RAPID

Monitoring the meridional overturning circulation at 26°N

Eleanor Frajka-Williams

The ocean conveyor is a term used to describe how a parcel of water initially at the surface in high northern latitudes might travel at depth to the Southern Ocean, and then return in surface currents (see Figure 1). The conveyor belt idea made its Hollywood debut in the film 'The Day after Tomorrow' in which a palaeoclimatologist shows a similar diagram to politicians. Soon after, large drops in temperature are recorded by weather buoys off Greenland — a warning that the world is undergoing a massive climate shift due to a shut down of the conveyor belt. In the film, the shutdown of the circulation plunged the world into a new ice age, with glacial conditions spreading equatorward more quickly than cars could drive. While the details of the film are only loosely based on science, it raises a valid question: could the conveyor shut down and what would be the consequences to the Earth climate system if it did?

*Meridional = north–south, as opposed to zonal = east–west

While the conveyor belt analogy is a popular choice for science communication, it is somewhat notorious among scientists because it greatly simplifies the state of knowledge about the ocean circulation. The conveyor belt is a representation of the ocean meridional overturning circulation (MOC), a global three-dimensional web of currents driven by winds and spatial variations in water density. Some of the general 'conveyor belt' ideas are broadly true – warm water moves northward, contributing to more temperate winters in the British Isles and north-western Europe. Winter temperatures in the British Isles are at least 10 °C higher than at similar latitudes on the North American or Asian continents. This heat transport is one of the roles that the MOC plays in the global climate system. However, the term 'conveyor belt'

The elegant simplicity of the 'ocean conveyor' hides the complexity of the meridional overturning circulation which it represents

