PAPER

Measuring the Atlantic Meridional Overturning Circulation

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ABSTRACT

The Atlantic meridional overturning circulation (AMOC) plays a crucial role in redistributing heat and salt throughout the global oceans. Achieving a more complete understanding of the behavior of the AMOC system requires a comprehensive observational network that spans the entire Atlantic basin. This article describes several different types of observational systems that are used by scientists of the National Oceanographic and Atmospheric Administration and their partners at other national and international institutions to study the complex nature of the AMOC. The article also highlights several emerging technologies that will aid AMOC studies in the future.

Keywords: Atlantic Ocean, meridional overturning circulation, observational systems, technological advances

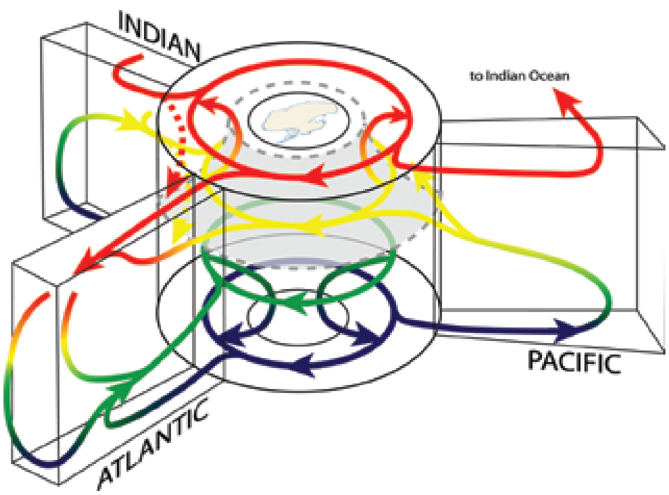
Introduction

The circulation of the world's oceans is complex, set into motion by wind forcing, atmospheric heating, and fresh water input. This global ocean circulation in turn can influence the atmosphere, changing the everyday weather and long-term climate. One of the most important parts of the ocean circulation system is the meridional overturning circulation (MOC). The MOC transfers water, heat, and salt northward and southward within individual ocean basins and eastward and westward between all of the ocean basins (Figure 1), playing a major role in global and regional heat and salt budgets. The Atlantic Ocean plays a fundamental role in the MOC because of its unique geography. The semi-enclosed nature of the northern North Atlantic basin requires that newly formed cold, dense ocean waters sink and slowly spread southward through the Atlantic Ocean (Figure 2) before they can reach the other ocean basins via the Southern Ocean (Figure 1). Over most of the basin, the Atlantic component of the MOC (hereafter AMOC) can be characterized as a vertical and north-south circulation cell with cold, dense water moving southward at depth and warm, light waters moving northward near the surface (black arrows in Figure 3). Below this main cell is a deeper, weaker cell where dense waters formed near Antarctica move northward, mix with deep waters formed in the North Atlantic, and then return southward (red arrows in Figure 3). This simple picture does not capture the wide range of intense variations in the AMOC system that can occur on many time scales. In particular, the strength of the overturning circulation at a given latitude can change on daily, weekly, annual, interannual, and longer time scales (e.g., Cunningham et al., 2007; Dong et al., 2009; Send et al., 2011; Zhang et al., 2011; Meinen et al., 2013; Smeed et al., 2014), and on some of those time scales there may be different changes experienced at different latitudes.

Numerical climate models suggest that changes in the AMOC and the amount of heat and salt carried by the AMOC can have a pronounced impact on a variety of socially important

FIGURE 1

Schematic of the global MOC, showing how the large-scale motion of warm upper water (red), cooler subsurface water (yellow, green), and cold deep water (blue) connect into a global conveyor belt connecting the Atlantic, Pacific, and Indian Oceans in the Southern Ocean around Antarctica (center of schematic). Arrows changing from one color to another represent transformation of water from one type to another. (Color versions of figures are available online at: http://www.ingentaconnect.com/content/mts/mtsj/2015/00000049/00000002.)

