ALAMY

A SEA CHANGE

A collapse in ocean currents triggered by global warming could be catastrophic, but only now is the Atlantic circulation being properly monitored. **Quirin Schiermeier** investigates.

Henry Ellis, captain of the British slave-trader *Earl of Halifax*, had a scientific bent. While sailing the subtropical Atlantic in 1751, he measured water temperatures at different depths, using a thermometer, a long rope and a bucket fitted with flaps that sealed water inside the vessel when it was raised. Ellis was surprised to find the coldest water in a mid-ocean layer around 1,200 metres below the surface. The Sun, he concluded, did not warm the ocean in proportion to depth.

The discovery proved useful for Ellis's crew: "By its means we supplied our cold bath, and cooled our wines or water at pleasure," he wrote in his notes. But the global significance of the Atlantic's cold depths escaped Ellis and pretty much everyone else for the next two centuries.

He had stumbled upon the generator of a world-girdling system of currents — an enormous flow of water known as the 'global conveyor belt'[1], which transports warm surface water towards the poles and cold deep water back to the tropics. Driven by differences in temperature and salinity, this 'thermohaline' circulation has in recent years become infamous as the possible cause of major climatic upheaval. But only in the past year have much-needed automated systems been installed to monitor this circulation almost constantly. "There's a crying need for these data," says Gavin Schmidt, a leading climate modeller at the NASA Goddard Institute for Space Studies in New York. "For the first time we'll be able to observe the ocean 'weather' in all its complexity."

The cold water Ellis had found in the Atlantic's depths comes from two regions at the ocean's north end, in the Greenland and Labrador seas. Here, saltier water coming northwards cools and sinks, before reversing south. This great submarine U-turn is peculiar to the waters of the North Atlantic, whose extreme cold temperatures and saltiness give it a higher density than is found in the Indian and Pacific oceans.

Evidence from the ice ages suggests that shifts in the thermohaline circulation have dramatic effects on the temperature in western Europe and beyond; past shutdowns of the conveyor drastically cooled the climate all around the North Atlantic in a matter of years by stalling the currents that bring warm water northwards[2]. And computer models suggest that, in a seeming paradox, intense regional cooling could be triggered by global warming[3]. By the beginning of this century, the apparent fragility of the thermohaline circulation had made it by far the best-known exemplar of the surprising, non-linear and potentially catastrophic shifts in climate that makes the prospect of a greenhouse world so scary.

RAPID

Harry Bryden's research suggests that Atlantic currents have slowed in recent years.

Current affairs

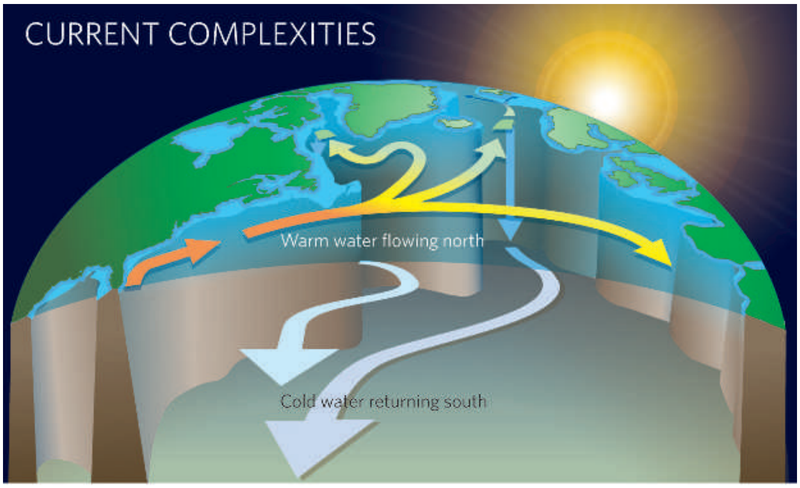
But the flows themselves remain surprisingly unmeasured. Until this year, almost all attempts to monitor what is happening in the Atlantic's depths have relied on some form of Captain Ellis's method — roaming along the surface and dredging up water from various depths as one goes. This year, scientists will have access to continuous measurements collected by 22 moored 'profilers' — sensors that travel up and down wires from buoys to moorings on the sea floor taking measurements as they go. The profilers were set up last year by a UK programme called Rapid Climate Change (RAPID), a £20-million (US$35 million), six-year programme of the Natural Environment Research Council which has installed these profilers as part of a wider scheme to quantify the likelihood and magnitude of rapid climate change in the future.

