THE PRESENT AND FUTURE SYSTEM FOR MEASURING THE ATLANTIC MERIDIONAL OVERTURNING CIRCULATION AND HEAT TRANSPORT

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ABSTRACT

The Atlantic Ocean circulation redistributes up to 25% of the global combined atmosphere-ocean heat flux and so is important for the mean climate of the Atlantic sector of the Northern Hemisphere. This meridional heat flux is accomplished by both the Atlantic Meridional Overturning Circulation (AMOC) and by basin-wide horizontal gyre circulations. In the North Atlantic subtropical latitudes, the AMOC dominates the meridional heat flux, while in subpolar latitudes and in the subtropical South Atlantic the gyre circulations are also important. Climate models suggest the AMOC will slow over the coming decades as the earth warms, causing widespread cooling in the Northern hemisphere and additional sea-level rise. Monitoring systems for selected components of the AMOC have been in place in some areas for decades, nevertheless the present observational network provides only a partial view of the AMOC, and does not unambiguously resolve the full variability of the circulation. Additional observations, building on existing measurements, are required to more completely quantify the Atlantic meridional heat transport. A basin-wide monitoring array along 26.5°N has been continuously measuring the strength and vertical structure of the AMOC and meridional heat transport since March 31, 2004. The array has

demonstrated its ability to observe the AMOC variability at that latitude and also a variety of surprising variability that will require substantially longer time series to understand fully. Here we propose monitoring the Atlantic meridional heat transport throughout the Atlantic at selected critical latitudes that have already been identified as regions of interest for the study of deep water formation and the strength of the subpolar gyre, transport variability of the Deep Western Boundary Current (DWBC) as well as the upper limb of the AMOC, and inter-ocean and intra-basin exchanges with the ultimate goal of determining regional and global controls for the AMOC in the North and South Atlantic Oceans. These new arrays will continuously measure the full depth, basin-wide or choke-point circulation and heat transport at a number of latitudes, to establish the dynamics and variability at each latitude and then their meridional connectivity. Modeling studies indicate that adaptations of the 26.5°N type of array may provide successful AMOC monitoring at other latitudes. However, further analysis and the development of new technologies will be needed to optimize cost effective systems for providing long term monitoring and data recovery at climate time scales. These arrays will provide benchmark observations of the AMOC that are fundamental for assimilation, initialization, and the verification of coupled hindcast/forecast climate models.

1. BACKGROUND

The earth's energy budget has a net heating equatorward of about 35° as a consequence of the difference between enhanced equatorial short-wave solar heating and the more globally uniform long-wave cooling. The Atlantic plays a distinct and somewhat non-intuitive role in the global energy balance, with heat transported northwards throughout the entire South Atlantic despite more typical poleward heat transport in subtropical gyres. The maximum northward heat flux of 1.3×10^{15} Watts is found in the subtropical North Atlantic, accounting for 25% of the global combined atmosphere-ocean heat flux ([1]). In the oceans the primary manifestation of this redistribution of energy is in the form of thermohaline driven overturning circulations (the thermohaline circulation is driven by buoyancy fluxes across the sea surface); near Antarctica, in the Labrador Sea and in the Nordic Seas, surface waters increase in density (by cooling, sea-ice formation or fresh-water fluxes), sink and flow equatorward. The production of deep water is balanced by diapycnal mixing globally and, in the Southern Ocean where deep water upwells to the surface, density changes can be forced by atmospheric exchanges and the formation of sea-ice. The new surface and intermediate waters compose the upper limb of the thermohaline circulation, with waters upwelled in the Pacific and Indian basins returning to the Atlantic Ocean mostly through the Agulhas Leakage ([2]) and transiting through the South Atlantic to the northern North Atlantic sinking regions after going through significant water masses transformations ([3]).

The Atlantic Meridional Overturning Circulation (AMOC) is the primary mechanism through which heat is transported meridionally across basins. The AMOC includes both thermohaline and wind driven components; individually the thermohaline circulation is difficult to quantify, however the overall AMOC can be defined and observed. Quantifying the magnitude and associated heat flux of the AMOC is a prerequisite for assessing the effect of the thermohaline circulation on climate ([4]).

On human timescales – years to decades – state-of-the-art coupled climate model simulations ([5]) predict a slowing of the AMOC during the 21st century (Fig. 1): reducing the northward oceanic heat transport and leading to substantial sea level rise along the northeast coast of the United States and the west European coasts ([6]). The strength of today's AMOC and its decrease in the 21st century, however, differs significantly between different climate models and we do not yet have sufficient observational evidence to critically test and evaluate these different projections.

Assessing the possibility of shifts in the AMOC in the geologic past as well as near future is a crucial part of understanding the risks posed by anthropogenic climate change. Internal variability ([7]) and externally forced changes ([5]) of the AMOC are both likely to impact sea surface temperature, sea-ice, marine ecosystems ([8]), the ocean carbon budget and global sea levels. AMOC slowing (Fig. 1) will have a significant socio-economic impact through global sea-level and temperature changes ([9] and [6]). Thus, there is an imperative to obtain knowledge of the present state of the AMOC, refine confidence in future change and effectively communicate these results to governments and other planning agencies.