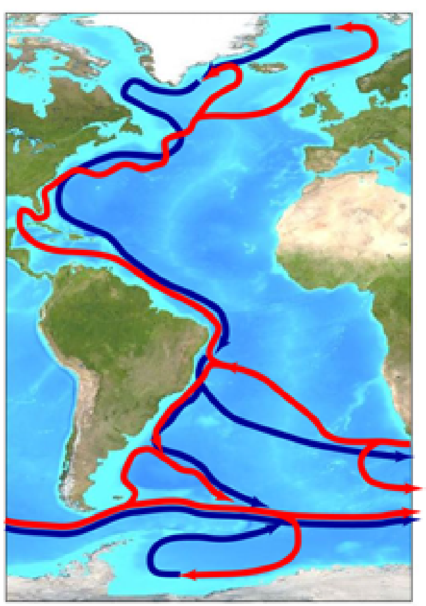


2001; Vellinga & Wood, 2002; Sutton & Hodson, 2005; Zhang & Delworth, 2006; IPCC, 2013). Quantifying and understanding how the AMOC changes over time is therefore crucial for improving our knowledge of how the climate system functions and for helping society assess future climate change.

Given the rich, multiple time-and-space-scale nature of the AMOC system, achieving a more complete understanding of its behavior requires a comprehensive observing system that spans the entire Atlantic basin (cf. Figure 4). This article describes many of the different types of measurement systems that are used by scientists of the National Oceanographic and Atmospheric Administration (NOAA) together with their partners at other national and international institutions to study the complex nature of the AMOC. Additional information on many of these observational systems can be found in the global ocean observing system article by Piotrowicz and Legler (2015) that appears in

FIGURE 2

Idealized schematic of the main AMOC cell. Blue arrows indicating the cold, dense water moving southward and exiting the Atlantic in the lower limb of the cell. Red arrows indicate the warm, light waters returning to the Atlantic and moving northward in the upper limb of the cell.



climate phenomena, including Atlantic hurricane activity, precipitation, and air temperature variability over North America and Western Europe, and changes in African and Indian monsoon rainfall (e.g., Enfield et al.,

FIGURE 3

Volume of water transported by the AMOC in units of Sverdrups (Sv). Color shading shows the average volume of water transported over years 101–150 of a high-resolution NOAA/GFDL coupled climate simulation (CM2.5, Delworth et al., 2012). The contour interval is 2 Sv (black lines). Thick black contour indicates zero mean transport. Black arrows indicate the direction of the flow in the main AMOC cell, and red arrows indicate the direction of the flow in the deeper AMOC cell.

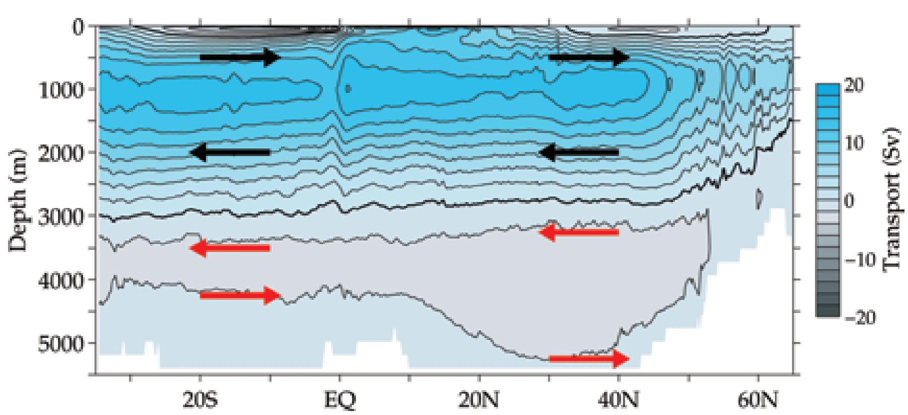
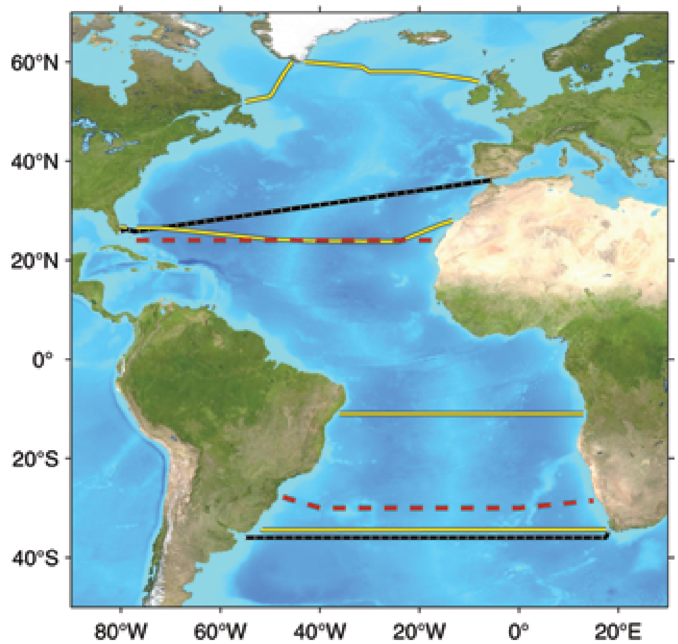