Climatologists worldwide are anxious to get hold of these data. The most recent shipboard study, published in *Nature* last year, suggested that the circulation might be yet more fragile than had been thought[4]. But at the same time, other research suggests that its potential to do harm may be much subtler than images of a Europe thrown into a mini ice age suppose.

The idea that changes in ocean circulation might be a key determinant of climate change dates back to the early twentieth century and to the great American geologist Thomas Chamberlin. In the 1950s, the oceanographer Henry Stommel pioneered scientific understanding of the three-dimensional structure of the Earth's oceans, and of the currents that flow one way on the surface and another way at depth. But the theorizing that brought the North Atlantic branch of the great conveyor to its present fame dates back only to 1984, when Wallace Broecker, a geochemist at Lamont Doherty Geophysical Observatory at Columbia University in New York, attended a talk in Bern by Hans Oeschger, a Swiss climatologist. While Oeschger outlined his latest findings about climate instabilities and large oscillations of atmospheric carbon dioxide during the most recent ice age, it occurred to Broecker that a switching on and off of the thermohaline circulation in the North Atlantic could be the missing link. Temporary failure of the Atlantic conveyor could have wreaked havoc on climate, he thought.

Although the carbon dioxide fluctuations Oeschger wanted to explain later proved to be artefacts, the idea that the conveyor could stop and start with planet-juddering effects took off. In 1985, Broecker and his colleagues published a landmark paper[5] drawing on early computer models of the ocean's flow. They proposed that the Atlantic circulation had two distinct stable modes — one with the conveyor on and one with it off — and that it was relatively easy for it to move from one mode to the other. The distinction between the two modes, they suggested, might explain the difference in climate between ice ages and warmer interglacials. Soon thereafter, computer models began to show that an increase of carbon dioxide in the atmosphere might, by increasing the temperature and thus the supply of fresh water to the North Atlantic, cause just such a shutdown.

The idea of a threshold that, if passed, could cause calamity, or as Broecker termed it, "a nasty surprise in the greenhouse", has played an increasingly important role in predicting the consequences of a greenhouse effect. In the late 1990s, William Calvin brought the idea to a wider audience with his article entitled 'The great climate flip flop,' which graced the cover of *The Atlantic* — as a neurophysiologist, Calvin had been interested in whether rapid climate change had been a decisive factor in human evolution. A few years later, a 2003 report for the Pentagon, 'Imagining the unthinkable', described how rapid climate change caused by such a shutdown could pose threats to whole societies and the peaceful coexistence of nations. Shortly thereafter, a film called *The Day after Tomorrow* pictured the citizenry of the United states chased over the Mexican border by an instant ice age; again, the North Atlantic was to blame.



Given the thermohaline circulation's pivotal role in discussions of climate change, there was much excitement when, last November, *Nature* published evidence suggesting that the system could have slowed down dramatically[4]. The evidence had been gathered by Harry Bryden, an oceanographer at the University of Southampton, UK, and his team, while on a research cruise that also put the finishing touches to the deployment of RAPID.

Comparing their 2004 measurements with data from 1957, 1981, 1992 and 1998, Bryden and his colleagues found that some of the warm surface water that used to flow northwards now seemed to remain trapped in the subtropical Atlantic, looping east and then returning south rather than heading north. Altogether, the 'overturning' circulation at 25° N — the latitude where Ellis had first probed the ocean 250 years before — seemed to have decreased by about 30%.

"For the first time we'll be able to observe the ocean 'weather' in all its complexity." — Gavin Schmidt

In too deep

The result came as a surprise to those in the field. Few scientists had thought that such dramatic slowing of the thermohaline circulation could happen so soon. Models suggest[6] that the increase in fresh water needed for a conveyor shutdown would not be expected without a global warming of 4–5 °C; warming in the twentieth century is currently put at 0.6 °C (ref. 3). The most complex computer models of the climate and oceans, the sort used to make climate predictions for the Intergovernmental Panel on Climate Change (IPCC), suggest that the flow might be expected to slow by an average of 25% by the end of the twenty-first century, but not to shut down completely[3].

