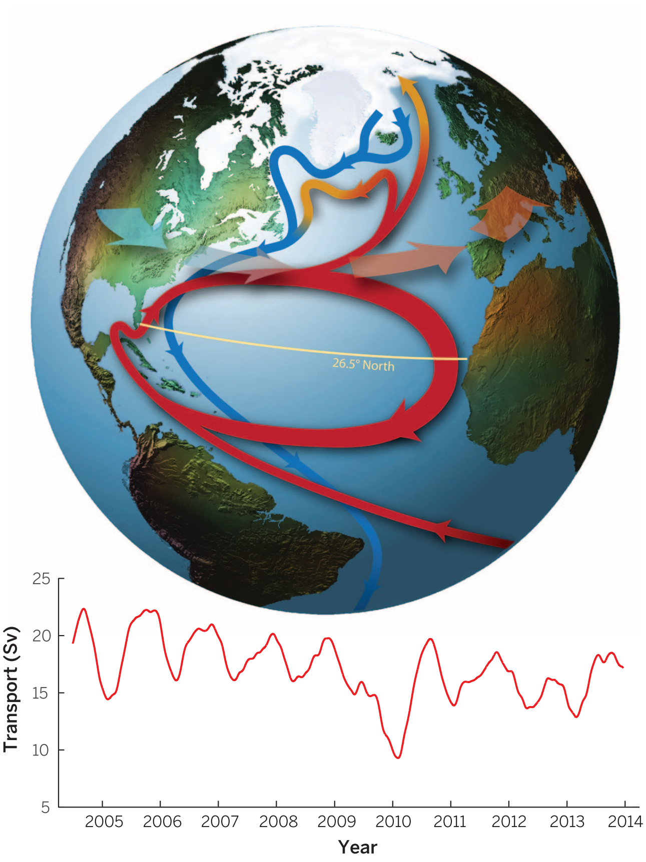
REVIEW SUMMARY

OCEAN CIRCULATION

Observing the Atlantic Meridional Overturning Circulation yields a decade of inevitable surprises

M. A. Srokosz* and H. L. Bryden

BACKGROUND: A 2002 report, *Abrupt Climate Change: Inevitable Surprises*, highlighted the North Atlantic circulation as possibly subject to abrupt change 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. As this circulation carries heat northward, giving the United Kingdom and northwest Europe a temperate climate, this generated renewed efforts to make observations of the AMOC. In particular, it led to the deployment of an observing system across the Atlantic at 26.5°N in spring 2004, which last year achieved a decade of measurements.



A simplified schematic (top) of the AMOC. Warm water flows north in the upper ocean (red), gives up heat to the atmosphere (atmospheric flow gaining heat represented by changing color of broad arrows), sinks, and returns as a deep cold flow (blue). Latitude of the 26.5°N AMOC observations is indicated. The actual flow is considerably more complex. (**Bottom**) The 10-year (April 2004 to March 2014) time series of the AMOC strength at 26.5°N in Sverdrups (1 Sv = 10^6 m^3 s^{-1}). This is the 180-day filtered version of the time series. Visible are the low AMOC event in 2009–2010 and the overall decline in AMOC strength over the 10-year period.

ADVANCES: In addition to the baseline decade of 26.5°N observations, there have been other ongoing measurements that capture components of the AMOC, some of which are not continuous or of much shorter duration. Together these observations are leading to a more complete picture of the AMOC. The 26.5°N AMOC observations have produced a number of surprises on time scales from subannual to multiannual. First, the range of AMOC variability found in the first year, 4 to 35 Sv (Sverdrup, a million cubic meters per second, the standard unit for ocean circulation), was larger than the 15 to 23 Sv found previously from five ship-based observations over 50 years. A similarly large range to that at 26.5°N has subsequently been observed at 34.5°S. Second, the amplitude of the seasonal cycle, with a minimum in the spring and a maximum in the autumn, was much larger (~6.7 Sv) than anticipated, and the driving mechanism of wind stress in the eastern Atlantic was unexpected as well. Third, the 30% decline in the AMOC during 2009–2010 was totally unexpected and exceeded the range of interannual variability found in climate models used for the IPCC assessments. This event was also captured by *Argo* and altimetry 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, with potential impacts on weather that are the subject of active research. Finally, over the period of the 26.5°N observations, the AMOC has been declining at a rate of about 0.5 Sv per year, 10 times as fast as predicted by climate models. Whether this is a trend that is a decline due to global warming or part of the so-called Atlantic Multidecadal Oscillation/Variability, inferred from sea surface temperature measurement, is also a subject of active research. There is no doubt that continuously observing the AMOC over a decade has considerably altered our view of the role of ocean variability in climate.