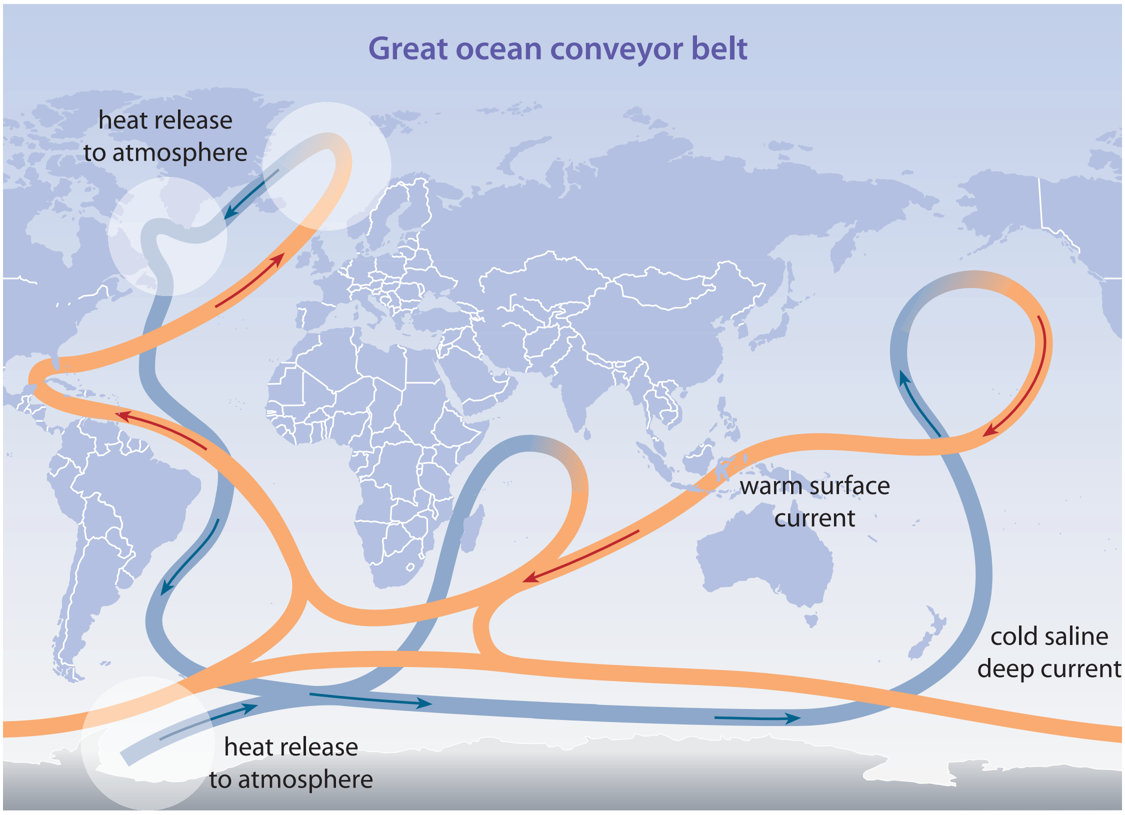


Figure 1 *The ocean conveyer belt. Red indicates warm currents, typically at the surface; blue indicates deep currents. Downwelling occurs through the process of deep convection in particular high-latitude regions, while upwelling is more spatially diffuse. The main regions of deep convection, indicated on the map, are the Greenland and Norwegian Seas, the Labrador Sea and the Weddell Sea.* (Source: IPCC)

suggests the presence of localised streams of water moving around, which in turn suggests that a slowdown of the belt in one region directly translates to a global slowdown everywhere. In truth, the web of currents making up the MOC is not only diffuse but dynamic. The positions of currents can change and they are subject to fluctuations on a range of time-scales. It is the potential for large-amplitude fluctuations – including a complete cessation of of the overturning circulation and its associated heat transport – that worries scientists, politicians and other informed people today.

Palaeo evidence and modelling

Palaeo evidence has shown that rapid shifts in climate are possible, and that the most likely culprits in large-amplitude global shifts are changes in the ocean circulation. One such event was the 8.2 kyr climate event during which glacial Lake Agassiz, in North America, drained into the subpolar North Atlantic, releasing roughly 9500 km^3 of fresh meltwater, the equivalent of a local rise in sea-level of 25–50 cm. In the present-day climate, cold winds blowing across the high-latitude Atlantic cool surface waters so that in certain locations (Figure 1) they become denser than the layers beneath and sink, forming the deep 'limb' of the conveyor.

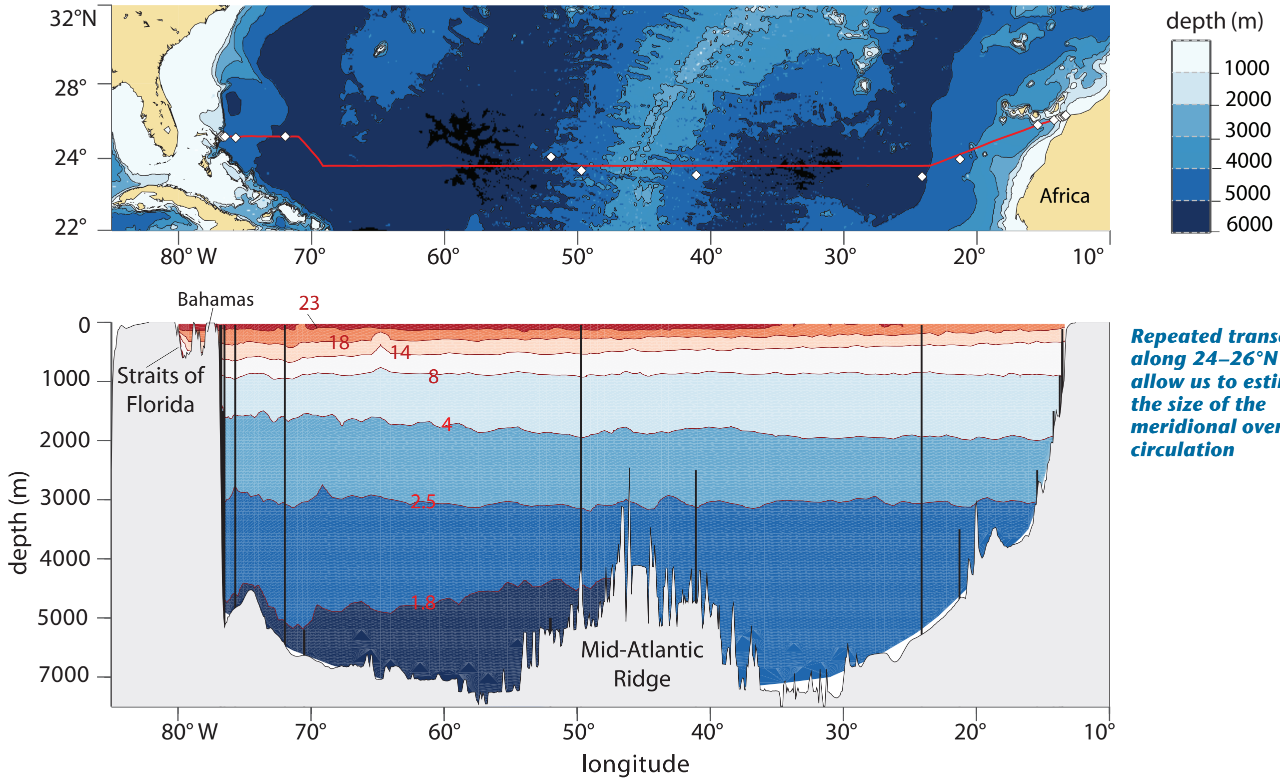
However, in the 'glacial Lake Agassiz' scenario, fresh water capped the regions where deep convection had previously occurred, so that the surface waters were too buoyant to sink. The result was a break in the conveyor, effectively shutting down the MOC and causing a cooling of the northern high latitudes.