Running complex models long enough to simulate some sorts of change, however, uses an unfeasible amount of computing power. So for some purposes 'intermediate' models can capture things better. Stefan Rahmstorf, an oceanographer at the Potsdam Institute for Climate Impact Research (PIK) in Germany recently compared the circulation's response to an influx of fresh water in 11 simpler models; all showed a threshold, called the bifurcation point, beyond which the thermohaline circulation cannot be sustained[7]. The size of the threshold suggests that the possibility of shutdown is real, but not immediate. Rahmstorf says, "It is very unlikely that it will become really critical for the thermohaline circulation within the next 100 years."

Among the first to see the effect of the global conveyor on climate was Wallace Broecker.

This is not to say that freshwater flows are not increasing; they are. The annual runoff of the six mightiest rivers draining into the Arctic Ocean, including Russia's Ob, Lena and Yenisey, is now 128 cubic kilometres greater than it was when routine measurements began 70 years ago[8], an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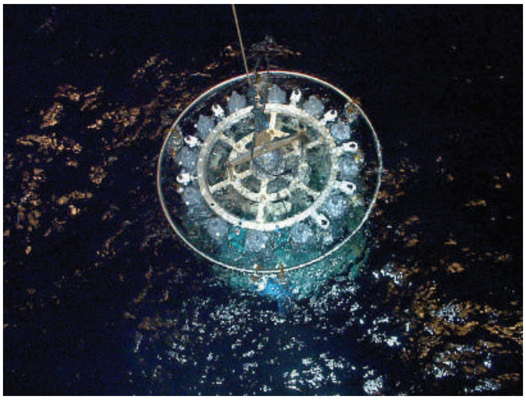
increase of about 7%. In addition, rising temperatures are making sea ice melt more rapidly. Perhaps most important, the huge Greenland ice sheet is showing worrying signs of disintegration; it is currently thought to be shrinking by 50 cubic kilometres per year[9].

Ruth Curry, an oceanographer at Woods Hole Oceanographic Institution in Massachusetts, has investigated how much of this extra fresh water lingers in the parts of the Greenland and Labrador seas that are critical for the functioning of the thermohaline circulation. Her recent analysis[10] of 1950 to 2005 salinity data suggests that 4,000 cubic kilometres — eight times the annual outflow of the Mississippi river — of fresh water have accumulated in the upper ocean layers since the 1960s. "The extra freshwater input is beginning to affect density," she says. But the amount of fresh water needed to shut down the thermohaline circulation in Rahmstorf's comparisons is an order of magnitude greater than the flux reported by Curry, and she agrees that the circulation will not be unduly affected this century. Peter Wadhams, an oceanographer at the University of Cambridge, UK, last year reported a substantial weakening of convection 'chimneys' down which surface water flows in the Greenland sea, but it is unknown how much of the observed effect is due to natural variability.

This is all hard to reconcile with Bryden's findings, which suggest that a strong slowdown is already under way. "Something strange is going on here," says Michael Schlesinger, a climate modeller at the University of Illinois at Urbana-Champaign who views the possibility of a thermohaline circulation shutdown as more likely and more worrying than many of his peers. "If Bryden's findings are real it means that the circulation is much more sensitive to fresh water than any model has ever predicted."

It is not just that the results are unexpected — they also seem hard to reconcile with other data. If the circulation were slowing down as Bryden suggests, one might expect that Europe would already be getting colder. The North Atlantic transports around a petawatt of heat — equivalent to the thermal output of about 500,000 large power stations — towards Europe. Interrupting that flow should have a cooling effect on the climate, but no such change has been seen.

Warming is increasing the flow of fresh water into the sea, which could trigger the collapse of currents.


RAPID

Profiles of salinity and temperature can now be obtained from sensors moored in the Atlantic ocean.