FIGURE 4

Map of existing trans-basin AMOC measurement systems. Yellow solid lines indicate locations of moored arrays, red dashed lines indicate repeat CTD transects, and black dotted lines indicate repeat XBT transects.



this issue. Emerging measurement technologies being developed by NOAA and its partners to measure the AMOC in new and innovative ways will also be discussed. Finally, a brief overview is given of insights already gleaned from existing AMOC observations and how they are being used to improve model simulations and projections.

Past and Present AMOC Measurement Systems

The strength of the AMOC is typically defined as the total volume of water carried northward by the upper limb of the main cell at any given time (northward black arrows in Figure 3) and is commonly measured in units of "Sverdrups." The upper limb strength is equivalent to the total southward volume transport in the lower limb of the main cell (e.g., Send et al., 2011), but because of its shallowness the upper limb is easier to observe with the majority of the measurement systems described here and will be the focus of this article. Each Sverdrup (Sv) is the equivalent of 1 million cubic meters of water moving past a location per second or approximately the combined flow of all the world's rivers into the oceans. The total amount of water moving north by both the main AMOC cell and the weaker cell below is essentially equal to the amount of water moving south (Figure 3). Because of this, the total volume of water transported by the AMOC across a constant latitude line is typically near zero whereas the maximum northward volume transport in the upper limb of the main cell is close to 20 Sv when averaged over time scales larger than a year (e.g., Cunningham et al., 2007; Lumpkin & Speer, 2007; Dong et al., 2009; Meinen et al., 2013; Smeed et al., 2014).

To measure the upper limb volume transport, one needs to have a way of estimating the north-south velocity as it varies with depth and longitude all the way across the basin from coast to coast. For example, at the latitude of Florida, that means measurements must be made all the way from Florida to northwest Africa. The measurements can then be summed across the basin and from the surface of the ocean down to the bottom of the upper limb where the water flow changes from northward to southward (typically around 1,000 m depth; see Figure 3). The estimates of north-south velocity that NOAA and its national and international partners make are obtained using various types of measurement systems. In this section, we describe five different types of AMOC measurement systems: repeat hydrographic surveys, subsurface moored instruments, a submarine cable, Argo profiling floats, and satellite-measurement system syntheses. These measurement systems either directly measure north-south velocity or make temperature, salinity, and/or sea surface height (SSH) measurements from which density gradients are estimated. These density gradients can then be used to estimate the buoyancy-driven component of velocity and can be combined with ancillary data to provide an estimate of the total velocity.

The optimal (i.e. most accurate) observing system for the AMOC, as well as the heat and salt carried by the AMOC, would directly measure the full water column temperature, salinity, and north-south velocity along a latitude from coast to coast and from surface to seafloor with very high spatial and temporal sampling. For example, horizontal scales might be as close as 10 km (or a fraction of a degree of longitude) spacing, vertical scales might be on the order of 100 m (tens of meters near the surface and sea floor), and temporal scales would be as often as daily measurements. These measurements would ideally be repeated at multiple latitudes in the North and South Atlantic Ocean and be sustained for long enough to resolve both higher-frequency changes to the AMOC (daily to annual) that can obscure climate critical signals and the slower climate-relevant (interannual to multidecadal) AMOC variations. However, no single observing system can do all of these things simultaneously without costing a prohibitive amount of money and imposing significant logistical constraints (e.g., personnel and/or ship-time requirements). Hence, compromises must be made to obtain the best cost-effective synergy among the different platforms. The observational systems described in the sections that follow are best used when the positive characteristics and insights gained from the individual platforms are taken together to produce synthesized estimates of the AMOC.