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OUTLOOK: The 26.5°N AMOC observations are stimulating the development of further AMOC observing systems both to the north, in the North Atlantic subpolar gyre, and to the south, in the South Atlantic. The aim is to obtain a holistic picture of the AMOC from south to north. Given the surprises and insights into the Atlantic circulation that observations have produced to date, it is not too much to expect that with the new observations there will be future "inevitable surprises." ■

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REVIEW

OCEAN CIRCULATION

Observing the Atlantic Meridional Overturning Circulation yields a decade of inevitable surprises

M. A. Srokosz[1]* and H. L. Bryden[2]

The importance of the Atlantic Meridional Overturning Circulation (AMOC) heat transport for climate is well acknowledged. Climate models predict that the AMOC will slow down under global warming, with substantial impacts, but measurements of ocean circulation have been inadequate to evaluate these predictions. Observations over the past decade have changed that situation, providing a detailed picture of variations in the AMOC. These observations reveal a surprising degree of AMOC variability in terms of the intraannual range, the amplitude and phase of the seasonal cycle, the interannual changes in strength affecting the ocean heat content, and the decline of the AMOC over the decade, both of the latter two exceeding the variations seen in climate models.

In 2002, the U.S. National Research Council Committee on Abrupt Climate Change published its findings in a book entitled *Abrupt Climate Change: Inevitable Surprises* (*1*). One process highlighted in that book, because it could possibly be subject to abrupt change in a warming climate, was the North Atlantic thermohaline circulation (THC). The work leading up to the publication of this book—together with the conclusions of the Intergovernmental Panel on Climate Change (IPCC) Working Group I Third Assessment Report (*2*) that most models showed a weakening of the THC over the 21st century—generated renewed efforts to make observations of the Atlantic Meridional Overturning Circulation (AMOC). In particular, it led to the establishment of the Rapid Climate Change program (RAPID) (*3*). A key element of RAPID was the proposal to monitor the AMOC (*4*, *5*) at 26.5°N in the Atlantic. The observing system (see schematic in Fig. 1) was deployed in March 2004 and results from the first year of observations published in 2007 (*6*, *7*). In 2014, the observing system reached a major milestone by completing a decade of operation. Here, we provide an updated description of what is known about the AMOC from recent observations and highlight some of the surprises that these observations have produced.

Background

The major characteristics of the AMOC are a near-surface, northward flow of warm water and a colder southward return flow at depth. As the ocean loses heat to the atmosphere at high latitudes in the North Atlantic, the northward-flowing surface waters become denser. These waters then sink and so form the deep return flow of the overturning circulation (Fig. 1). The AMOC transports heat northward across the equator, which makes the Atlantic different from the Indian and Pacific Oceans, where the ocean transports heat away from the equator toward the poles. The maximum northward oceanic heat transport in the Atlantic is 1.3 PW (1 PW = 10^{15} watts) at 24° to 26°N, which is ~25% of the total (atmosphere and ocean) poleward heat transport at these latitudes (*8*, *9*). Further north, at mid-latitudes, the strong transfer of heat from the ocean to the atmosphere contributes to the temperate climate of northwest Europe (*10*–*12*). In addition, changes in sea level around the periphery of the North Atlantic are related to changes in the AMOC (*13*–*15*). Therefore, future changes in the AMOC could have substantial impacts (*16*, *17*).

The importance of the AMOC for climate was highlighted by Broecker (*18*) with his "great ocean conveyor" picture, based on paleoclimatic evidence (*19*, *20*). From the results of calculations using a simple two-box model, Stommel (*21*) suggested that the circulation could switch between "on" and "off" states under appropriate forcing, such as the addition of freshwater at high latitudes (*22*, *23*). Although this picture of the circulation is now acknowledged to be too simple, the possibility that the AMOC could switch between different states has been shown to occur in more complex climate models (*24*, *25*), so that the AMOC could be bistable.