Global numerical models have shown similar processes: large inputs of fresh water to the northern North Atlantic can reduce deep convection, and thus slow the MOC. The adjustment of the MOC to changes in northern latitudes can be quite quick, on the order of one month (see Further Reading) as a result of wave processes travelling down the coast and resetting the stratification.

Observations of the MOC

Observational estimates of the MOC are sparse due to the global nature of the circulation and the expense of making large-scale measurements. However, repeat observations *have* been made along ~ 26° N in the Atlantic. To the west, Florida and the Bahamas confine the very fast, northward-flowing Gulf Stream in the Straits of Florida, where it has been measured since 1982 by recording the voltage induced across a submarine telephone cable. Since seawater is a conductor, as it moves through the Earth's

Figure 2 Upper *Bathymetry of the North Atlantic beneath the southern part of the subtropical gyre. The red line from the Bahamas to Africa represents the track of the 2004 hydrographic section whose temperature distribution is shown in the panel below. This transect, and other ocean-wide transects just to the north and south of it, made since 1957, are allowing us to estimate meridional overturning transport.* ***Lower*** *The temperature distribution for the transect shown above. Also shown, to the west of the Bahamas, is the temperature distribution within the northward-flowing Gulf Stream in the Straits of Florida. In the Atlantic above 1000 m, the isotherms sloping up to the east are indicative of the southward flow of surface and thermocline water in the subtropical gyre (cf. Figure 3).*



Repeated transects along 24–26°N allow us to estimate the size of the meridional overturning circulation

magnetic field, it induces an electric field. The strength of the field varies with the speed of the Gulf Stream, and can be detected in the telephone cable as changes in voltage, which have been extensively calibrated with direct velocity measurements in the Gulf Stream. Ship-based observations of density structure along 25° N have been carried out six times (in 1957, 1981, 1992, 1998, 2004 and 2010). As the vessel crosses the Atlantic, salinity, temperature and pressure (depth) profiles are retrieved at a number of hydrographic stations. From these data, density is calculated, and by assuming geostrophic balance, meridional currents and volume transports between stations are estimated. Surface Ekman transport (flow in the wind-driven layer, at right-angles to the wind) is estimated using the zonally-integrated wind stress from QuikSCAT satellite data. Combining the zonal integral of geostrophic transport estimates with estimates of Gulf Stream transport and the meridional component of Ekman transport, gives us an estimate of the amount of water that is moving meridionally, either northward or southward. Since mass is assumed to be conserved across the 26° N section (the amount of water that flows north must equal the amount that flows south), the total integrated transport is adjusted to be zero. The resulting quantity of interest is the overturning – the amount of water going north at shallow depths, and the equal amount of water going south at greater depths.

A recent paper using the sections up to 2004 indicated that the MOC had slowed by 30% in 40 years, from 22.9 Sv in 1957 to 14.8 Sv in 2004 (1 sverdrup (Sv) = $10^6\,m\,s^{-1}$) (see Further Reading). For comparison, the River Amazon transport is roughly 1/6 Sv. This apparent slowdown caused quite a stir. If transport has reduced by 30% in 40 years, are we in the middle of a dramatic shift in ocean circulation? At the brink of a global 'ice age'? How will we know? This controversial paper set the stage for the long-term observational project RAPID-MOC, now RAPID-WATCH (Will the Atlantic Thermohaline Circulation Halt?).

The National Oceanography Centre is one of the major partners in the RAPID 26° N monitoring system, which is a joint US/US project. The mission of RAPID is to develop a cost-effective system to monitor the Atlantic MOC continuously for a decade, from 2004 to 2014. From the observations, we then quantify the MOC and determine the major drivers of its variability. This monitoring system can be used to diagnose the state of the MOC, improve climate models, and refine risk assessments for a marked slowing of the MOC.