Repeat Hydrographic Surveys

CTD Repeat Hydrographic Surveys

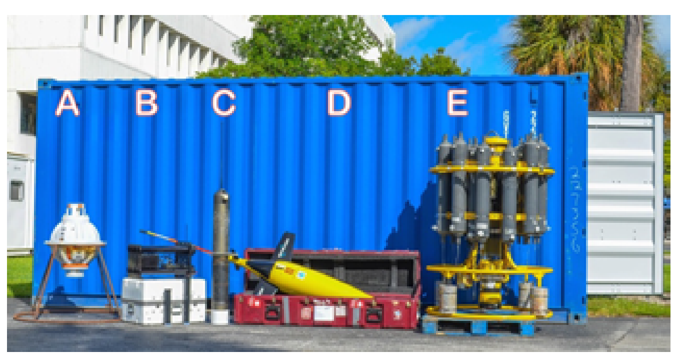
The United States Repeat Hydrography CO_2/Tracer Program (http://ushydro.ucsd.edu) is a systematic and global re-occupation of hydrographic sections selected based on their historical record and geographic importance for capturing ocean circulation features. The measurements made on these cruises span all of the ocean basins and the full-depth water column, with measurements of the highest possible accuracy, attainable only with research ships and ship- or shore-based specialized analytical instruments.

The program aims to reoccupy selected trans-basin sections previously occupied over the last 50 years to document changes in concentrations of carbon, nutrients, oxygen, and trace gases and changes in the transport of volume, heat, and fresh water in the ocean. The sections are occupied approximately every decade by United States (NOAA and NSF) and international investigators, and each section typically takes 1 to 2 months of ship time to complete. Despite numerous technological advances over the last several decades, ship-based hydrography remains the only method for obtaining high-quality, high-spatial, and vertical resolution measurements of a suite of physical, chemical, and biological parameters over the full water column. These are accomplished through the use of a metal frame (rosette) that can be lowered to 6,000 m depth carrying sensors to measure the conductivity (from which salinity is calculated), temperature, and depth (CTD). The CTD frame (Figure 5E) is also used as a platform for other equipment that can be mounted on the frame. This typically includes upward and downward looking Acoustic Doppler Current Profilers (ADCPs) to measure water velocity, and approximately 24 Niskin bottles to collect water samples at depth for later chemical analysis (Figure 5E). The sampling depths can be user selected in real time and can span the full water column, and the horizontal spacing between stations is at most 30 nautical miles but can be as fine as 5 nautical miles within 1 to 2° of the coasts and over mid-ocean ridges.

For the Atlantic sections shown in Figure 4, these velocity, temperature, and salinity observations can be used to determine a decadal snapshot (i.e., all of the points are sampled within the time it takes for the ship to complete the section) of both the total and buoyancy-driven flow of water across each section and, thus, the strength of the AMOC when the section was collected. Individual chemical species and water properties can also be used to estimate the strength of the large-scale circulation by providing the time since the water was last exposed to the atmosphere or was last in a water mass formation region such as the North Atlantic or the

FIGURE 5

AMOC measurement technologies including (A) a PIES mooring, (B) an XBT autolauncher and two canisters containing XBT probes, (C) an Argo float, (D) an underwater glider, and (E) a CTD frame with Niskin bottles and two ADCPs.



Antarctic Oceans. Hence, these observations provide both a direct and an indirect estimate of the AMOC through changes in the physical properties and chemistry of the oceans, respectively. These data are often incorporated into inverse models, which blend numerical models and observations to produce global estimates of the MOC strength (e.g., Ganachaud, 2003; Lumpkin & Speer, 2007). While CTD repeat surveys represent the "gold standard" for hydrography, they require significant resources in terms of personnel and ship time and are typically only occupied once a decade.

XBT Repeat Transects

An expendable bathythermograph (XBT) is a probe that is dropped from a ship and measures the temperature as it falls through the water (Figure 5B). The electronic circuit for measuring the water temperature is comprised of a thermistor in the head of the probe and a very thin twin-wire that connects the probe to the data acquisition system on the ship. The probe is designed to fall at a known rate, so that the depth of the temperature profile can be inferred from the time after it enters the water. In a joint effort between research and government institutions and the private industry, XBTs are usually launched from cargo, research, and cruise ships. Deployments can be made using manual or automatic launchers (auto-launcher shown in Figure 5B). Currently, XBTs are mostly deployed along 50 fixed transects that have been recommended by the international scientific and operational community.

