Launching a mooring from the rear deck of the RRS *Discovery*.

Inevitable surprises in the Atlantic Ocean

What have we learned from a decade of monitoring how water and heat circulate through the North Atlantic? As Meric Srokosz explains, a great deal – much of it unexpected.

In 2002, a report – entitled *Abrupt Climate Change: Inevitable Surprises?* – highlighted the possibility of sudden shifts in the North Atlantic circulation in a warming climate. Likewise the 2001 Intergovernmental Panel on Climate Change (IPCC) report suggested that the Atlantic Meridional Overturning Circulation (AMOC) could weaken over the 21st century.

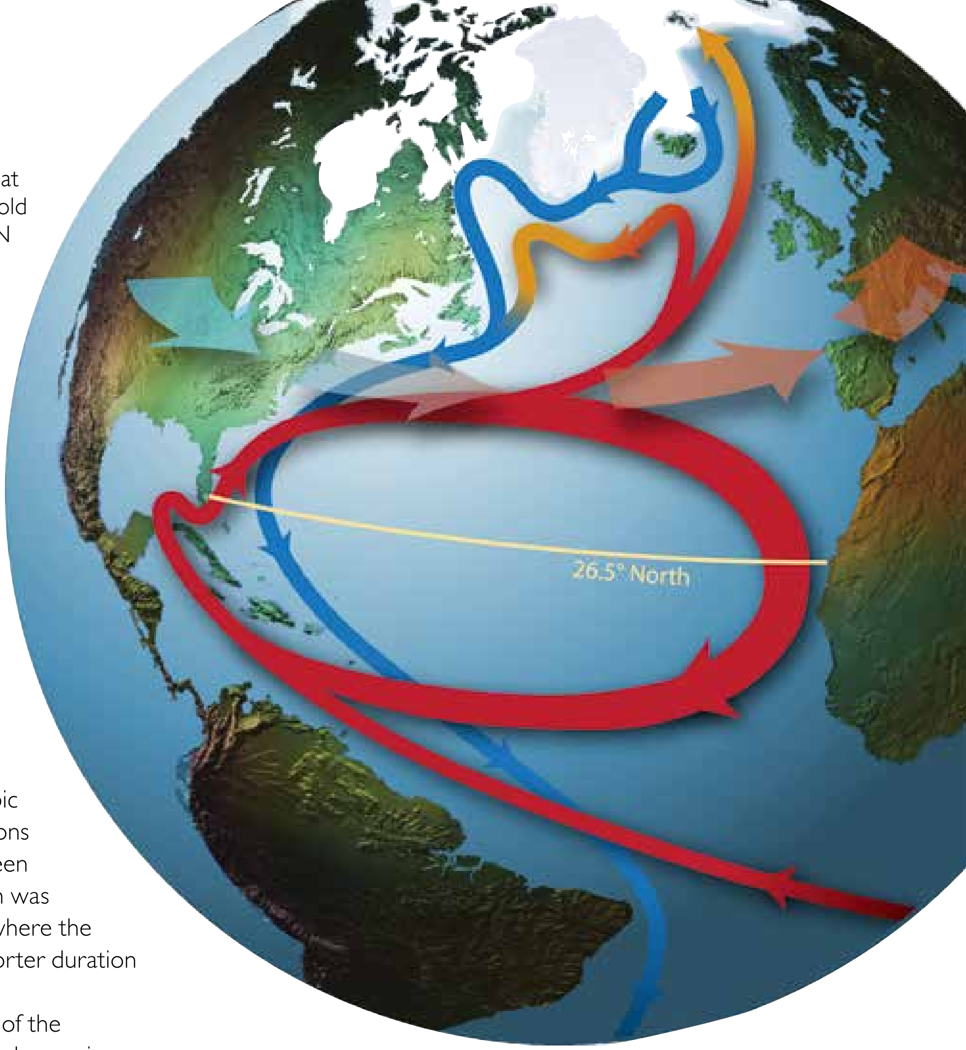
The AMOC transports heat northwards across the equator; this makes the Atlantic different from the Indian and Pacific Oceans, where the ocean transports heat away from the equator towards the poles. The warm northward flow is balanced by a cold deep return flow, as the waters cool and sink having given up their heat to the atmosphere above. We already knew this is important for the climate, and models predict it will slow down under global warming, with significant effects. AMOC is what gives the UK and North-west Europe their temperate climate, so ironically in a warming world these areas could get cooler due to weakening ocean circulation. Changes in the AMOC could also affect sea levels around the periphery of the North Atlantic.

All this meant scientists renewed their efforts to make observations of the AMOC. In particular, it led to the deployment of the NERC-led joint UK-US RAPID observing system across the Atlantic at 26.5°N in spring 2004. Last year this system achieved ten years of measurements; during that decade it has indeed provided some inevitable surprises.