Quasi-continuous observations of the western boundary components of the AMOC, the cold, deep limb in the DWBC and the warm, shallow limb in the Florida Current/Gulf Stream started in the early 1980s off Florida and New England and in the southern Caribbean Sea in 2000-2001. The subtropical time series program provided the cornerstone of an international basin-wide mooring array at 26.5°N through the collaboration of several international programs (see Tab. 1). Operating since 2004 this transatlantic array has been providing twice daily estimates of the basin-wide integrated strength and vertical structure of the AMOC at 26.5°N ([11] and [12]). The array has proven to be an excellent method for monitoring the AMOC at that latitude. Reference

[13] shows that in the ECCO (Estimating the Circulation and Climate of the Ocean) state estimation and in several high-resolution ocean models the vertical structure of the AMOC is poorly reproduced. They attribute this lack of realism to spurious mixing of overflows in the models resulting in a much too shallow overturning. Indeed the circulation in the models is very weak at depths below 1500m. Reference [14] shows that the assimilation of the FC (Fiberoptic Connector) cable and mid-ocean transports from the 26.5°N array has a significant impact on the ECCO state estimates. In particular, the assimilation of these observations strengthened both the northward upper branch of the AMOC and the southward return flow between 2000 and 3000 m depth. These changes also impacted the AMOC over a latitude range of ±15°.

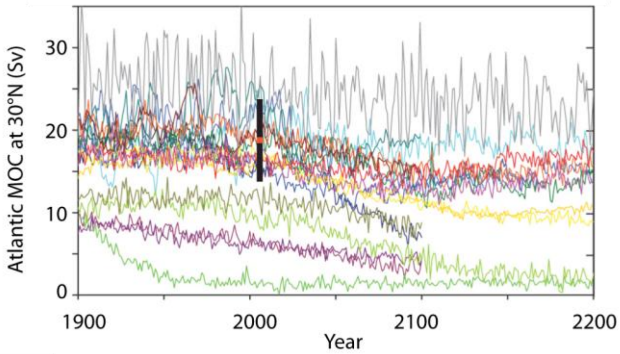

Figure 1. Evolution of the Atlantic meridional overturning circulation (AMOC) at 30°N in simulations with the suite of comprehensive coupled climate models from 1850 to 2100 using 20th Century Climate in Coupled Models (20C3M) simulations for 1850 to 1999 and the SRES (Special Report on Emissions Scenarios) A1B emissions scenario for 1999 to 2100. Some of the models continue the integration to year 2200 with the forcing held constant at the values of year 2100. Observational estimate of the mean AMOC and its variability observed at 26.5°N for 3.5 years from 1st April 2004 (black bar). The mean AMOC for this period is 18.5 Sv with a standard deviation of ±4.9 Sv (for twice-daily values). Three simulations show a steady or rapid slow down of the AMOC that is unrelated to the forcing; a few others have late-20th century simulated values that are inconsistent with observational estimates. Of the model simulations consistent with the late-20th century observational estimates, none shows an increase in the AMOC during the 21st century; reductions range from indistinguishable within the simulated natural variability to over 50% relative to the 1960 to 1990 mean. Adapted from [10].

At other locations (e.g. Denmark Straits overflow), critical monitoring arrays already exist that observe some of the important components of the AMOC that can in turn be used to verify and assimilate into models. Here we argue for both maintaining the existing AMOC observing systems and significantly expanding the observing system at key locations throughout the Atlantic. Specifically we require new long-term measurements of the AMOC in both the North and South Atlantic Oceans to quantify its wind driven and thermohaline components and associated heat fluxes at key latitudes as well as the inter-ocean and intra basin exchanges. These measurements will establish the frequency spectra of AMOC variability at different latitudes and the meridional coherence of variability at different timescales. These new observations will *independently and unambiguously* provide dynamical constraints for the present observational network and dynamically constrain global state estimations of circulations and fluxes. An additional key requirement will be for observational and modeling research to inform one another; integrating research projects such as the US CLIVAR (Climate Variability and Predictability) AMOC Science Team and the European project THOR (Thermohaline Overturning – at Risk?) (www.eu-thor.eu), will have a significant role to play by coordinating observational data and creating close links between the modeling and observational communities.

2. THE OCEAN'S MEAN OVERTURNING CIRCULATION AND HEAT FLUX

During the last thirty years estimates of the mean strength and zonal and vertical distributions of the AMOC have been made by evaluating (1) at a few latitudes in the South and North Atlantic using trans-basin hydrographic sections ([1]) where the meridional

$$\psi(y,z,t)=\int_{-z}^{0}\int_{x_{east}(y,z)}^{x_{west}(y,z)} v(x,y,z,t)\,dxdz \qquad (1)$$

overturning streamfunction $\psi(y,z,t)$ is calculated by integrating the meridional velocity $v(x,y,z,t)$ by longitude x and depth z at time t and at any given latitude y.

Basin-wide hydrographic data at a few sections in each hemisphere of the Atlantic reveal two meridional overturning cells (Fig. 2). In the upper cell we find northward flow of 13 to 18 Sv at 1300 dbar between 32°S and 56°N ([15], [16], [17] and [18]). The global mean strength of the deep overturning cell associated with production of AABW (Antarctic Bottom Water) around Antarctica is less well known, but is comparable to the strength of the upper cell. The total production of AABW is 8-9.5 Sv ([19]) and results in a deep cell of northward flowing AABW estimated to be 14 Sv combining Pacific, Indian and Atlantic branches ([20]). In the Atlantic, the AABW is found deeper than 5000m and is strongly constrained by the bottom topography with the transport diminishing northward as it mixes with the southward circulation of the upper cell.

The mean strength of the AMOC during the WOCE (World Ocean Circulation Experiment) period is known with errors of around 30% ([21]). Most of this error is associated with the natural variability of the baroclinic velocity field limiting quantification of future changes by traditional snapshot hydrographic sections ([22], [11] and [23]).