XBTs are widely used to observe the vertical thermal structure of the upper ocean at very high vertical resolution (approximately 0.7 m). The typical maximum sampling depth is 800 m. Before the introduction of Argo profiling floats, XBTs constituted more than 50% of the global ocean thermal observations. Currently, the 15,000 to 20,000 annual XBT observations represent approximately 15% of global temperature profile observations. Temperature observations derived from XBTs are used for repeat monitoring of the thermal structure and volume transport of surface and subsurface (to 800 m deep) currents, in particular surface boundary currents, and to estimate the meridional volume and heat transport across trans-basin transects.

Two Atlantic zonal XBT transects (black dotted lines in Figure 4), which began in the mid-1990s to early 2000s, were originally chosen to monitor the upper ocean temperature across the center of the subtropical gyres. Data from these transects are now used to assess the strength of the AMOC and the heat transport by the AMOC (e.g., Garzoli & Baringer, 2007; Dong et al. 2009; Johns et al., 2011; Garzoli et al., 2013). These transects are occupied by ships crossing the Atlantic approximately four times a year near 30°N between Florida and the Straits of Gibraltar and near 35°S between South America and South Africa. XBTs are used to capture snapshots of the upper-ocean currents contributing to the AMOC at very high horizontal resolution (approximately 25 km spacing). Each transect requires 1 to 2 weeks of ship time and one technician, thereby reducing ship time and personnel requirements and allowing the transects to be occupied four times a year. As XBTs do not directly measure salinity or sample below 800 m depth, ancillary information from other observing systems (e.g., Argo, CTD, etc.) are used to complete the AMOC calculation.

Subsurface Moored Instruments

Time series measurements from instruments moored in the ocean play a critical role in observing the AMOC, producing continuous hourly or daily records that are used to understand both the lower- and higher-frequency variations of the AMOC. Moored instruments fall into two categories, direct and indirect measurement systems, and NOAA and its partners use both types of system in the Atlantic Ocean. Since 2004, the joint United States/United Kingdom array at 26°N (e.g., Cunningham et al., 2007; Meinen & Garzoli, 2014; Smeed et al., 2014) has utilized four types of these measurement systems: a submarine cable (discussed in the next section), dynamic height moorings, current meter moorings, and pressure-equipped inverted echo sounders (PIES). Dynamic height moorings involve a series of temperature-salinity-pressure sensor triplets (similar to the measurements made by the CTD described in CTD Repeat Hydrographic Surveys) connected at several depths along a wire that stretches from 50 m below the surface down to the ocean bottom. Current meter moorings are similar, but the instruments on the mooring are acoustic devices that measure the ocean velocity past the sensor via Doppler shifts. PIES (Figure 5A) provide bottom pressure measurements, which yield indirect estimates of bottom velocity or direct estimates if the mooring is augmented with a current meter that measures velocity 50 m above the seafloor (C-PIES). PIES and C-PIES also provide observations of the round-trip full-depth acoustic travel time that can be combined with hydrographic data from the region (e.g., CTD, Argo) to indirectly estimate full-depth temperature and salinity profiles. All of these instruments have strengths and weaknesses associated with cost and accuracy and which fields they measure directly or must infer through use of ancillary information.

The developing international (United States, Argentina, Brazil, France, and South Africa) trans-basin AMOC array at 34.5°S utilizes a similar array of current meters, PIES, C-PIES, and dynamic height moorings to capture AMOC variability at the entrance/exit of the Atlantic (e.g., Meinen et al., 2013; Ansorge et al., 2014), and new trans-basin arrays have recently been deployed in the high latitude North Atlantic (United States, United Kingdom, Canada, Germany, and the Netherlands) and in the low latitude South Atlantic (Germany). Further observations of AMOC components are being made at numerous locations around the Atlantic (e.g., Send et al., 2011; Toole et al., 2011; Elipot et al., 2013). The international flavor of these projects highlights the fact that subsurface moored arrays are typically the most costly systems for observing the AMOC, both in terms of equipment and ship time requirements, and as such they can be deployed in only a limited number of strategic areas. For example, many of the moorings are deployed near the coasts and only a few moorings are located in the interior near ocean ridges such as the Mid-Atlantic Ridge.