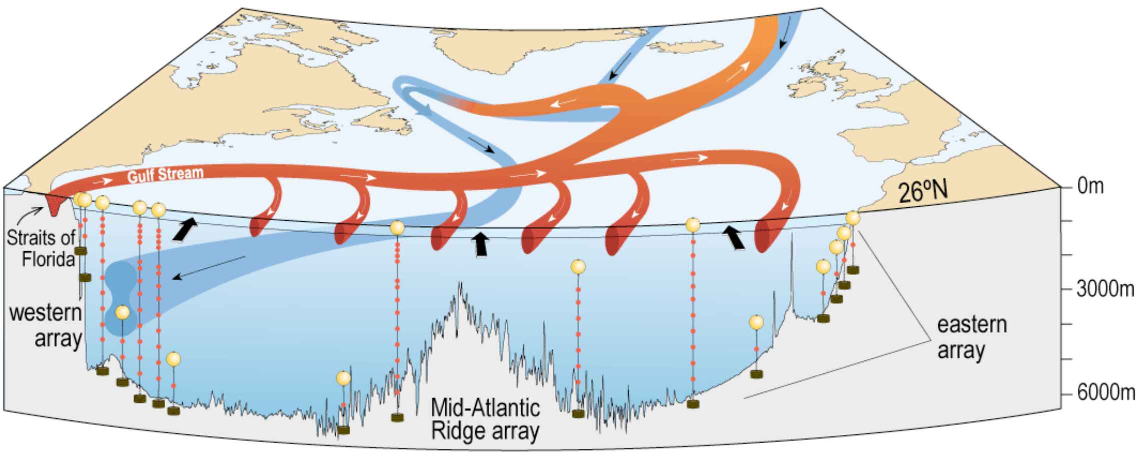
Rather than ship-based observations, this system is based on estimates of density from arrays of moorings at the eastern and western boundary of the Atlantic at 26°N (Figures 3 and 4). The same principle of geostrophic balance is applied to the moorings, but instead of calculating transports between multiple pairs of hydrographic stations, the zonally integrated transport is calculated between a single pair of density profiles created by combining density estimates from the mooring arrays off the Bahamas in the west and those off the Canary islands in the east. These data are combined with direct current measurements within 25 km of the Bahamas. Once a year, moorings are recovered and data are downloaded before moorings are redeployed for the following 12 months.

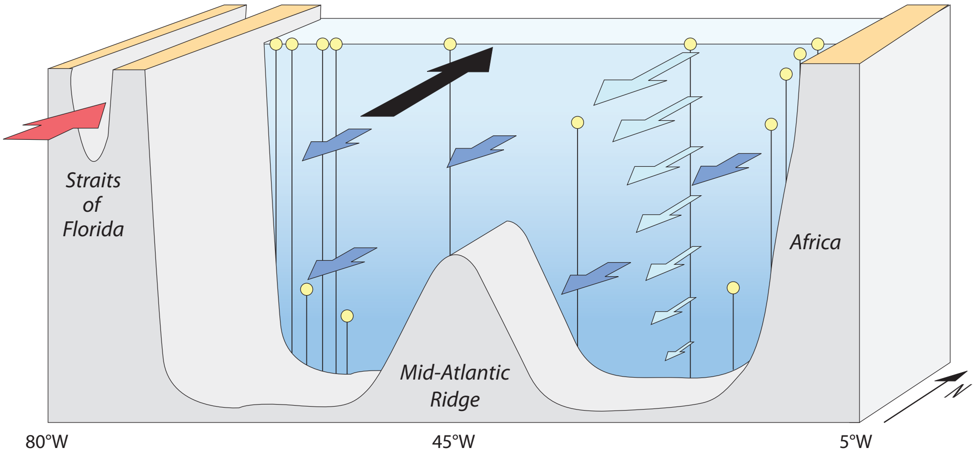
The benefit of using moored instrumentation is that it measures water properties very frequently (every 30 minutes) and continuously (since 2004). Ship-based hydrographic measurements

Figure 3 *Schematic representation of the MOC in the North Atlantic, consisting of (red) flow in the Gulf Stream/North Atlantic Current and the subpolar and subtropical gyres, (blue) the deep return flow concentrated along the western boundary, and (broad black arrows) near-surface wind-driven Ekman transport arising from the zonal wind stress. Also shown are the RAPID mooring arrays along ~26° N. Note that in the eastern and western Atlantic, where the continental slope and rise are relatively steep, the observations from a number of moorings (an array) are 'stitiched together' to provide a longer profile than would otherwise be possible.*