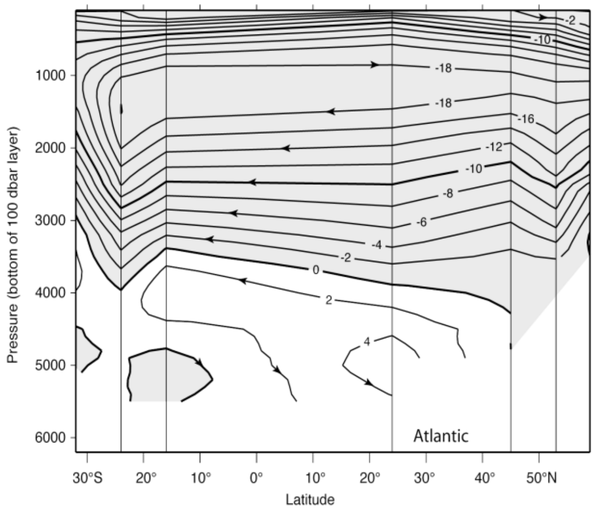

Figure 2. Meridional overturning stream function (Sv) for the Atlantic taken from [15].

Whilst the AMOC dominates the Atlantic meridional heat flux at some latitudes [1] emphasize that it is also important to consider the contribution of horizontal circulation to the net heat flux. For example the partition between overturning and horizontal heat flux in the subtropical Atlantic at 30°S [24] is $0.55x10^{15}$ W and $-0.3\ x10^{15}$ W respectively and at 36°N [25] is $0.86x10^{15}$ W and $0.39\ x10^{15}$ W. Contrast this with 26.5°N where the annual-mean overturning heat flux is about $1.3\ x10^{15}$ W with a horizontal contribution of about $0.1\ x10^{15}$ W ([26]). At latitudes where the net meridional heat flux is partitioned between the AMOC and horizontal components then it is necessary to supplement the AMOC measurements to ensure that correlated fluctuations of velocity and temperature across the full width of the basin are resolved so that the net meridional heat flux can be determined.

An AMOC and heat flux array has been in continuous operation at 26.5°N since April 2004 and is a template for the extension of continuous AMOC monitoring and is described in detail below. Future components of the AMOC observing system will provide benchmark observations of the full-depth, continent-to-continent AMOC defined by Eq. 1 will complement the existing observations and will provide independent dynamical constraints of the AMOC throughout the Atlantic for verifying assimilations, coupled climate model hindcasts and for ocean initialization for climate forecasts.

3. SUMMARY OF EXISTING PROGRAMS MEASURING VARIOUS COMPONENTS OF THE MERIDIONAL OVERTURNING CIRCULATION AND REGIONAL SCIENTIFIC FINDINGS

Many programs are in place that measure boundary current evolution of the deep circulation, choke points, and to varying degrees key components of the AMOC. A summary of these existing programs highlights some of the physical features of the circulation and challenges to augmenting these measurement systems to measure the complete net meridional transports of heat, mass and fresh water. Below we describe the only existing basin-wide AMOC and heat flux array followed by existing observational programs that are likely to be developed into more complete programs. The latitudes actively developing are near 47°N, 16°N and 32°S. Further elements of an AMOC observing system include overflows, boundary current arrays, Southern Ocean measurements and hydrographic sections.

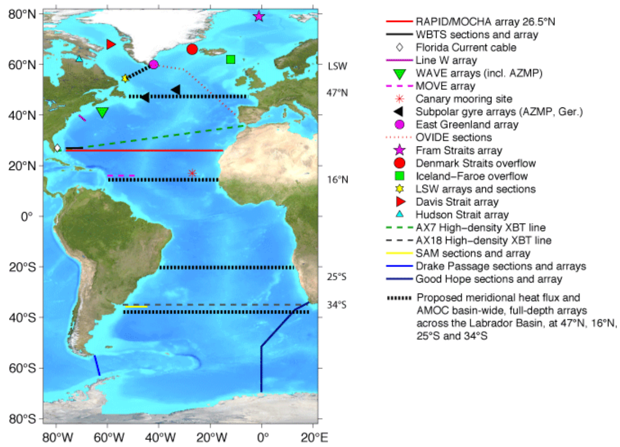

Figure 3. Observational programs presently measuring components of the AMOC (see also Tab. 1).

3.1. The Atlantic Meridional Overturning and Heat Flux Array at 26.5°N

At 26.5°N, more than 90% of the heat transport is accomplished by the AMOC. Fluctuations in heat transport (and other properties) are a consequence of velocity fluctuations justifying the focus on the AMOC as the principle physical mechanism for ocean heat transport at this latitude. The 26.5°N array is both practical and cost effective and is successfully demonstrating that the AMOC can be monitored from continent to continent over the full water column on a daily basis and that AMOC variability may be understood in terms of both density and bottom pressure variability.

The 26.5°N section is separated into a Florida Strait section west of the Bahamas where the Gulf Stream transport is monitored from cable voltage measurements and a mid-ocean section from the Bahamas to Africa. Variability in the wind-driven surface-layer Ekman transport is derived from QuikSCAT (Quick Scatterometer Satellite) satellite-based observations. Mid-ocean flow is monitored by an array of moored instruments along the section. The basic principle of the array is to estimate the zonally integrated geostrophic profile of northward velocity on a daily basis from time-series measurements of temperature and salinity throughout the water column at the eastern and western boundaries and on either side of the mid-Atlantic Ridge. Inshore of the most westerly measurements of temperature and salinity, the transports of the Antilles current and DWBC are monitored by direct velocity measurements.