Submarine Cable

Much of the warm upper limb of the AMOC is carried by the northward western boundary current, which at 26°N is constrained to pass between Florida and the Bahamas as the Florida Current. This has led to an unusual measurement technique that researchers at NOAA pioneered in the 1980s (e.g., Baringer & Larsen, 2001)—a system that for various physics reasons is only really practical in the Florida Straits. A submarine cable, formerly used for telephone communications between the United States and the Bahamas, is used to capture daily estimates of the volume transport by the Florida Current through an innovative use of basic electromagnetic theory. The salt ions in the seawater carried by the Florida Current create an electric field when they move through the magnetic field of the Earth. By measuring the voltage induced on the old telephone cable, an estimate of the volume transport of seawater over the cable is produced. These cable-based observations form an integral part of the longest living and most complete trans-basin AMOC observing system at 26°N (see Subsurface Moored Instruments). Calibration of the voltages into volume transport is periodically tested through comparison with ship-based sections using dropsondes (free-falling floats equipped with Global Positioning System antennas) and lowered-ADCPs, illustrating again the necessity of using many different technologies to capture important AMOC measurements. As this system does not measure temperature or salinity, ancillary measurements are also needed to estimate heat or salt transport by the Florida Current.

Argo Floats

The Argo array (e.g., Roemmich et al., 2009) is a global set of more than 3,000 free-drifting floats (designed to provide a nominal 3° by 3° horizontal resolution) that sample the upper global ocean to a maximum pressure level of 2,000 decibars (dbar). The data come from battery-powered autonomous floats (Figure 5C) that spend most of their life drifting at a "parking depth" (nominally 1,000 dbar) where they are stabilized by being neutrally buoyant. At typically 10-day intervals, the float descends from the "parking depth" to 2,000 dbars to begin sampling, and then rises to the surface over a 6-h period while measuring temperature and salinity. Using the Argos satellite transmission system, the float sits on the surface for 12 h awaiting a satellite to pass over its position, so that it can transmit its data to satellite. With the advent of Iridium technology, the satellite transmissions can occur in a much shorter time window (a few to 30 min) and the float can spend less time at the surface. In addition, it is possible to communicate and exchange information with the float and even alter mission parameters via Iridium technology. After transmission the float returns to its "parking depth," until the cycle is repeated. Floats are designed to make about 150 such cycles during their lifetime. The distance the Argo float drifts during the 10-day period also allows for estimation of the drift velocity at 1,000 dbar.

Argo has revolutionized the way temperature and salinity profiles are obtained in the global ocean. However, for applications such as estimating the strength and variability of the AMOC, ancillary observations are needed. The present generation of Argo floats are configured to dive down to a maximum pressure of 2,000 dbar (approximately 2,000 m depth) in the open ocean, and as such they do not typically sample in shallow regions like the continental shelf or the upper part of the continental slope, nor can they observe at depths below 2,000 m depth. Hence, they do not resolve the contributions to the overturning circulation from boundary currents and interior currents below 2,000 m depth. In addition, the Argo floats are passive drifting floats that follow ocean currents, and gaps in data coverage can occur. To overcome these limitations, ancillary hydrographic observations collected on the continental shelf and upper slope (e.g., mooring, CTD, XBT, and altimetric data) are used to complete the AMOC calculation by providing data where the Argo float data does not exist.

Satellite Measurement System Syntheses

Satellite measurements with their globally spatially unbiased coverage have been widely used to aid in estimating the AMOC in various ways, and they are essential components of the global ocean circulation observing system. Blended wind products merge the existing satellite scatterometer and microwave radiometer observations to generate multi-decadal wind speed or wind stress data sets (e.g., Atlas et al., 2011). These satellite-based wind products are used to estimate the wind-driven component of the AMOC for all of the measurement systems mentioned above, and they provide crucial information about the wind-driven near-surface flow across the entire basin.

In addition, satellite altimeter measurements of SSH variations can be combined with independent oceanographic observations, such as those from XBTs or Argo profiling floats, to estimate the AMOC at various latitudes (e.g., Willis, 2010). This is possible because SSH variations can be closely linked with changes in the integrated upper ocean temperature (i.e., heat content) or density profiles (e.g., Willis, 2010; Schmid, 2014) at many latitudes. Statistical relationships can then be constructed, which allow researchers to infer subsurface temperature or density profiles from satellite altimeter measurements. These reconstructed subsurface temperatures or densities provide a means to estimate the AMOC following the same methodology applied to hydrographic data from CTDs, XBTs, moorings, or Argo floats. These altimetry-based estimates of the AMOC can then be used to investigate temporal and spatial variations in the AMOC over the entire altimetry period (1993 to present) at weekly or monthly intervals and at various latitudes. However, this measurement technique works best in regions where independent oceanographic observations (e.g., XBTs, Argo, etc.) exist to create significant statistical relationships.