Given the importance of the AMOC, and its potential to decline and perhaps even switch off, the observing system deployed at 26.5°N in the Atlantic became the first attempt to continuously measure the strength and vertical structure of the AMOC. The measurements began on the last day of March 2004 and have continued since then (*26*). The key components of the AMOC (Fig. 1) and the methods by which they are quantified are the Gulf Stream transport through the Florida Straits measured by seabed cable; the Ekman transport calculated from wind stress; and the midocean transport measured by an array of moorings at the western and eastern boundaries and the mid-Atlantic Ridge (*27*–*29*). The first year of measurements established that the system was able to accurately measure the AMOC (*30*) and subsequent studies have confirmed this initial assessment (*31*–*33*). It is important to note that the measurements provide information not only on the AMOC strength itself but also on the major components of the circulation: Gulf Stream, Ekman, upper midocean recirculation, southward flow of the Upper and Lower North Atlantic Deep Water (UNADW and LNADW), and the northward flow of the Antarctic Intermediate Water (AAIW). In addition to RAPID, there have been other ongoing measurements of the AMOC, but these capture only part of the AMOC, or are not continuous, or are of much shorter duration. They include

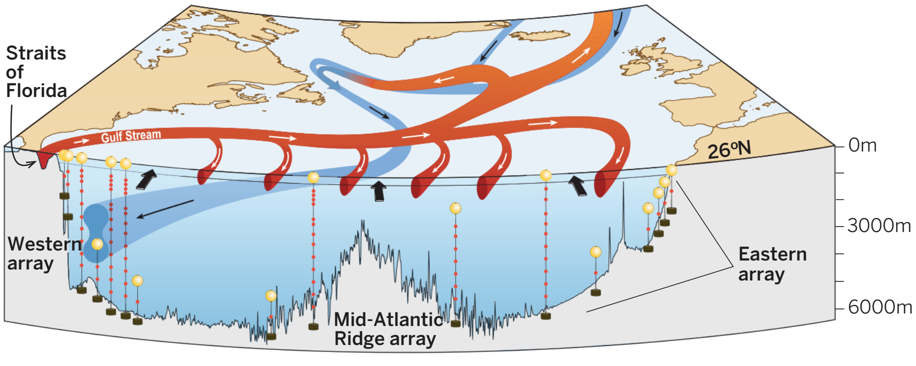

Fig. 1. Schematic showing the components of the RAPID AMOC observing array at 26.5°N in the Atlantic. The flow through the Florida Straits is measured by underwater cable, the midocean flow by the array of moorings at the eastern and western boundaries and the mid-Atlantic Ridge (using geostrophy), and the surface Ekman flow from ocean surface winds (*28*, *29*).

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the Meridional Overturning Variability Experiment (MOVE) array at 16°N (*34*), the Deep Western Boundary Current (DWBC) arrays at around 39°N (*35*) and 53°N (*36*), the 34.5°S array (*37*, *38*), the use of altimetry and Argo at around 41°N (*39*, *40*), and the Observatoire de la Variabilité Interannuelle et Décennale en Atlantique Nord (OVIDE) hydrographic sections (*41*). Recently, a new component of the AMOC, the so-called East Greenland spill jet, has been identified from a year of mooring observations (*42*), but its importance in the long-term for the overall AMOC remains to be confirmed.

The focus of this Review is on observations of the AMOC (*43*), because models still show considerable differences in their representations of the overturning circulation (*44*). Figure 2 shows the full 10-year AMOC time series at 26.5°N obtained to date by RAPID. These measurements provide insights into the changes occurring in the AMOC, which include a number of surprises on all time scales: intraannual, seasonal, interannual and multiannual.

Intraannual and seasonal AMOC variability

The first surprise was the range of values found for the strength of the AMOC during the initial year of RAPID observations. Although the annual average strength of 18.7 sverdrups (Sv) (*45*) was not unexpected, the range from a minimum of 4 Sv (February) to a maximum of 34.9 Sv (September) was a surprise (*6*). Before the deployment of the 26.5°N observing system, the five ship-based hydrographic measurements of the AMOC made at this latitude since the 1950s had shown a range of ~15 to 23 Sv (*46*), so the first year's intraannual variability exceeded the historical estimates of the AMOC. Subsequently, a similar range of intraannual variability (3 to 39 Sv) has been found in the 20 months of measurements of the AMOC made at 34.5°S (*37*).