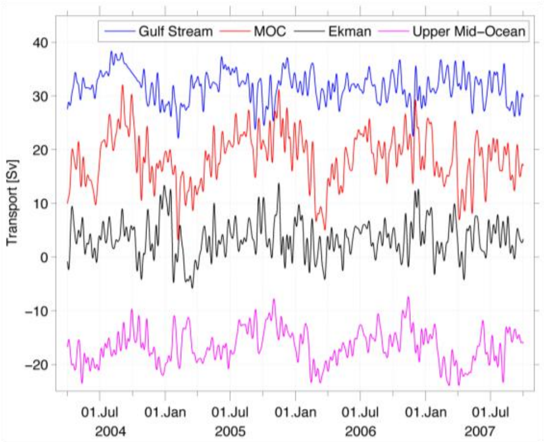

Figure 4. Twice daily time series of Florida Straits transport (blue), Ekman transport (black), upper mid-ocean transport (magenta) and overturning transport (red). Transports in Sv, positive northward. Florida Straits transport is based on electromagnetic cable measurements. Ekman transport is based on QuikSCAT winds. The upper mid-ocean transport is the vertical integral of the transport per unit depth down to 1100 m. Overturning transport is the sum of Florida Straits, Ekman and upper mid-ocean transport ([11]). The mean±standard deviation of Gulf Stream, Ekman, upper-mid ocean and overturning transports are 31.7±2.8 Sv, 3.5±3.4 Sv, -16.6±3.2 Sv and 18.5±4.9 Sv respectively.

Results from the first year of measurements ([12]) show that the independently measured Gulf Stream, Ekman and mid-ocean transports largely compensate at periods longer than 10 days, thus confirming the validity of the monitoring system. From the first 3.5 years of observations (Fig. 4), the mean AMOC is 18.5±4.9 Sv. Based on the integral timescales of variability the standard error is about 1.5 Sv, hence monitoring the interannual variability in the annual mean AMOC with a resolution of 1.5 Sv.

The frequency distribution of the Gulf Stream, Ekman, upper mid-ocean and AMOC transports is shown in Fig. 5. At periods less than 180 days, the Ekman variability is larger than the Gulf Stream and upper mid-ocean variability, such that the Ekman variability dominates variability in the AMOC. However, at periods longer than about 180 days (semi-annual and annual), the situation is reversed and the Gulf Stream and upper mid-ocean variability are larger than the Ekman variability and dominate the variability in the AMOC. This means that seasonal variability in the AMOC is dominated by geostrophic transports of upper mid-ocean and Gulf Stream transports. The annual mean meridional heat transport due to the AMOC is 1.3×10^{15} Watts. Short-term variability has a range of 0.1×10^{15} to 2.5×10^{15} Watts. About half is due to Ekman transport variability, and the remainder due to geostrophic variability ([26]).

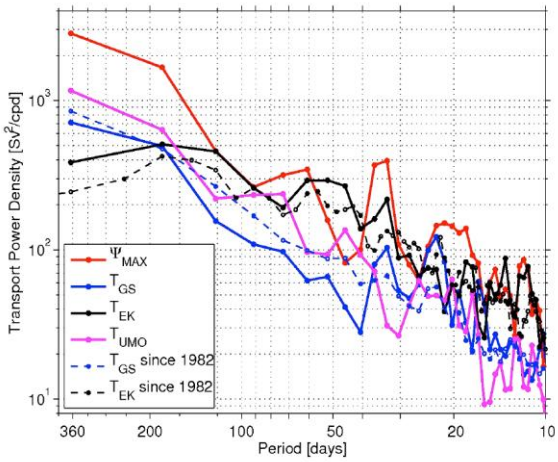

Figure 5. Solid lines denote power spectra of the maximum of the overturning stream function (ψ_{max} red), Gulf Stream (T_{GS} blue), Ekman (T_{EK} black) and upper-mid ocean (T_{UMO} magenta) for the period from April 2004 to October 2007. Also shown for reference purposes as dashed lines are transport spectra of T_{GS} (blue) and T_{EK} (black) based on time series between March 1982 and January 2008. The long T_{EK} time series is based on NCEP/NCAR (National Centers for Environmental Prediction/National Center for Atmospheric Research) re-analysis data. The spectra are based on Welch's periodogram method using a 365-days-wide Hamming window and 182 days overlap between consecutive data segments.

At 26.5°N, combining the observations from several independent sources [12] demonstrated that within known observational errors the net meridional volume transport was effectively in balance. That the net volume transport through the Atlantic is small provides a very powerful constraint on any observing system.

This was demonstrated in a number of eddy-permitting models with realistic topography and forcing that were used to test the observational strategy ([27] and [28]). These studies emphasized the need to understand the force-balance of circulation components to verify the observational strategy. This necessary demonstration allowed several groups to identify which components of the array they could fund and operate: it provides a template for international cooperation and such studies should be the priority for other latitudes.

The 26.5°N array demonstrates that it is possible to continuously observe the strength and structure of the AMOC and heat flux using a carefully designed basin wide array. Based on this system, some considerations for instrumenting other latitudes are: 1.) Resolving barotropic currents systems adequately which may mean avoiding western boundaries where currents flow over gently sloping bathymetry – otherwise extensive mooring arrays are required to directly measure the flow and; 2.) Identifying and measuring the parts of the circulation responsible for the meridional heat flux. Any complex mid-ocean barotropic flows must be resolved and mid-ocean bathymetry must also be carefully considered for flows along, through or over it.