Traditionally, the AMOC has been measured by sending a research ship across the Atlantic, stopping every 50km and lowering instruments right to the seabed to measure the temperature and salinity of the water. The water is typically 5km deep, so this is a slow process and a single crossing of the Atlantic at the 26.5°N latitude can take 35 days.

Only six such transects have been made since the 1950s. Clearly this is not a viable way to continuously measure the AMOC – hence the need to create a long-term observing system. It consists of instrumented moorings at the eastern and western boundaries, and on either side of the mid-Atlantic ridge, together with an undersea cable that measures the flow through the Florida Straits.

As well as the baseline decade of RAPID observations of the full AMOC at 26.5°N, there have been other ongoing measurements during this period that capture components of the AMOC (for example, just the deep return flow). Some of these are not continuous, or of much shorter duration. Yet the RAPID measurements are unique – they are the only



A simplified version of the Atlantic Meridional Overturning Circulation (AMOC). Warm water flows north in the upper ocean (red), gives up heat to the atmosphere, sinks and returns as a deep cold flow (blue). The yellow line represents the 26.5°N AMOC observations.

ocean-wide continuous measurements of the AMOC's strength and vertical structure. They have produced several surprises – some of them taking place on timescales shorter than a year, others lasting the full length of the observations.

Fluctuations in the flow

The first surprise was that in the first year of measurement, the AMOC seemed to vary far more than we'd expected. Its flow fluctuated between 4 and 35 Sverdrup (Sv – this is the standard unit for measuring ocean circulation; one Sverdrup is a million cubic metres per second). Five ship-based observations over the previous 50 years found a flow between 15 and 23Sv. A similarly large range of variation was subsequently observed in the South Atlantic, where the observations are more recent and of much shorter duration – just 20 months.

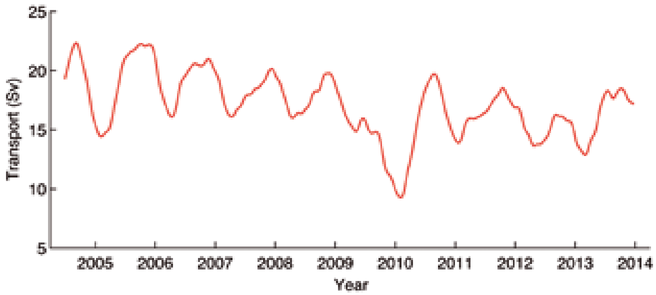
The second surprise was that the amplitude of the seasonal cycle, with a minimum in the spring and a maximum in the autumn, was much larger (around 6.7Sv) than anticipated.

The third big surprise was that the AMOC temporarily declined by 30 per cent during 2009-10. This was completely unexpected, and exceeded the range of year-to-year variations found in climate models used for the IPCC assessments. It was also captured by Argo – these are free-floating buoys that measure temperature and salinity down to 2km – and by satellite altimeter observations of the upper limb of the AMOC at 41°N. This dip was accompanied by significant changes in the heat content of the ocean. These would have affected the weather, perhaps contributing to the severe winter of 2009-10. The decline has also been linked to an unprecedented sea-level rise on the eastern seaboard of the USA during the same period, so scientists are now working to understand why it happened.

The final surprise was that over the first decade of the RAPID observations, the AMOC has declined by about 0.5Sv per year – ten times faster than climate models predict. Whether this is a trend caused by global warming, or just part of the so-called Atlantic Multi-decadal Oscillation – a long-term cycle taking place over 60-80 years observed in sea-surface temperatures – is another question scientists are still trying to answer. There is no doubt that continuously observing the AMOC over a decade has significantly changed how we view the ocean circulation in the North Atlantic, how it varies and its impact on our climate.

The RAPID observations are now stimulating the development of further AMOC observing systems both in the North Atlantic Subpolar Gyre, south of Greenland and Iceland – a project called OSNAP (Overturning in the Subpolar North Atlantic Programme) in which the UK is playing a major part – and in the South Atlantic.

The aim is to combine the new observations with the RAPID ones and so obtain a holistic picture of the AMOC from south to north in the Atlantic. Given the surprises and insights into the Atlantic circulation that RAPID observations have produced so far, it is not too much to expect that the new observations will lead to future 'inevitable surprises'.



AMOC strength in Sverdrups over ten years to March 2014. Note the low AMOC event in 2009/10 and the overall decline in AMOC strength over the period.

Professor Meric Srokosz works on marine physics and the relationship between the ocean and the climate at the National Oceanography Centre in Southampton.
Email: mas@noc.ac.uk.
For more on the RAPID programme see www.rapid.ac.uk
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