Emerging AMOC Measurement Technologies

The existing observational systems provide a wealth of information about the spatial and temporal variability of the AMOC. However, there is always a need to seek out more efficient, accurate, and cost-effective measurement technologies. Furthermore, the existing systems do not adequately sample the deep ocean at the spatial and temporal resolution needed, and new measurement technologies are required to address this gap in data coverage.

Deep Argo

As noted above, observations of subsurface changes in the temperature, salinity, oxygen, and other quantities can be used to infer changes in the state of the AMOC. For example, the abyssal ocean (depths greater than 4,000 m in all the deep ocean basins) stores a significant amount of heat, and warming has been detected across large parts of the global abyssal oceans since 1990 (e.g., Purkey & Johnson, 2010). Freshening of the bottom waters has also been observed around Antarctica (Rintoul, 2007; Purkey & Johnson, 2013). These changes in water properties represent a significant contribution to both heat and fresh water content changes and SSH variability. One instrument being developed and tested to expand temperature and salinity observations below 2,000 m is the Deep Argo float.

The Deep Argo program aims to extend the vertical range of the Argo profiling floats to depths of as much as 6,000 m with a repeat profiling cycle of 10 to 30 days. The proposed array would include about 1200 floats covering the globe with a nominal 5° by 5° horizontal resolution. This target design would greatly aid studies of decadal changes in heat and fresh water content in the deep ocean.

Underwater Gliders

Underwater gliders (Figure 5D) have been in use for roughly two decades to study many upper-ocean phenomena. They are autonomous devices that can change their buoyancy similar to the method used for Argo floats, but underwater gliders have "wings" and can be programmed to "fly" and follow a trajectory as opposed to being a passive drifting float. Underwater gliders can provide higher-resolution temperature and salinity data along their programmed trajectories and are typically configured to sample the upper 1,000 m of the water column.

Recent advances in underwater glider design are making them more feasible for use in AMOC research. Researchers at Scripps Institution of

Oceanography and other institutions have pursued using gliders as a means to retrieve data from subsurface moorings. For example, the underwater glider can be parked near a mooring site and acoustically collect data from ocean bottom instruments. When the glider surfaces, the data can be transmitted via satellite. Deep gliders that can sample down to 6,000 m are also in development and have been considered as possible replacements for tall subsurface moorings, although gliders at present have a low maximum swimming speed, so mooring replacement is only feasible in low-flow regions. At present gliders are too costly (both equipment and piloting are expensive) to deploy in a high-resolution global array. However, they can provide a cost-effective observational system for certain AMOC-related research goals. In particular, they can be used to survey certain boundary current regions with high horizontal and vertical resolution.

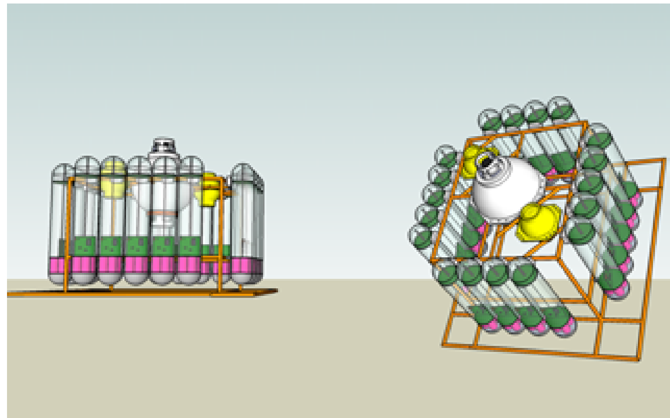
Data Pods

The development of instruments able to telemeter their data to a ship over the site, such as what exists for PIES and C-PIES (see Subsurface Moored Instruments), was a significant advance toward the solution of obtaining near real-time data from bottom-moored instruments. Given the high costs of operating research vessels, however, telemetering data from instruments deployed in remote locations still poses a significant challenge.

NOAA is developing a system utilizing expendable "data pods" to obtain data from subsurface instruments called the Adaptable Bottom Instrument Information Shuttle System (ABIISS). The ABIISS frame is mounted on the seafloor and with data pods that collect data from a central instrument (Figure 6). The data pods self-release at a user preprogrammed interval (e.g., every 3 or 6 months), reach the surface, and transmit their data back to land via satellite. The main advantage of this system is that deployments could be made in remote areas, with a substantial reduction in ship time associated with mid-deployment data retrieval. Another advantage of this system is its adaptability, as it has been designed to accommodate different types of bottom-moored instruments (e.g., PIES, ADCPs). Data pod technology shows great promise and can reduce the cost associated with transit to moorings deployed in the interior (e.g., near ocean ridges) for mid-deployment data retrieval. Several other institutions around the world are working towards data pod systems, but development is still at the prototype stage and more deep-water deployments are needed before these systems become common.