3.2. Monitoring the Exchanges Between the Atlantic and the Arctic Across the Greenland-Scotland Ridge

Three current systems exchange water, heat, salt, and other properties between the Atlantic Ocean and the Arctic region across the Greenland-Scotland Ridge. The Atlantic inflow (to the Arctic), the overflow of dense water at depth (from the Arctic), and the surface outflow (from the Arctic) and they have large impacts on the Arctic, as well as on the AMOC. The northward heat flux across the Ridge maintains the Arctic much warmer than it would otherwise be, and large areas are kept free of ice. Most of the Atlantic inflow is converted to dense overflows that flow southwards through the deep passages across the Ridge. Crossing the Ridge, they entrain sufficient water to approximately doubling their volume flux, generating about two thirds of the source water for the AMOC.

The flow of warm and saline Atlantic water towards the Arctic crosses the Greenland-Scotland Ridge in three current branches. Since the mid 1990s, extensive monitoring with quasi-permanent moorings and regular CTD (Conductivity-Temperature-Depth) cruises has been in operation. Averaged over the years 1999 to 2001, values of volume, heat (relative to 0ºC), and salt flux by the total Atlantic inflow were estimated as 8.5 Sv, 313 TW, and 303 million kg/s, respectively ([29]).

Intensive fishing activities put strong restraints on the types of moorings that can be deployed. Much of the current meter data is therefore acquired by Acoustic Doppler Current Profilers (ADCPs) that can be moored below the fished zone or in protective frames on the bottom. Temperature and salinity of the water on the section is monitored, partly by moored instruments, and partly by regular (usually 4 times annually) CTD surveys.

The overflow of cold dense water from the Arctic region southwards across the Greenland-Scotland Ridge is focused through two narrow channels: the Denmark Strait, through which half of the overflow passes, and the Faroe Bank Channel (FBC) that contributes another third. The remaining overflow water crosses the Iceland-Faroe and Wyville Thomson ([30]) Ridges as more sluggish, intermittent, and broad flows that are not as well localized and more difficult to monitor.

The most accurately monitored overflow branch is the FBC overflow, which has been continuously equipped with moored ADCPs for more than a decade. The Denmark Strait is wider and requires more moorings to reach the same accuracy.

Independent model estimates of the FBC overflow series show remarkably agreement to the observations ([31]). It has a seasonal component and also shows interannual variations, but it has no indication of any trend over the decade-long observational period. Since the Denmark Strait and FBC are more than 80% of the total overflow observing these two branches are the most essential components of overflow monitoring.

3.3. Arrays Monitoring the Southward Evolution of the Deep Western Boundary Current North of the Gulf Stream in the North Atlantic

It is not well understood how changes in the deep limb of the AMOC transfer from high to low latitudes ([32]). The DWBC is a system of focused boundary currents providing a rapid connection from the Nordic Seas to the Southern Ocean for the export of North Atlantic Deep Water. At present there are several boundary arrays measuring this southward flux (Tab. 1). A notable gap exists south of Greenland at Cape Farewell that may be considered a key pivot section ([33]), where the combined flux of Nordic Seas overflows may be measured and as an end point for fluxes into the Labrador Basin to the west and Iceland and Irminger Basins to the east. The East Greenland-Irminger Current transports water masses transformed in the eastern Subpolar Gyre into the Labrador Sea via the West Greenland Current. Mesoscale eddies shed from the West Greenland Current play a critical role in preconditioning the Labrador Sea for deep convection and in its subsequent restratification ([34] and [35]).

The Labrador Sea Water export into the subtropical gyre through the boundary current is monitored at 53°N and at 47°N (Tab. 1). At 53°N, the flux of the DWBC as measured by current meter arrays is found to be steady and is characterised by a remarkably high signal-to-noise ratio (relatively stable current with weak eddy kinetic energy), so is potentially well suited for the detection of low-frequency variations. Coupled with the repeat hydrographic sections along AR7 west and east, this makes a good argument for a subpolar line near this mooring array. Reference [36] report that, east of the Grand Banks, the DWBC has the same mean transport in the periods 1993-1995 and 1999-2005. It can be argued that all of the deep waters formed in the subpolar seas have to pass this site, as it is downstream of all known deepwater formation areas and well upstream of the interactions with the North Atlantic Current and Grand Banks, which appears to result in complex branchings of the DWBC). Modelling results suggest decadal changes of the DWBC at 53°N are correlated with the buoyancy-forced part of the AMOC further south ([37]).

Absolute geostrophic transports between Greenland-Portugal (A25) from high frequency repeat lines show AMOC variability that is reproduced favourably by models. The results were significantly improved by incorporating direct current measurements in the western boundary, and showed a good consistency with two current meter arrays in the East Greenland Current and in the DWBC at 60°N. A sustained array at 60°N would provide additional information on the time variability of the currents, while the sections give a precise description of the water mass anomalies and of the tracer fields.

At about 44°N a DWBC array (the Halifax array) measures pressure along the continental slope between 2000 and 4100 m depth, to estimate the variability in the lower limb of the AMOC (Tab. 1).

Further south located on the continental slope south of New England (near 40ºN, 70ºW) Line W is one component of a long-term climate observing system that is positioned to quantify variability in the deep limb of the AMOC. Arrays of moored instruments combined with shipboard observations, directly measure the time dependence of volume transport, advection of property anomalies, and propagation of topographic Rossby waves and boundary waves in the equatorward flowing DWBC between the U.S. and Bermuda (Tab. 1).

