Risk of sea-change in the Atlantic

Stefan Rahmstorf

Emissions of greenhouse gases could weaken or even halt ocean overturning in the North Atlantic, radically altering the regional climate. It seems that the rate of greenhouse-gas increase may be as important as the final concentrations reached.

Will man-made climate change disrupt the ocean currents that have guaranteed Europe's mild climate for the past 10,000 years? A number of recent computer simulations as well as simple physical reasoning have hinted at such a possibility, but until now no systematic sensitivity study had been performed. On page 862 of this issue[1], Stocker and Schmittner present such a study, albeit with a highly simplified climate model. They conclude that ocean circulation stability depends not only on the total amount of greenhouse gas emitted by human activities, but also on the rate at which the gases are pumped into the atmosphere. It could make all the difference whether greenhouse gas emissions are reduced or continue unabated in the coming decades.

The reasons why climate researchers regard ocean circulation with concern are simple. The oceans transport massive amounts of heat around the planet. The northern North Atlantic in particular benefits from this — it receives around 10^{15} W of heat from the Gulf Stream and the North Atlantic Current (Fig. 1). This heat is released to the atmosphere and warms the winds that blow across Europe. The bulk of the heat is transported not by wind-driven ocean currents, but by the so-called thermohaline circulation, which is driven by temperature and salinity (and therefore density) differences in sea water. This circulation is basically a gigantic overturning motion, sometimes dubbed the 'ocean conveyor belt'. Warm surface waters flow north throughout the Atlantic, give off their heat and sink at high latitudes, and return south as cold water at a depth of about 2 km.

The crux of the matter is that the strength of the circulation, and thus the rate of heat transport, depends on small density differences, which in turn depend on a subtle balance in the North Atlantic between cooling at high latitudes and the input of less-dense fresh water from rain, snowfall and river runoff. More freshwater input would slow down the overturning, but not in a simple linear manner. Little happens at first, as the circulation continually removes the freshwater and replaces it with more salty water from the south. But there is a well-defined critical threshold — a saddle-node bifurcation, in mathematical terms — beyond which the thermohaline circulation cannot cope with additional fresh water, and breaks down. (Surface warming can have a similar effect, although at high latitudes the sea water density is less sensitive to temperature.) The existence of this threshold was first proposed by Henry Stommel[2] in 1961 and has since been confirmed by a wide variety of ocean models, including global general circulation models[3].

Deep ocean sediments and the Greenland ice cap contain a rich climate record which strongly suggests that the thermohaline circulation has broken down or at least changed drastically in the past after pulses of freshwater entered the Atlantic, and that this caused cold spells lasting for hundreds of years. The last of these events was the so-called Younger Dryas event 11,000 years ago. They do not necessarily give us indications for future events, as they occurred under ice age conditions, but they show that the possibility of a circulation breakdown is real. Global warming is expected to warm the surface waters and increase precipitation in high northern latitudes, both of which will reduce water density and move the Atlantic closer to the threshold. The crucial question is: how close?

Global warming simulations performed with coupled ocean–atmosphere circulation models generally show that the Atlantic thermohaline circulation weakens by 15–50 per cent for a doubling of atmospheric carbon dioxide; Manabe and Stouffer[4] found that after a quadrupling of carbon dioxide, the deep circulation in their model ground to a complete halt.

Such models would require more supercomputer time than is practical to explore the sensitivity of the ocean circulation to a wide range of parameters. That is why Stocker and Schmittner have used a highly simplified (but well-tested) model: a three-basin ocean model, averaged at each latitude, with simple atmospheric feedbacks. Although it is often said that 'the more feedbacks included, the more stable the model', the net effect of neglected feedbacks can be negative or positive; comparisons have shown that the ocean circulation in simple climate models can in fact be more stable than in the most sophisticated ones. Stocker and Schmittner's model gains credibility from the fact that it is consistent with the coupled circulation model of Manabe and Stouffer.

Nevertheless, a simple model like this cannot be expected to make accurate quantitative predictions. The key result of their study lies not in exact numbers, it is in the principle that the *rate* at which greenhouse-gas concentrations increase is crucial for the stability of the ocean circulation. Higher concentrations of greenhouse gases can be tolerated if they are approached more slowly. The implications for policy are clear: by starting to reduce emissions soon, we can buy greater climatic resilience and security later on.