A fragile balance

It may be that the system has a previously unexpected level of natural variation. Or it could be that Bryden recorded noise, rather than a signal — did a set of readings, through coincidence, the presence of ocean eddies and other natural disturbances, make it seem that the circulation was slowing when it wasn't? A statistical artefact cannot be excluded. "The results are based, after all, on just five snapshots of an extremely noisy and under-sampled system," says Carl Wunsch, a physical oceanographer at the Massachusetts Institute of Technology, who harbours long-standing doubts about the significance of the thermohaline circulation and its possible shutdown. "The story is appealing, but it is a very extreme interpretation of the data. It's like measuring temperatures in Hamburg on five random days and then concluding that the climate is getting warmer or colder."

In response to his critics, Bryden points to data on the density of the ocean at various depths gathered at the same time as the flow readings, which provide independent support for the idea that the circulation is slowing. But although other scientists are less harsh than Wunsch, many remain cautious. "Bryden's results are extraordinary," says Schmidt, "but this is exactly why they also require extraordinary evidence."

If Bryden's results are correct, there is another explanation of the lack of cooling in Europe: that a slowdown of the thermohaline circulation will not have the dire effects that have been suggested. It may be that, in today's climate, the role of the thermohaline circulation in warming Europe has been overestimated. A paper published in 2002 suggested that the westerlies, the dominant winds in mid-latitudes that blow from west to east play a much larger role

FOX-WARNER

The shutdown of the Atlantic currents plunged New York into an ice age in *The Day After Tomorrow*.

than was long thought[11]. But much of the heat transported in the atmosphere ultimately comes from the ocean. "It is true that the atmosphere does the heavy lifting," says Jeff Severinghaus, an oceanographer at the Scripps Institution of Oceanography in La Jolla, California, who was once a student of Broecker's. "But the ocean exerts the control, just like the driver of a car."

Evidence for the huge effects of past thermohaline shutdowns is near indisputable. The best case is that of a 1,300-year cold period that occurred around 12,000 years ago, known as the Younger Dryas. The carbon isotope ratios in fossilized plankton from the period suggest that the thermohaline circulation was much slower than it is today (slow circulation allows light carbon isotopes to build up near the ocean's surface).

This slowdown coincided with a vast surge of fresh water into the North Atlantic. The melting of the ice-caps as the ice age ended created a vast reservoir of fresh water known as Lake Agassiz. It was far larger than any of today's Great Lakes, over parts of Minnesota, Dakota and Manitoba — Lake Agassiz. To the east, the lake was bordered by a tongue of the Laurentide ice sheet. When the tongue collapsed, a huge amount of water flooded down the St Lawrence River and into the Atlantic.

According to ice cores drilled in Greenland, similarly large temperature oscillations — the Daansgard-Oeschger events that first piqued Broecker's interest in the 1980s — took place throughout the 90,000 years of the most recent ice age. It is likely that they were also caused by the thermohaline circulation stalling.

But in this respect, as in others, the past may not be a straightforward guide to the present. The consequences of a shutdown could depend on the climate at the time the current stalls. Broecker now believes that the cooling in the Younger Dryas and the Daansgard-Oeschger events came about because the shutdown of the thermohaline circulation was exacerbated by a positive feedback, in the form of enhanced winter sea-ice formation. An influx of fresh water at high latitudes encourages the formation of sea ice, because fresh water freezes more easily. Because ice reflects sunlight, and stops heat from the ocean below reaching the atmosphere, spreading sea ice would strongly amplify cooling due to thermohaline slowdown, especially in winter. Studies of moraines in Greenland and Scandinavia show that during the Younger Dryas the cooling in summers was relatively moderate, whereas in wintertime temperatures must have been more than 30 °C lower than now.

It is hard to evaluate the amplifying role of sea ice very precisely. Most coupled ocean–atmosphere models include a sea-ice component, but the representation is crude and leads to an unrealistic simulation of sea-ice distributions. If this feedback is as important as Broecker thinks, then the effects of a thermohaline circulation shutdown in a warmed world may be very different from those seen during the ice ages and their immediate aftermath. Today, satellite images show sea-ice cover at a historic low. In a world that had undergone the degree of warming needed to trigger a thermohaline shutdown in most models there would be almost none.

Rahmstorf speaks for many climate researchers when he rejects the idea that a thermohaline shutdown in today's climate would lead to a rerun of the Younger Dryas, in which large parts of Europe were frozen. "You can't just assume a linear relationship and say that everything will happen on a 5° higher level," says Rahmstorf. Broecker still believes that global warming may have surprises in store, possibly including a collapse of the thermohaline circulation, but he agrees that "the notion that it may trigger a mini ice age is a myth".