FIGURE 6

Conceptual drawing of ABIISS mooring with 18 data pods, data controller, and a PIES mounted in the center.



Broader Impacts

The different types of existing and emerging measurement systems described in this article (see Table 1) complement one another, and each provides trade-offs and advantages for different aspects of AMOC study which are described in Past and Present AMOC Measurement Systems. These trade-offs and advantages include better spatial and/or temporal coverage due to technological design vs. lower financial costs or fewer logistical constraints (e.g., ship-time, personnel requirements). For this reason, present AMOC observing systems involve a patchwork of different measurement systems.

Observations collected thus far from the AMOC measurement systems described in Past and Present AMOC Measurement Systems have already given many important AMOC insights. For example, the time mean and time variability of the AMOC and components of the AMOC circulation from daily to decadal time scales have been characterized at many latitudes (e.g., Cunningham et al., 2007; Dong et al., 2009; Send et al., 2011; Zhang et al., 2011; Meinen et al., 2013; Smeed et al., 2014), and the impact of AMOC variations on heat transport and salt transport in the Atlantic basin has also been observed (e.g., Dong et al., 2009; Johns et al., 2011; Garzoli et al., 2013). As new

TABLE 1

Platforms used by NOAA researchers and their partners to make key measurements of the AMOC.

Present Platforms	**Coverage**	**Parameter**	**Sampling Characteristic**	**Data Type**
CTD Repeat Hydrographic Surveys	Along fixed transects, full water column, varied horizontal resolution	Temperature, salinity, dissolved oxygen, velocity, tracers	Nominally decadal	Delayed time or real time
XBT Repeat Transects	Along fixed transects, upper 800 m, nominal 25 km horizontal resolution	Temperature	Nominally quarterly	Real time
Subsurface Moored Instruments	Full or partial water column at limited fixed sites	Vertical acoustic travel time, bottom pressure, ocean velocity, temperature, salinity	Hourly to daily	Delayed time
Submarine Cable	Florida Current	Volume transport	Daily	Real time
Argo Floats	Global, upper 2,000 m, nominal 3° × 3° horizontal resolution	Temperature, salinity, parking-depth velocity	Profiles every 10 days	Near real time
Satellite Data	Global, gridded products	Wind speed, wind stress, sea surface height anomalies	6-hourly to monthly	Delayed time or near real time
Developing Platforms	**Coverage**	**Parameter**	**Sampling Characteristic**	**Data Type**
Deep Argo	Global, upper 6,000 m, nominal 5° × 5° horizontal resolution	Temperature, salinity, oxygen, parking-depth velocity	Profiles every 10 to 30 days	Near real time
Underwater Gliders (Deep Gliders)	Upper 1,000 m (6,000 m)	Temperature, salinity	Hourly to weekly	Real time or near real time
Data Pods	Full or partial water column at limited fixed sites	Various based on instrument type	Hourly to monthly	Near real time

measurements continue to be made, AMOC research will continue with an emphasis on understanding the physical processes that drive the variability on daily to decadal time scales. A new forefront of AMOC studies going forward will be to characterize the interhemispheric variations and the mechanisms that cause the AMOC to evolve differently over time at different latitudes in the North and South Atlantic Oceans.

These varied AMOC observations will allow researchers to examine the realism of ocean-only and coupled climate model simulations and provide guidance as to physical processes that may or may not be correctly simulated by the present generation of numerical models (e.g., Msadek et al., 2013; Dong et al., 2014; Duchez et al., 2014; Zhao & Johns, 2014). Some inverse models combine measurements of temperature, salinity, and/or SSH data with a numerical model to provide a blended estimate of the ocean state (e.g., Carton & Giese, 2008) and are used to initialize forecast models that are used for seasonal to decadal predictions. Since the strength of the AMOC is a quantity that is not directly incorporated into these inverse models, AMOC observations also provide a stringent test for the models. These model-data comparisons will allow us to expand our skill in reproducing the AMOC variability, to better diagnose the mechanisms that produce AMOC variability, and to forecast the future evolution of the AMOC.

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