Slowing of the AMOC could be identified first in the subpolar North Atlantic, where the northward flow of warm, saline water in the upper ocean is linked to the formation of deep water in the Labrador and Nordic Seas. Hence, the continuous measurement of the meridional heat and volume transport at one or more of these northern sections such as 47°N will allow us to address the following: how are changes in deep-water formation rates and in the strength of the subpolar gyre linked to changes in the AMOC? What are the mechanisms causing AMOC variability on different time scales from <1 year to decadal? What is the temporal and meridional coherence of the AMOC between the subtropical and subpolar gyres? Where are the pathways of the AMOC outside the western boundary and how much of the volume and heat transport occurs in the interior of the basins? Is there a correlation between transport fluctuations at the western boundary and in the interior? For example, a 47°N array needs mainly C-Pressure Inverted Echo Sounder (CPIES) in the basin's interior and current meter moorings including MicroCATS (Microprocessor Controlled Command & Telemetry System) (T/S/P (Temperature/Salinity/Pressure) sensors in the boundary current. A sufficiently close spacing of the CPIESs will allow not only to measure the baroclinic and barotropic velocity fluctuations (from the acoustic travel time and the variability of the bottom pressure sensor), but also the mean velocity field at the depth of the current meter. Measuring these barotropic flows in the subpolar gyre has been shown ([28]) to be a critical component of an AMOC observing system in these latitudes. Acoustic travel times measured by the Pressure Inverted Echo Sounder are converted to temperature and salinity profiles by reference to travel time anomalies computed from a database of CTD measurements from Argo floats using Gravest Empirical Modes. The 47°N AMOC measurements would be accompanied by an annual to biannual estimate of the Labrador Sea Water formation rate (continuing the time series started in 1997 [38], [39]) and [40] gave an estimate of the strength of the subpolar gyre when entering the eastern Atlantic. The latter array was first deployed in August 2006 and consists of Pressure Inverted Echo Sounder - and starting in July 2009 will be additionally equipped with current meter moorings and MicroCATS - and it is planned to continue the measurements at least till 2013 (Tab. 1). At the present time, the eastern basin is observed biannually with CTD and tracer measurements.

3.4. Meridional Overturning Array at 16 N

Moored of the strength and vertical structure of the North Atlantic Deep Water transport across 16°N have been obtained continuously since February 2000 as part of the ongoing Meridional Overturning Variability Experiment (MOVE) ([41] and [42], http://mooring.ucsd.edu). MOVE currently consists of two full water column dynamic height moorings located at the base of the Lesser Antilles continental rise (60.5°W), and east of the Mid-Atlantic Ridge (50.5°W), equipped with a combination of MicroCAT CTD sensors and bottom pressure sensors, to monitor the southward geostrophic flow in the depth range between 1000 and 5000 m. The assumption is that this is compensated by the northward upper layer flow, and thus represents the lower limb of the AMOC. The steep continental slope allows only a small fraction of the southward DWBC to pass through the wedge to the west of the geostrophic array. This part is captured by current meter sensors attached to the western dynamic height mooring and to an additional mooring in the centre of the continental slope. The zonal extent of the array covers the entire western basin of the Atlantic, which is only 1000 km at this latitude. Dynamics associated with transport variations from daily to interannual periods have been described ([43]). Water mass data, dynamical considerations, and model simulations suggest that on long timescales the western-basin transports follow closely the basin-wide transport integral. With 9.5 years of observations to date, low-frequency changes in the strength of the southward North Atlantic Deep Water flow can thus be linked to the basin-wide AMOC.

With 45 degrees of freedom and nearly 10 years of continuous observations, the time-series now is long enough to start detecting trends with some confidence (Fig. 6). The data reveal a weakening AMOC transport with 85% certainty. The trend of approximately -0.3Sv/yr is consistent with the model hindcast by [44]. Most of the NADW (North Atlantic Deep Water) transport trend results from the upper and middle layers of the NADW.

Long-term observations of this kind are essential as they provide hard constraints for climate models, allow decadal-scale climate forecasts, and eventually should isolate anthropogenic from natural AMOC changes. A new full water column time series station north of the Cape Verde Islands at 24° - similarly equipped with CTD and bottom pressure sensors – now extends the MOVE array to near full-basin width.

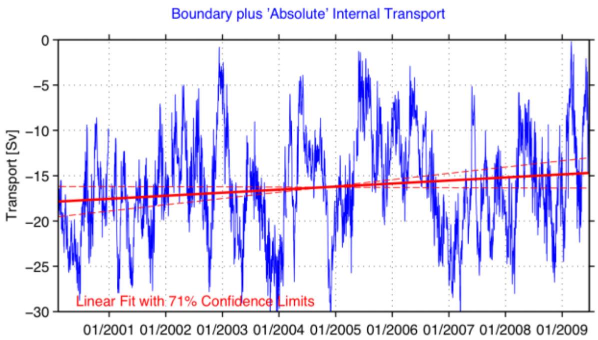

Figure 6. AMOC estimated as southward NADW transport time-series over 9.5 years from internal (density-derived) transport and boundary/slope contribution. The trend is 0.35Sv/yr, and is different from zero with 85% certainty.