The next surprise came from the analysis of the AMOC seasonal cycle after 4 years of RAPID observations had been acquired (*47*). Because the longer-term observations of the Gulf Stream (*27*, *48*) had shown that it exhibited a seasonal cycle of ~4 Sv with a maximum in summer, the seasonal cycle of the AMOC of ~6.7 Sv, with a minimum in the spring and a maximum in the autumn, came as a surprise. In addition, the perceived wisdom was that the seasonality in the AMOC would be dominated by wind-driven northward Ekman transport, but this was found to be small. The result that the seasonal cycle was dominated by the wind stress curl forcing at the eastern boundary came as further surprise (*47*). Results from the OVIDE analysis (*41*) of the Portugal to Greenland hydrographic section similarly show, from 1993 to 2010, a seasonal cycle with a peak-to-peak amplitude of 4.3 Sv, mostly due to the geostrophic component, with a much weaker Ekman component. The Argo and altimeter estimates of the AMOC upper limb at around 41°N from 2002 to 2009 show a small and irregular seasonal cycle (*39*).

Characterization of the seasonal cycle allowed the previous five ship-based hydrographic estimates of the AMOC strength at the RAPID latitude (*46*) to be corrected for seasonal sampling bias, because they had been acquired at different times of the year. This resulted in a reassessment of the apparent decline of the AMOC between 1957 and 2004 as partially being an artifact of the sampling (*49*).

The first 4 years of RAPID observations also confirmed the average strength of the AMOC at 26.5°N to be 18.7 ± 2.1 Sv, in agreement with the annual average for the first year. However, the result that the mean strength of the AMOC seemed to be unchanging, despite large seasonal and intraannual fluctuations, seemed at odds with the expectation that the AMOC might decline, although the time series was acknowledged to be too short at that time to draw any strong conclusions. Nevertheless, the apparent stability of the seasonal cycle paved the way to the next surprise.

Interannual AMOC variability

After having observed 5 years of relatively stable seasonal cycles of the AMOC, when the data for 2009–2010 were recovered from the 26.5°N array, another surprise was in store. From spring 2009 through spring 2010, the AMOC was found to have taken a large ~30% dip in strength before recovering later in 2010 (Fig. 2) (*50*). For the previous 5 years, the average strength of the AMOC had been 18.5 Sv, whereas in 2009–2010 it was 12.8 Sv (years are taken to run from April to March, due the initial deployment of the observing array in late March 2004). This dip in strength was also seen in the Argo and altimetry observations of the upper limb of the AMOC at 41°N but not in the 16°N observations of the deep western basin return limb of the AMOC (*51*). This raises the question of the meridional coherence of changes in the AMOC, a point to be discussed below.

The 2009–2010 dip in strength can be partially attributed to an extreme negative North Atlantic Oscillation (NAO) winter that affected the wind field, reducing—and for a period reversing (December 2009 to March 2010)—the northward Ekman transport component of the AMOC. In addition, the upper midocean recirculation component of the AMOC strengthened starting in spring 2009 before the negative NAO winter, leading to a reduction in the AMOC. Finally, the AMOC deep southward return limb flow, the so-called Lower North Atlantic Deep Water (LNADW) at a depth of 3000 to 5000 m, weakened in concert with the upper ocean northward-flowing limb. This change in AMOC strength was found to lie well outside the range of interannual variability predicted by coupled atmosphere-ocean climate models (*52*).

Because the AMOC carries ~90% of the ocean heat transport at this latitude (with the gyre circulation carrying the remainder) (*53*), this AMOC reduction had a considerable impact on the heat transport into, and the heat content of, the North Atlantic (*54*, *55*). The heat transported north by the AMOC at 26.5°N in previous years was ~1.3 PW (*53*), and this transport was reduced by 0.4 PW, resulting in cooler waters to the north and warmer waters to the south. Observations showed that there was an abrupt and sustained cooling of the subtropical North Atlantic in the upper 2000 m between 2010 and 2012, primarily due to the reduction of the AMOC. From late 2009 over a 12-month period, the ocean heat content, between the latitudes of 26.5° and 41°N, reduced by ~1.3 × 10^{22} J (*54*, *56*) and then increased again into 2011. Corresponding to this cooling of the subtropics was a warming of the tropics to the south of 26.5°N in 2010 (Fig. 3). This warming of the region of the Atlantic associated with hurricane genesis coincided with the strongest Atlantic hurricane season since 2005