Even the most sophisticated coupled climate models suffer from problems relevant to ocean circulation stability: *ad hoc* adjustments to the flux of heat and fresh water are often made in order to stop the models drifting to unrealistic situations, and these may artificially stabilize the ocean circulation; ocean convection is too small-scale to be

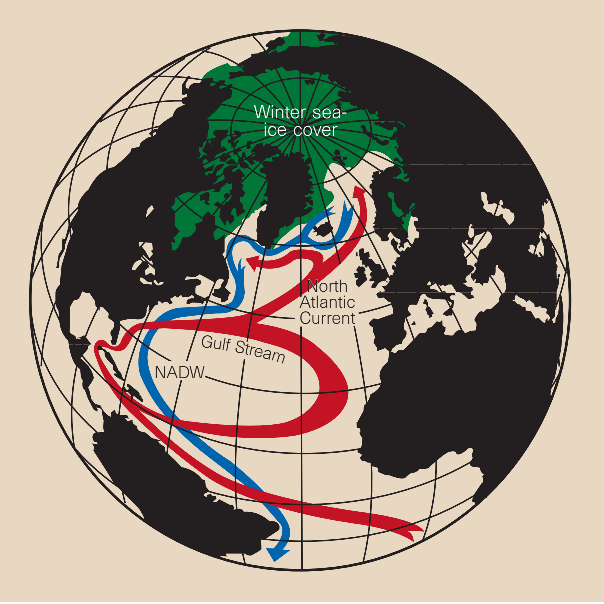


Figure 1 **Europe's heating system. This highly simplified cartoon of Atlantic currents shows warmer surface currents in red and cold North Atlantic Deep Water (NADW) in blue. The thermohaline circulation heats the North Atlantic and Northern Europe. It extends right up to the Greenland and Norwegian Seas, pushing back the winter sea-ice margin. A rapid rise in greenhouse gas concentrations could disrupt the thermohaline circulation.**

resolved explicitly in the models; and the physics of downslope flow of dense water near the sea bottom is not properly included. This last hampers the overflow of deep water over the sills between Greenland, Iceland and Scotland, so that too much of the models' deep water is formed south of the sills. Another source of uncertainty comes from the atmosphere models: changing precipitation is the major factor in changing ocean circulation, but it is much harder to predict than temperature changes.

The consequences of a disruption of the Atlantic thermohaline circulation are still under debate. Studies[5,6] of the effects of an artificially triggered shutdown of the circulation, without accompanying global warming, typically find local sea surface cooling of 5–8 °C, with an even larger cooling in the atmosphere because increased sea-ice cover reflects more sunlight. Air temperature reduction is largest near Iceland, but affects much of Europe. In contrast, studies that show weakened or stopped circulation but include global warming find only a region of moderate cooling or reduced warming of the atmosphere, south of Greenland[4,7,8]. Global warming can roughly compensate for the reduced oceanic heat transport in these experiments, because the ocean circulation winds down only slowly.

There are several caveats here. That the maximum effect is south of Greenland points at the overflow problem mentioned above. One can only speculate whether the response would be larger if the models formed more deep water north of the sills, so that the 'conveyor belt' would reach further north and interact with sea ice as it does in the real world. And a much faster circulation change (such as those seen in the ice-age climate records) may be possible through a different, convective type of instability[3], which has its own critical thresholds and depends on regional detail poorly represented in present climate models.

But whatever the effects on air temperature, such a change in ocean circulation would certainly have a severe effect on marine ecosystems and fisheries. Even small fluctuations in ocean currents have led to the collapse of fish stocks and sea-bird populations in the past. Another concern is that a reduced thermohaline circulation would weaken the carbon dioxide uptake of the ocean[9], effectively making the climate system more susceptible to anthropogenic emissions.

So a collapse of the Atlantic thermohaline circulation would probably have serious consequences, involving risks that no nation bordering the North Atlantic would willingly take. Climate models are still too coarse to accurately predict how vulnerable the ocean circulation is, but they suggest that crossing a critical limit is within the range of possibilities for the next century. A disruption of the thermohaline circulation cannot be ruled out if we continue to pollute the atmosphere at the present rate. The work of Stocker and Schmittner is a timely reminder, before the Kyoto climate summit in December, that swift action is needed to reduce the risk of unwelcome climatic surprises. □

Stefan Rahmstorf is at the Potsdam Institute for Climate Impact Research (PIK), PO Box 60 12 03, D-14412 Potsdam, Germany.
e-mail: rahmstorf@pik-potsdam.de