3.5. Heat Transport and Interocean Exchanges in the South Atlantic

Starting in the year 2002, high-density XBT (Expendable Bathythermograph) lines are conducted at nominally 35°S. It has been demonstrated ([45] and [46]) that the data collected from the AX18 XBT cruises (nominally 35°S) can provide measurements of the heat transport across this latitude to within an accuracy of ±0.18 $x10^{15}$ W (mean value = 0.54 $x10^{15}$ W). The uncertainty derives mainly from the fact that XBT observations are made only in the upper kilometre of the ocean, with an additional significant uncertainty due to the high-frequency variability of the flows at the boundaries. However, [45] demonstrate, via an analysis of a high-resolution model, that another important source of error is the lack of observations of the barotropic component of the flow, particularly west of 47°W. This is important because, at the western boundary, the Malvinas Current and the North Atlantic Deep Water flow both in the same direction creating a strong barotropic flow whose magnitude and variability is practically unknown. At the eastern boundary the Benguela Current, which carries much of the upper limb of the AMOC, is a combination of steady flow plus transients in the form of Agulhas rings. The variability of the heat transport across nominally 35°S is shown in Fig. 7.

To better resolve the eastern and western boundary currents, a pilot array was started along 34.5°S. Infrastructure considerations such as collaboration and ship availability by international partners from Argentina, Brazil and South Africa largely determined the latitude of the deployments. The pilot array includes two CPIES deployed near the coast of South Africa by Université de Bretagne Occidentale in February 2008, and three PIES and one CPIES deployed near the South American coast by NOAA/AOML (National Oceanic and Atmospheric Administration/Atlantic Oceanographic and Meteorological Laboratory) in March 2009.

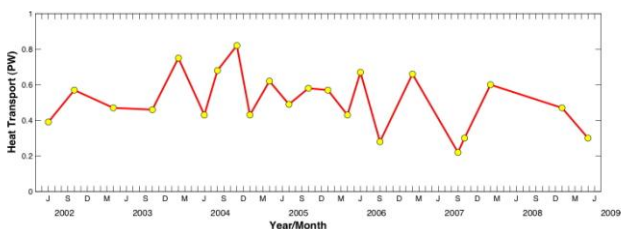

Figure 7. Total heat transport [units of 10^{15} W] across nominally 35°S (Dong et al, personal communication).

Program Name	Objective
Northern North Atlantic	
Fram Strait http://oceanography.npolar.no/oceanography/research/framstrait_fw.html	Fram Strait fresh-water export
Monitoring the Atlantic Inflow toward the Arctic (MAIA) [31] http://www.bodc.ac.uk/projects/european/maia/	Monitoring the inflow of warm Atlantic water to the Nordic Seas.
Denmark Strait Overflow [31]	Export from the Nordic Seas to the Atlantic through the Denmark Strait.
Faroe Bank Channel Overflow [31]	Export from the Nordic Seas to the Atlantic through the Faroe Bank Channel.
Davis Strait (ARCUS) http://www.arcus.org/search/catalog/258	An Observational Array for High Resolution, Year-Round Measurements of Volume, Freshwater, and Ice Flux Variability in Davis Strait.
Measuring the Freshwater Flux Through Hudson Strait http://www.whoi.edu/science/PO/people/fstraneo/hudson/hudsonmoor.html	A Mooring Array to Measure the Freshwater Through Hudson Strait
Labrador Sea moored arrays http://www.ifm-geomar.de/index.php?id=a2&L=1	Deep convection in the Labrador Sea, its effect on the water masses and circulation in the region, and its variability and dense water boundary current export.
Labrador Sea Water Formation Rates [86], [39] and [40] http://www.ocean.uni-bremen.de/index_eng.html	Labrador Sea Water formation rates from biannual changes in tracer inventories of CFCs and SF6 in the subpolar North Atlantic. Started 1997.
Observatoire de la Variabilité Interannuelle à Décennale » of currents in the North Atlantic (OVIDE) http://www.ifremer.fr/lpo/ovide/	A sustained Greenland-Portugal hydrological section that provides absolute transports across the section in June every two years.
Subpolar gyre array http://www.ocean.uni-bremen.de/en/oz_projects.html#Northatlantic	Pilot study to measure the transport fluctuations of the North Atlantic Current along a line parallel to the Mid-Atlantic Ridge between 47°N and 53°N by moored Pressure Inverted Echo Sounder and conventional moorings. Started 2006.
Deep Western Boundary Current transport array at 47°N http://www.ocean.uni-bremen.de/en/oz_projects.html#Northatlantic	Monitor Deep Western Boundary Current transports and temperature/salinity characteristics at 47°N in the Newfoundland Basin using an array of Pressure Inverted Echo Sounders, acoustic current meters and T/S sensors, Started 2009.
Atlantic Zone Monitoring Programme (AZMP) http://www.meds-sdmm.dfo-mpo.gc.ca/isdm-gdsi/azmp-pmza/index-eng.html	Seasonal and opportunistic sampling along "sections" to quantify the oceanographic variability in the Canadian NW Atlantic shelf region,
Western Atlantic Variability Experiment (WAVE) http://www.pol.ac.uk/home/research/theme10/rapidII.php	A monitoring array along the western margin of the Atlantic.
Line W http://www.whoi.edu/science/po/linew/index.htm	A sustained measurement program sampling the North Atlantic Deep Western Boundary Current and Gulf Stream at 39°N.
EuroSITES http://www.eurosites.info/	An integrated European network of nine deep-ocean (>1000m)