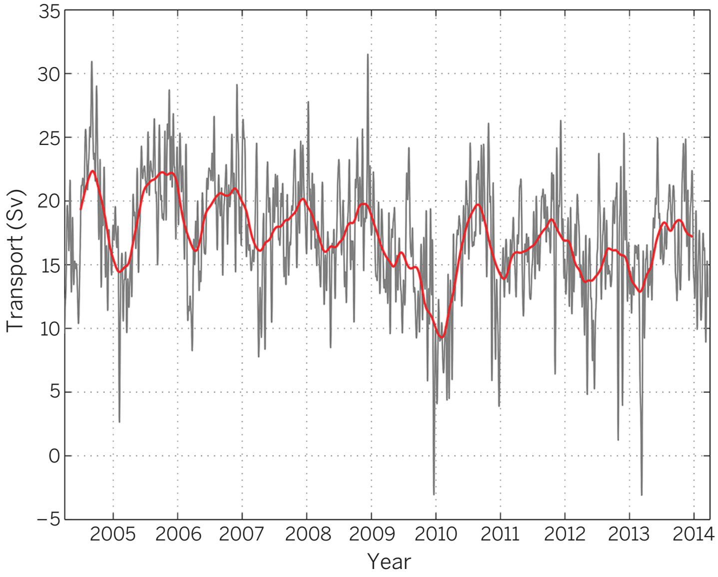

Fig. 2. The 10-year time series of the AMOC measured at 26.5°N. The gray line represents the 10-day filtered measurements, and the red line is the 180-day filtered time series. Clearly visible are the low AMOC event in 2009–2010 and the overall decrease in strength over the 10 years.

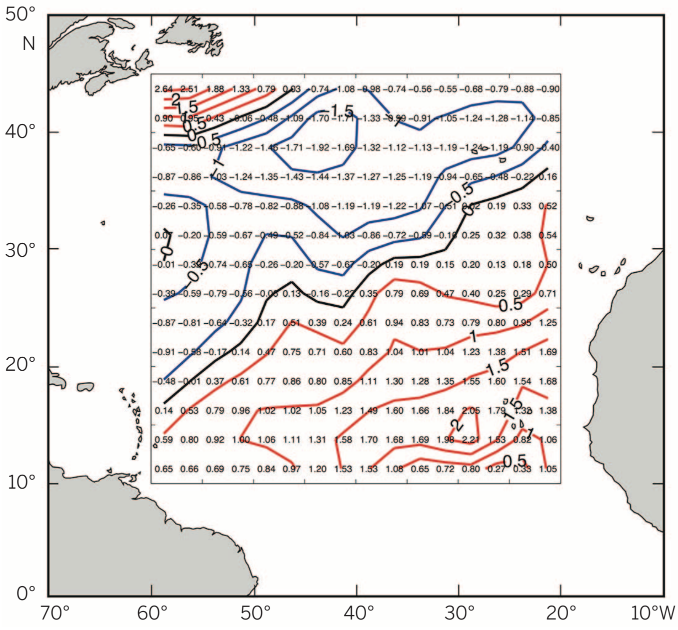

Fig. 3. North Atlantic temperature anomaly (°C) at 50-m depth, averaged for May to July 2010 at the end of the 2009–2010 AMOC slowdown event (93). Temperature data are from Argo floats, and the anomaly is calculated relative to the Hydrobase seasonal climatology. Note the cooling (blue contours) of the upper ocean to the north and warming (red contours) to the south of 26.5°N, the latitude of the RAPID observations and of the maximum northward heat transport by the Atlantic.

(as measured by accumulated cyclone energy) (57). The links between changes in the AMOC, upper-ocean heat content, and atmospheric response represent an active area of research. For example, the ocean has been implicated in the reemergence of sea surface temperature anomalies from the winter of 2009–2010 during the following early winter season of 2010–2011, which contributed to the persistence of the negative winter NAO and wintry conditions in northern Europe (58). Such behavior may lead to improved predictions of the NAO and winter conditions (59, 60).

