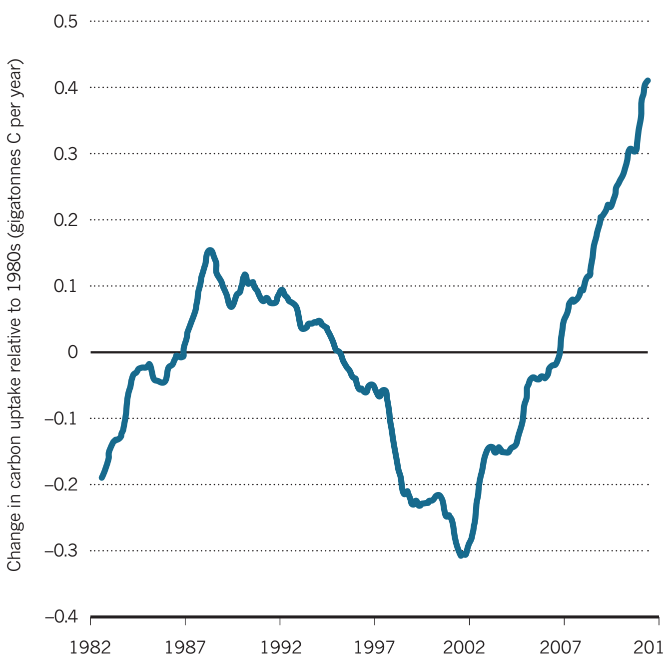
The Southern Ocean is the starting point for a network of currents that carry water, heat and nutrients throughout the ocean basins. Near Antarctica, surface waters normally grow cold and dense enough to sink to the bottom of the ocean, forming abyssal currents that hug the sea floor as they flow north into the Pacific, Atlantic and Indian oceans.

Much of what scientists know about these currents comes from ship surveys conducted every decade or so since the early 1990s. In 2010, when researchers analysed data from the surveys, they found a pronounced warming trend in abyssal waters, which were somehow absorbing about 10% of the excess heat arising from global warming[5].

The level of warming in the deep ocean came as a surprise, and researchers have proposed several explanations that centre on the

THE UNRELIABLE SINK

The amount of carbon dioxide absorbed by the Southern Ocean has fluctuated markedly. In the 1990s, the region lost some of its capacity to take up the greenhouse gas. It started to suck in more in 2002, but this trend could reverse.



DATA FROM L. LANDSCHÜTZER

Southern Ocean. One factor could be that surface waters around Antarctica have become less salty, in part because of an increase in summer rainfall over the ocean. Fresher surface water is less dense, so that change would choke the supply of cold water sinking to the sea floor to feed the bottom currents. "The deep water warms up because it's not getting as much cold-water replenishment," says Gregory Johnson, an oceanographer with the National Oceanic and Atmospheric Administration (NOAA) in Seattle, Washington, who co-authored the 2010 analysis.

An as-yet-unpublished analysis, based on initial data from the third round of ship surveys, finds similar trends, but researchers have longed for more frequent measurements to provide a fuller picture. That could happen if a proposed international project moves forward. Called Deep Argo, this would be an array of floats that regularly dive all the way to the bottom of the ocean. Johnson is involved in a US consortium that is testing 13 floats in a basin off the coast of New Zealand, and another nine south of Australia.

Others are using moorings to monitor deep water flows. Since 1999, Gordon has maintained an array of moorings in the Weddell Sea, one of the main areas where cold surface waters sink to form ocean bottom currents. He has seen the deep water growing less salty in some areas, but the long-term trends are not clear[6].

"We are really only scratching the surface of how bottom waters are changing, and how that is impacting the large-scale global ocean circulation," he says.

ALONG THE EDGE

In January 2015, oceanographers aboard the Australian icebreaker *Aurora Australis* were cruising off the coast of Antarctica when they were presented with a unique opportunity. Following a crack in the sea ice, they were able to reach the edge of the Totten Glacier, one of the biggest drainage points for the East Antarctica ice sheet. No other expedition had reached within 50 kilometres of the glacier.

The team deployed floats and gliders into the waters around and underneath the glacier, which is 200 metres thick at its front edge. What they found came as a shock. The water at the front of the glacier was 3 °C warmer than the freezing point at the base of the glacier.

"We always thought Totten was too far away from warm water to be susceptible, but we found warm water all over the shelf there," says Steve Rintoul, an oceanographer at the Antarctic Climate and Ecosystems Cooperative Research Centre in Hobart, Australia.

Scientists had already shown[7,8] that warm-water currents are undercutting the West Antarctic ice sheet in many areas along the peninsula where the glaciers extend into the ocean. But Rintoul says that this expedition provided some of the first hard evidence that these same processes are affecting East Antarctica, raising new questions about the longevity of the mammoth ice sheets that blanket the continent.

There is no clear answer yet for what is driving the warming of these near-surface currents. Some explanations invoke changes in the winds over the Southern Ocean and the upwelling of warm waters. Others focus on fresher surface waters and an expansion of sea ice in some areas. The combination of extra sea ice and fresher surface waters could create a kind of cap on the ocean that funnels some of the warmer upwelling water towards the coast.

"Every scientist, including me, has their favourite explanation," Gordon says. "But that's how science works: the more you observe, the more complicated it gets."

Finding the answers may require recruiting some of Antarctica's permanent residents. Meredith's team at the British Antarctic Survey plans to equip Weddell seals with sensors so that the animals can collect water measurements as they forage below the sea ice along the continental shelf. This zone has particular importance because it is precisely where cold water begins its descent into the abyss.

"The processes that happen in that shelf region are very important on a global scale, but measuring them is very difficult," Meredith says. "The seals sort of transcend that barrier."

The Weddell seals are just one component of the expedition's arsenal. The team will also send autonomous gliders under the sea ice on pre-programmed routes to collect temperature and salinity data down to depths of 1,000 metres. Measurements taken from ships will help fill in the picture of what happens in this crucial region around Antarctica — and how it relates to the rest of the global ocean circulation.

Getting the data is only half the challenge. Ultimately, scientists need to improve their models of how currents transport heat, CO_2 and nutrients around the globe. Even armed with better measurements, results suggest that modellers have a way to go.

An analysis of data from the ship surveys suggests that upwelling ocean water does not rise in a simple pattern near Antarctica. Rather, it swirls around the continent one and a half times before reaching the surface. And Sarmiento's team at Princeton found that only the highest-resolution models could accurately capture that behaviour. Sarmiento says that it could be a while before the models can simulate what really happens in this region, but he is confident that day will eventually arrive.

For Russell, it's as if scientists are at last lifting the veil on the Southern Ocean. After she returned from her maiden voyage in 1994, she turned to modelling because there wasn't enough data at the time to quantify the effects of the upwelling she encountered. Today she has it both ways. Russell is heading the modelling component of the SOCCOM project, and she is getting more data than she ever dreamt of.

"It's just a wonderful time to be an oceanographer," she says, "even as we are carrying out this really scary geophysical experiment on our planet." ■

Jeff Tollefson *writes for* Nature *from New York.*

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