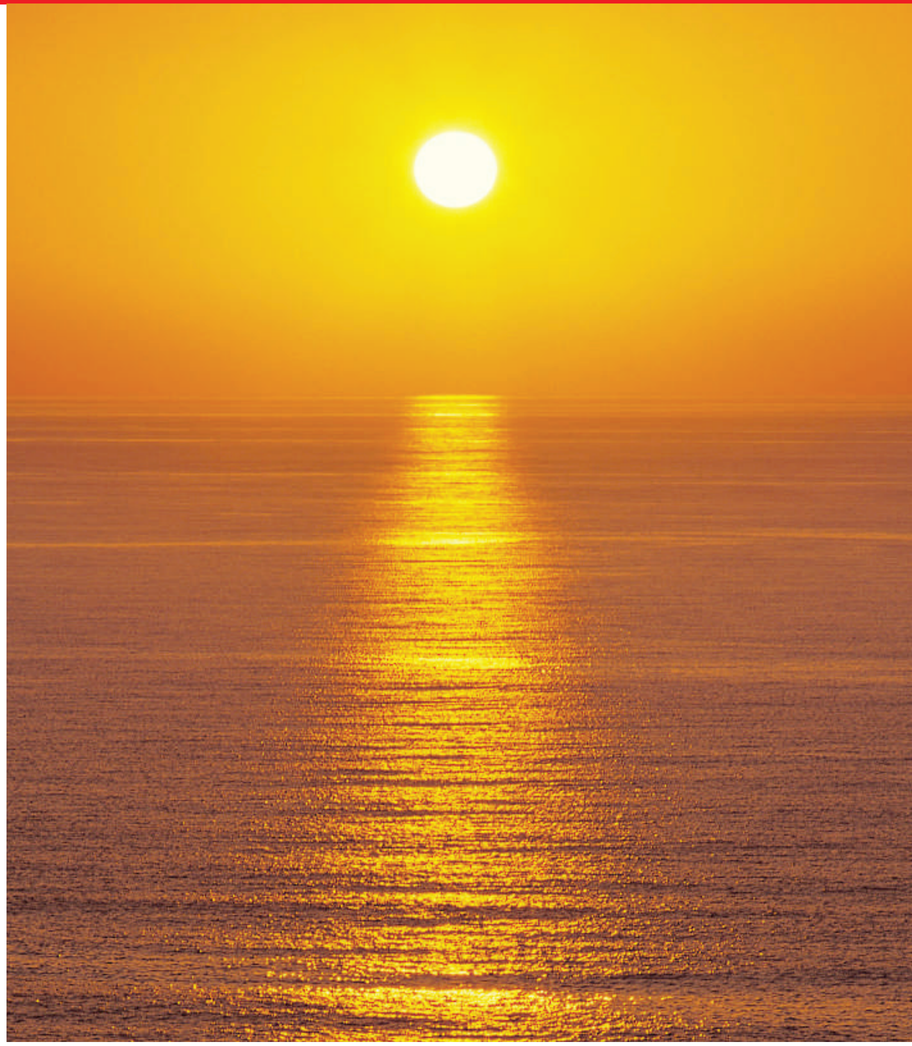
Earth watch

The fact that a future shutdown might not have the predicted effects on climate might go some way to explaining how Bryden could observe the circulation slowing — or at least fluctuating — without major climatic consequences, at least so far. Although Severinghaus agrees that this may be part of the story, he and many of his peers would rather believe that there was a randomly wrong signal in the data. "It just doesn't quite fit," says Schmidt. "If the circulation has been 30% down for a decade, it should at least have produced a 1–2° drop in sea surface temperature even if it didn't cool Europe. But no such thing has been observed."

Carl Wunsch believes the effect of Atlantic circulation on climate has been overblown.