The origin of and explanation for the 2009–2010 event remain uncertain. Various explanations have been proposed (61, 62) but so far have failed to explain the changes in LNADW (and the lack of change in the UNADW at depths between 1000 and 3000 m) (50). This, together with the fact that the event lies well outside the range of interannual variability predicted by coupled atmosphere-ocean climate models, poses a considerable research challenge.

Multiannual AMOC variability

Although the 26.5°N observing system has only just completed its first decade of observation, and it is premature to comment on decadal change, there is one further surprise that the observations have provided on the multiannual time scale over that decade. Analysis of the first 8-1/2 years of the observations has shown a decline in the AMOC over that period (April 2004 to October 2012; see also Fig. 2) (63). The estimated trend was a decline of ~0.5 Sv/year, which exceeds the decline predicted by IPCC-class climate models over the next 100 years, which is on the order of ~0.05 Sv/year (64, 65). This result is robust with respect to the inclusion or exclusion of the 2009–2010 AMOC event described above (63). Although changes in the Gulf Stream and Ekman contribute to the decline, the major components of the AMOC that are changing are increasing southward transport in the upper midocean, that is, a strengthening of the subtropical gyre recirculation and a corresponding decrease in the southward transport of LNADW (63). Earlier observations from the MOVE array at 16°N, which observes the deep western basin limb of the AMOC, found a decline in that flow of ~3 Sv over a decade (2000 to 2009) (34). In contrast, observations of the outflow from the Labrador Sea for 1997 to 2009 show no indication of a decline, but again these only measure one component of the AMOC (36). Another recent study, using a model and observations in the North Atlantic (although not direct measurements of AMOC) seems to confirm that the AMOC may be declining at the present time (66). Of course, it is possible that the decline may be part of a longer-term cycle such as the so-called Atlantic Multidecadal Oscillation (AMO) or Variability (AMV) (67), or simply decadal variability, rather than a response to climate change. This underlines the need for continuing observations of the AMOC in order to be able to distinguish between the different mechanisms that might be responsible for the observed changes (100).

Given the lack of direct observations over multiannual and longer time scales, researchers have generally resorted to the use of proxies to try to understand longer-term changes in the AMOC. Until such proxies can be validated against direct measurement of the AMOC there will always be a question regarding their ability to capture the true behavior of the AMOC. Nevertheless, here we describe two recent attempts to study the AMOC using proxies (68). First, consider the study based on the so-called OVIDE hydrographic section from Portugal to Greenland (41). This makes use of six hydrographic sections from 1997 to 2010 and a proxy based on radar altimeter and Argo measurements from 1993 to 2010 to span the gaps between the sections and extend back in time to 1993. The analysis was carried out in density coordinates and shows an average AMOC strength of 18.1 Sv, with an overall decline of 2.5 Sv over 1993 to 2010. Second, consider another recent study (69) that uses the difference between the surface temperature in the North Atlantic subpolar gyre and the whole Northern Hemisphere as a proxy for the AMOC. Based on temperature reconstructions for the past 1000 years, the study concludes that there has been an exceptional 20th-century slowdown of the AMOC. Of course, how strong a conclusion this is depends crucially on the link between the proxy and the AMOC, over what time scales that link exists, and whether it is robust.

AMOC bistability?

On a more speculative note, one possibility for future AMOC surprises is the issue of the bistability of the AMOC noted earlier. This is related to the transport of freshwater in and out of the South Atlantic (70). Observations (71) suggest that the AMOC transports freshwater southward in the South Atlantic, implying that the AMOC could be bistable with on and off modes (72). Most climate models exhibit northward freshwater transport, seemingly at odds with the observations, implying that the AMOC is stable (73). Some recent climate model results show that their freshwater transports can match the southward freshwater transport in the observations, but in such climate models the AMOC does not shut down under greenhouse gas forcing (64). In point of fact, most climate models do not include a dynamically interactive Greenland ice sheet, so they are unlikely to correctly account for freshwater input into the Atlantic from Greenland melting (74, 75). In addition, the Arctic Ocean supplies freshwater to the North Atlantic, which would affect the stability of the AMOC (76). If the rate of freshwater input were to be greater than currently anticipated, that could lead to unexpected changes in the AMOC. Thus, there is a possibility that the ocean might respond in a way that most climate models cannot. This point has been made previously from a paleoclimate perspective (77, 78), because paleoclimatic evidence suggests that the AMOC can undergo rapid changes that are difficult to reproduce with climate models.