(Modified from an original figure by Neil White and Lisa Bell, CSIRO)

At 26°N, the surface and deep components of the MOC are both concentrated in western boundary currents





To obtain an estimate for the overturning transport at 26°N, we need to quantify four different flow components

Figure 4 *The various components of the zonal transport across 26°N: Gulf Stream transport through the Straits of Florida (red), wind-driven Ekman transport (broad black arrow) arising from the zonal wind stress, and the contribution from geostrophic currents (pale blue arrows), calculated between adjacent pairs of 'moorings' (vertical lines). Mid-blue arrows indicate a spatially constant velocity correction that ensures mass balance across the section.*

(By courtesy of Joël Hirschi)

are high-quality, revealing full zonal and depth structure, but they are expensive and slow. For the most recent transect undertaken in 2010, the ship took 55 days to cross the ocean, while measurements were being made at a total cost of tens of thousands of pounds per day. As a result, transects across the Atlantic can only be undertaken infrequently, and it is difficult to deduce long-term changes in the MOC from six estimates. However, unlike hydrographic estimates, the moored technique provides little zonal structure of the MOC transport.

The MOC at 26° N consists of broadly southward flowing water (pale blue arrows in Figure 4), the northward flowing Gulf Stream (red) and Ekman transport (black arrows), and a barotropic compensating flow (mid-blue). As before, the Gulf Stream contribution is estimated by means of the telephone cable across the Straits of Florida, and Ekman transport is estimated from QuikSCAT wind data. The compensating flow is derived from the measurements by assuming mass balance every 10 days. Together these data produce a daily estimate of overturning strength, providing an unprecedented look at the temporal variability of the MOC at 26° N.

Findings so far

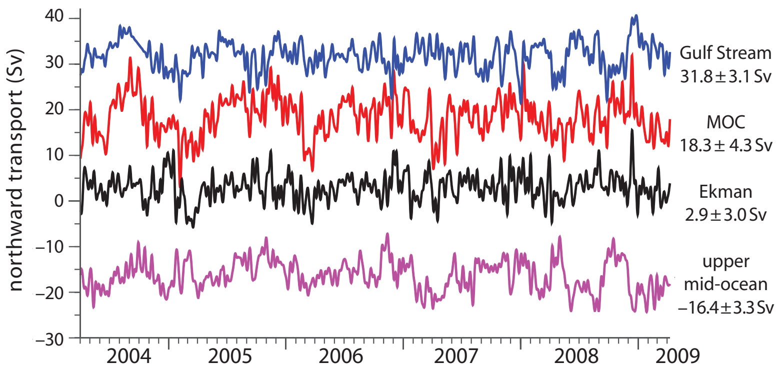
The findings to date have been surprising, and overturn the view of the ocean conveyor belt as in a relatively steady state. In the first year alone, the average overturning was 18.7 Sv but with a range of 4.0 to 34.9 Sv. This easily encompasses the entire range measured from hydrographic sections between 1957 and 2010. The MOC time-series up to April 2009 is shown in Figure 5. The MOC is the overturning transport, corresponding to approximately 18 Sv of net northward transport above 1000 m and 18 Sv of net southward flow below 1000 m. In the first 5-year period, all components varied on a wide range of time-scales, but there is no compelling evidence for a large reducing trend.

One striking finding of the observations is the strength of the seasonal cycle of the MOC. The seasonal range in the MOC is roughly 6.7 Sv (cf. Figure 5), itself a large fraction of the the range in the MOC from 1957 to 2004. In fact, a comparison of the seasons in which these hydrographic sections were occupied, indicated that most of the reducing trend was simply an aliasing* of the seasonal cycle into the long-term trend (Figure 6, overleaf). Part of the seasonal cycle is due to the influence of eastern boundary upwelling on the MOC. When the eastern and western density contributions to the zonal density gradient were examined separately, it

*Aliasing occurs when the spacing of observations is such that the deduced variability is not a true representation of reality.