Bryden says that the new RAPID system for monitoring flow in the Atlantic should allow them to know within a decade whether they found a long-term slowdown or a natural fluctuation. Other new approaches may also help. The ARGO system, part of the international Global Climate Observing System, is a fleet of robotic floats that monitors temperature, salinity and current in the upper 2,000 metres of the Indian, Atlantic and Pacific oceans. The free-drifting floats sink to pre-established depths and then surface to transmit their data to satellites. ARGO data are invaluable for monitoring changes in remote ocean regions, according to Lynn Talley, a physical oceanographer of the Scripps Institution of Oceanography in San Diego, California. For example, they have already revealed a spectacular warming of the southern ocean surrounding Antarctica, she says.

And *in situ* monitors are not the only way of keeping an eye on the deep ocean. A weakening of the thermohaline circulation would change the entire topography of the sea surface, says Rahmstorf. Such large-scale changes could be picked up by satellites. A recent simulation[12] suggests that the sea level of the North Atlantic could rise locally by up to a metre as a result of adjustments to the density flows below the surface; in some regions the rate of change could be up


ALAMY

to 2.5 centimetres per year. Scientists have begun using satellite altimetry to see if such changes are already observable; again, they expect robust results within a decade.

Modellers also have much to do. Most model studies, such as those used by the IPCC, look at how a freshwater-induced shutdown of the thermohaline circulation might change temperatures if everything else remained the same. A harder question is what a shutdown might mean in a world that is, on average, getting warmer. Bryden's findings have caused a stir throughout the climate research community; lead authors of the chapters on ocean physics and circulation in the IPCC's fourth assessment, due in 2007, are reworking their submissions.

Future unknown

Wolfgang Cramer, an ecologist at PIK, predicts complex changes in the climate, with some effects exacerbating each other and some that cancel each other out. For example, Cramer says, meteorological perturbations caused by a thermohaline shutdown could lead to a dramatic increase in the frequency of major floods and storms in large parts of Europe even if overall temperatures do not drop. "It's not the mean, it's the extremes that are most worrying," he says.

One aspect of the problem is that the thermohaline circulation is not just a climatic affair. Its effect on ocean circulations means it influences the rates at which nutrient-rich bottom water rises to the surface all around the world. A recent simulation suggests a shutdown might lead North Atlantic plankton stocks to collapse to less than half their current biomass[13]. Globally, a decline of more than 20% might be expected thanks to reduced upwelling of nutrient-rich deep water and gradual depletion of upper-ocean nutrient concentrations.

"Plankton builds the base of the marine food web. So a decline in global plankton biomass and productivity can be expected to have consequences for fish, squid and whales as well," says Andreas Schmittner, a climate researcher at Oregon State University in Corvallis. "A weaker Atlantic overturning circulation could result in a reduced fish supply to people living along the shore lines of the Pacific and Indian Oceans."

Other possible effects of a shutdown predicted by models include warming in the tropics, or, rather surprisingly, over Alaska and Antarctica. Rainfall patterns might change, too. A southern shift of the thermal equator — which has accompanied thermohaline circulation shutdowns during ice ages — could lead to monsoon failures, and droughts in Asia and the Sahel region, says Severinghaus, and these effects seem to be independent of sea ice. Such shifts could have severe consequences for poor farmers in many parts of the world, consequences that may be considerably more disruptive than colder winters in affluent northern Europe, says Severinghaus. And, as Schlesinger points out, a weakening or stopping of the thermohaline circulation would reduce the carbon dioxide uptake of the ocean, which would mean a positive feedback on global warming. The oceans currently absorb about a third of the carbon dioxide released from fossil fuels, although the proportion is set to decrease as emissions climb.

"The notion that a collapse of the thermohaline circulation may trigger a mini ice age is a myth." — Wallace Broecker

Some 250 years after Captain Ellis first probed the Atlantic, its depths still hold secrets and threats. Even in a new age of constant monitoring and improved modelling, it will be some time before the likelihood, and the probable effects, of a thermohaline circulation slowdown can be predicted with accuracy. The intricacies of a system that depends on delicate balances between fresh and salt water over vast ocean basins, on the details of atmospheric circulation, wind-driven currents and the topography of deep sea floors will not yield answers quickly. "If you would like to learn how a planet operates you would probably not choose the Earth," remarks Schlesinger. We greenhouse dwellers, alas, do not have a choice. ■

Quirin Schiermeier is *Nature*'s German correspondent.

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