Recent impacts of AMOC variability

The possible impacts of AMOC variability have been discussed in previous reviews (5, 94, 98) so will not be detailed here. However, much recent work has focused on the effect of changes in the AMOC on sea levels on the eastern seaboard of the United States, so we will briefly discuss that work. As noted earlier, the AMOC affects the sea level around the periphery of the North Atlantic and specifically along the U.S. east coast (*13*–*15*, *79*), although this a point of some controversy (*15*, *80*–*83*). A reduction in the AMOC leads to a rise in sea level along the east coast of North America. Recently, the major reduction in the AMOC in 2009–2010, combined with a negative NAO event, has been shown to lead to an extreme sea level rise on the northeast coast of North America (*84*). Within a 2-year period the sea level was found to rise by 128 mm, a 1-in-850–year event. The authors state that the event caused persistent and widespread coastal flooding and beach erosion almost on a level with that due to a hurricane. This suggests that a longer-term downturn in the AMOC, which might be in progress, could have important impacts on the U.S. east coast.

Another possible effect identified recently is the role that the AMOC may have in the present so-called "hiatus" in global warming (*85*). Here, the AMOC is invoked to explain increased heat storage in the North Atlantic, thus reducing the rate of global temperature rise. However, other explanations for the hiatus involving the oceans have been suggested (*86*), so the role of the AMOC in the hiatus is uncertain.

Unanswered questions and future surprises?

Despite the observational efforts over the past decade, many questions remain unanswered. First, the AMOC is changing, but will these changes persist or will the AMOC "bounce back" to its earlier strength? Second, are the changes being observed at 26.5°N coherent latitudinally in the Atlantic? Third, was the 2009–2010 decrease in the AMOC unusual or not? Fourth, is the AMOC bistable? Could it "flip" from one state to another (*87*)? Finally, and perhaps most important, what are the effects of changes in the AMOC?

The existence of the 26.5°N AMOC observations is stimulating the development of further AMOC observing systems, both to the north in the North Atlantic Subpolar Gyre and to the south in the South Atlantic. This is an acknowledgment that the 26.5°N observations, although providing many novel insights into the AMOC, cannot by themselves fully characterize the circulation from south to north in the Atlantic. As a result, in 2014 the Overturning in the Subpolar North Atlantic Program (OSNAP) (*88*) deployed instruments, along a line from Canada to Greenland to Scotland, to observe the AMOC in the subpolar gyre, complementing the 26.5°N observations in the subtropical gyre. At the same time, a South Atlantic MOC observing system is being deployed gradually at 34.5°S. Known as the South Atlantic MOC Basin-wide Array (SAMBA) (*89*), this will observe the so-called Agulhas ring corridor (which is important for transfer of heat and salt from the Indian to the Atlantic Ocean) and the eastern and western boundary currents. Another complementary measurement of the AMOC upper limb is that being made by combining data from Argo floats (which measure temperature and salinity down to 2000 m) and radar altimeter sea surface height data (*39*–*41*). This approach is limited to regions where the main upper ocean flows are in water depths of 2000 m or greater, thus allowing use of Argo.

Studies are beginning to be made to try to link observations of the AMOC at different latitudes in order to understand its meridional coherence and so obtain a holistic picture of the circulation (*90*–*92*). For example, these suggest coherence between measurement of the AMOC between 26.5°N and 41°N on near-annual time scales, with 41°N leading 26.5°N by approximately a quarter of an annual cycle.

Each additional year of observations made by the AMOC observing systems contributes to a better understanding of climate variability and the ocean's role in that variability. Irrespective of whether the present decline in the AMOC continues, ends, or reverses, the observations will provide a stringent test of different climate models' abilities and whether their projections will prove valid. Likewise, another event similar to that which occurred in 2009–2010, leading to ocean heat content changes with possible links to NAO winter weather, tropical hurricanes, or sea level rise could stimulate further advances in seasonal forecasting.

The AMOC observations over the past decade have provided both surprises and insights into the Atlantic circulation, but many questions remain unanswered. Perhaps it is not too much to expect that, together with the new observations being made at various latitudes, there are likely to be further "inevitable surprises."

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