Figure 5 *Time-series of Gulf Stream, Ekman, upper mid-ocean and MOC transport from 29 March 2004 to 10 April 2009. The mid-ocean contribution includes both the current meter measurements within 25 km of the Bahamas and the geostrophic contribution between arrays on the western and eastern boundaries. RAPID moorings provide the upper mid-ocean transport as the vertical integral of transport per unit depth down to the deepest northward velocity (~1100 m). MOC transport (maximum northward transport of upper-layer waters on each day) = sum of the other three components.*

The MOC time-series suggests an overturning volume of ~18 x 10^6 $m^3 s^{-1}$



An apparent decline in the strength of the MOC was actually a reflection of the times of year that measurements had been made

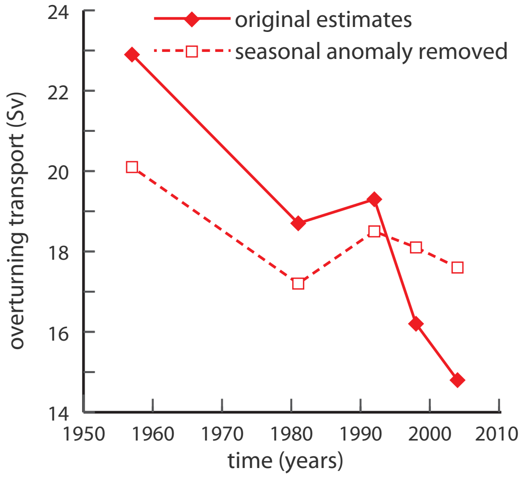


Figure 6 *Red diamonds: The overturning transport inferred from five hydrographic sections carried out in autumn 1957, summer 1982, summer 1991, winter 1998 and spring 2004. Open squares: The overturning adjusted to take into account the seasonal cycle measured by the RAPID arrays.*

(Based on a figure by Torsten Kanzow)

was found that the annual cycle of overturning is phase-locked with the variation in wind stress at the eastern boundary. In particular, upwelling-favourable winds raise the isopycnals at the boundary, increasing the net density gradient between east and west, and hence intensifying deep southward geostrophic currents.

On even shorter time-scales, large-amplitude, high-frequency variability abounds. Westward propagating Rossby waves encounter the coast near the mooring locations, and topographic waves travel rapidly northward and southward along the boundaries. The impact of eddies on the MOC is debated, however. One recent paper suggested that all variability in the MOC was due to eddy activity, and any longer term fluctuations are simply the superposition of different eddies, just as the 'beating' between two semidiurnal tides can produce the lower frequency spring–neap cycle. A second paper showed that eddy variability at the mooring locations very close to the boundaries is actually relatively weak. Modelling studies suggest that eddy energy or Rossby waves may contribute to feeding the meridional currents, in which case they are part of the signal. (See Further Reading for details of all these papers.)

Challenges ahead for RAPID

The more we learn about the MOC, the more complexity we uncover. We have made leaps in our understanding of the variability of the MOC and its seasonal cycle, and are unravelling the dynamical sources of large, high-frequency variability. However, we are only beginning to understand the low-frequency interplay between components of the MOC. For example, we do not understand why the 2008 seasonal pattern of the mid-ocean geostrophic transport deviated from previous years' observations: in 2008, it was dominated by a semiannual cycle, which was out-of-phase and significantly anticorrelated with the Gulf Stream, whereas in (all) previous years there was no relationship between the Gulf Stream and mid-ocean transport.

Adjustments in one or more components of the MOC in response to changes in another, and intrinsic seasonal and eddy variability, all modulate the behaviour of the MOC. These fluctuations directly impact the meridional heat transport which further influences sea-surface temperature and atmospheric circulation. Rapid climate change pervades palaeoclimate records, and were it to occur in the present-day world, would have devastating effects on human civilization. The global change in these palaeo scenarios appears to be due primarily to shifts in the MOC and its redistribution of heat in the climate system. The goal of RAPID is to observe the MOC strength and structure continuously, and to improve models and our understanding of the dynamics controlling MOC variability. As the record-length increases, we will have more confidence in determining longer term changes in the MOC, in particular whether it is speeding up, slowing down, or changing its basic ciirculatory pattern altogether.

Further Reading

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Eleanor Frajka-Williams is a senior research fellow with the RAPID project, based at the National Oceanography Centre in Southampton. She joined the project after completing her Ph.D at the University of Washington in Seattle, USA where she used Seagliders to study deep convection in the Labrador Sea. Her aim is to contribute to understanding of the dynamics of the MOC and the impact of future changes, both at high latitudes and within the RAPID 26 °N project. e-fraika-williams@noc.ac.uk