1. Stocker, T. & Schmittner, A. *Nature* **388,** 862–865 (1997).
2. Stommel, H. *Tellus* **13,** 224–230 (1961).
3. Rahmstorf, S. *Nature* **378,** 145–149 (1995).
4. Manabe, S. & Stouffer, R. J. *Nature* **364,** 215–218 (1993).
5. Manabe, S. & Stouffer, R. J. *J. Clim.* **1,** 841–866 (1988).
6. Schiller, A., Mikolajewicz, U. & Voss, R. *Clim. Dyn.* **13,** 325–347 (1997).
7. Cubasch, U. *et al. Clim. Dyn.* **11,** 71–84 (1995).
8. Hirst, A. C., Gordon, H. B. & O'Farrell, S. P. *Geophys. Res. Lett.* **23,** 3361–3364 (1996).
9. Sarmiento, J. L. & Le Quéré, C. *Science* **274,** 1346–1350 (1996).

Biological hydrostats

Wrapping the armadillo's penis

Richard Wassersug

A multitude of soft-bodied organisms (such as worms) and parts of organisms (such as the tube feet of echinoderms, the trunks of elephants, and even our own tongues) are biological hydrostats. They lack solid skeletons, yet hold their shape because of the internal fluid pressure, which is resisted by tension in the sheath that surrounds the fluid space. These enwrapping sheaths are reinforced with fibres that classically spiral up and down the long axis of the structure, forming a crossed helical array.

The penis is also a biological hydrostat, and in the *Journal of Morphology* Diane A. Kelly[1] reveals that, in the nine-banded armadillo (*Dasypus novemcinctus*; Fig. 1), it is reinforced by investing fibres that run, not helically, but orthogonally to the long axis of the penis. That is, the fibres run lengthwise and circumferentially (Fig. 2, overleaf), and the penis is the first biological structure known to have such a pattern.

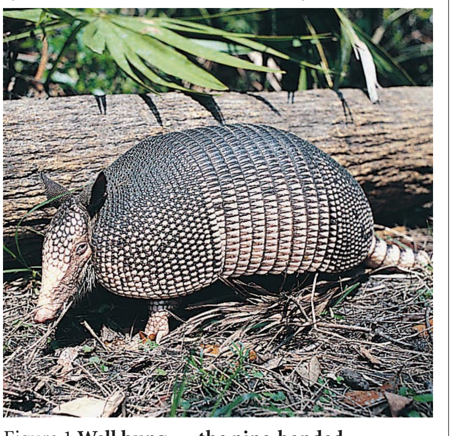
The mechanical properties of biological hydrostats are greatly affected by the angle of the supporting fibres within the sheath[2]. When the fibres cross the long axis of the structure at about 55° — which they typically do — the structure can easily bend without buckling, while it retains a constant volume. This is fine for worms and tongues, but what about hydrostats that need the opposite physical properties? Suppose one has a biological structure that must be able to increase its volume enormously, and then resist any bending or long-axis compression. Such a structure is the mammalian penis.

The supporting fibres in the armadillo penis are made of collagen and lie in the tunica albuginea, the thin layer of fibrous tissue that surrounds the erectile tissue (corpus cavernosum). Kelly[1] shows that fibres in the armadillo's tunica are precisely orientated at either 0° or 90° to the long axis of the penis. When the penis is flaccid the fibres are massively pleated. These pleats allow for the great increase in the length and width of the penis during erection, and they disappear when the penis is fully tumescent.

The mechanical properties of a hydrostat with an axial orthogonal array (such as that of the penis) were understood by biologists even before they realized that there were biological structures with this pattern[2]. An orthogonal array, unlike a helical one, provides the penis with maximum flexural stiffness when erect. This is essential for effective intromission — the armadillo whose penis buckles when it should not, is left out in the cold without descendants.

If bending loads on the erect penis are excessive, the longitudinal fibres can rupture, leading to a fractured penis. This can happen to humans if the penis is exposed to blunt trauma[3], although it is thankfully rare because of the enormous strength of the collagen array in the tunica albuginea. Whether armadillos in nature ever fracture their penises is not known. But Kelly was able to reproduce the situation by inflating armadillo penises in the laboratory and testing their strength under various loading regimes. She confirmed that they failed by buckling, under the same loading regimes as those that lead to fracture of the penis in humans.

From Kelly's unpublished survey of other mammalian species, it is likely that all mammalian penises are wrapped the same way as the armadillo's, in orthogonal-fibre arrays. So why has it taken us so long to realize this? One can only surmise that most scientists (or the male ones at least) have been



JEFF FOOTT/BBC NATURAL HISTORY

Figure 1 **Well hung — the nine-banded armadillo, *Dasypus novemcinctus*.**