	observatories.
Subtropical North Atlantic	
NOAA/AOML High-density XBT estimates of Atlantic Meridional Heat Transport http://www.aoml.noaa.gov/phod/hdenxbt	AOML collects XBT data on two lines spanning the subtropical oceans: in the North Atlantic since 1995 along AX7 running between Spain and Miami, Florida and in the South Atlantic since 2002 along AX18 between Cape Town, South Africa and Buenos Aires, Argentina. These data capture the upper limb of the AMOC transport.
Western Boundary Time Series (WBTS) and Florida Current Cable http://www.aoml.noaa.gov/phod/wbts/index.php	This project consists of two components to monitor the western boundary currents in the subtropical Atlantic: the Florida Current transport measurements using a submarine telephone cable plus calibration cruises and the Deep Western Boundary Current transport and property measurements using dedicated research ship time and moorings.
Monitoring the Atlantic Meridional Overturning Circulation at 26.5°N (RAPID-WATCH) http://www.noc.soton.ac.uk/rapidmoc/	A pre-operational prototype system to continuously observe the strength and structure of the AMOC.
Meridional Overturning Circulation and Heat Flux Array (MOCHA) http://www.rsmas.miami.edu/users/mocha/new/	MOCHA is a collaborative project, partnered with the UK RAPID Program, to measure the AMOC and ocean heat transport in the North Atlantic Ocean.
Meridional Overturning Variability Experiment (MOVE) [87]	Monitoring fluctuations of deep (>1180 m) meridional flow by means of end-point moorings in the western basin of the Atlantic Ocean at 16°N.
South Atlantic	
South Atlantic MOC ("SAM") at 34.5°S http://www.aoml.noaa.gov/phod/SAMOC/	Array of Pressure Inverted Echo Sounder/C-Pressure Inverted Echo Sounder measuring the Deep Western Boundary Current and Brazil Current near the western boundary.
Chokepoint monitoring from Africa to Antarctica (GOODHOPE) http://wwz.ifremer.fr/lpo/la_recherche/equipe_maaia/projets_en_cours/goodhope	Indo-Atlantic interocean exchanges.
Southern Ocean current observations http://tryfan.ucsd.edu/antarctic	Southern Ocean Current Observations from the US Antarctic Research Vessels
Dynamics and Transport of the Antarctic Circumpolar Current in Drake Passage (cDRAKE) http://tryfan.ucsd.edu/cdrake/	Quantify the transport and understand the dynamical balances of the Antarctic Circumpolar Current (ACC) in Drake Passage.
Chokepoint monitoring from South America to Antarctica http://www.noc.soton.ac.uk/JRD/HYDRO/drake/index.php	Pacific-Atlantic interocean exchanges.

Table 1. Observational programs currently measuring components of the Atlantic Meridional Overturning circulation, but not including global-scale programs such as Argo, the Global Drifter Array or satellite observations of surface parameters and meteorology. Programs are listed approximately by decreasing latitude starting in the North Atlantic.

A recent paper ([47]) demonstrates that for monitoring the AMOC, the transport variability in the interior is comparable in magnitude with that along the eastern and western boundaries, suggesting that measurements of the interior are critical as well as the boundary current. Boundary currents that require routine observations include the Brazil and Malvinas Currents (before the Confluence), the Malvinas Return flow, the DWBC along the South American continent (in particular where it joins the Malvinas Return), and the Benguela Current.

The newly constituted, international GoodHope research venture aims to address this knowledge gap by establishing a program of regular observations across the Southern Ocean between the African and Antarctic continents ([48]). A recent array of Pressure Inverted Echo Sounder (Donohue, pers. Comm.) has been deployed in 2007 in the Drake Passage. More complete instrumentation of Drake Passage and the passage south of Africa (i.e. the "Good Hope" line) is required to better monitor the inter-ocean exchanges of mass and heat associated with the AMOC and these sections play a critical part of a Southern Ocean Observing system.

Models have shown that the freshwater flux through the South Atlantic may be a precursor to changes in the AMOC further north (e.g. [49]). Other theories for forcing variability in the AMOC include the role of wind stress variability in the Southern Ocean (e.g. [4]) suggesting that long term changes in the AMOC may first be measured in the Southern Ocean. Hence, it is recommended to expand and initiate a new South Atlantic AMOC time series of for the whole water column to be retrieved at climate time scales (three to six month); and to further instrument the GoodHope line and Drake Passage using the current observations as the back bone of the observing system. New technology maybe needed to maintain long term cost effective observations at these latitudes ([50]).

3.6. Hydrographic Sections

Ship-based hydrographic sections are presently the only method for obtaining full depth, continent-to-continent measurements of physical, chemical and biological parameters that are necessary for the computation of fluxes when combined with the proposed AMOC observing system. Zonal sections are of particular importance (e.g. A5 and A10) and are required for the proposed AMOC observing system ([51]).

4. RATIONALE FOR EXPANDING THE CURRENT OBSERVING SYSTEM TO INCLUDE FULL DEPTH, CONTINENT-TO-CONTINENT CIRCULATION AND HEAT FLUX ESTIMATES

The current observational network measures a number of components of the thermohaline circulation such as deep-water production rates, choke point fluxes, boundary currents and the temperature and salinity distributions away from boundaries. However, the thermohaline circulation is not unambiguously quantified by these observations, and interpreting the variability in the thermohaline circulation from them is complicated by their partial nature. The strength, vertical structure and variability of the AMOC can be quantified by the measurement of the basin-wide, full depth circulation (Eq. 1); however, zonal integrals such as this can obscure many of the details of changing water masses and source regions to which variations should be attributed. In building a better, more complete AMOC observing system the present observational network will be used as the backbone of an expanded AMOC monitoring array enabling basin-wide estimates of circulation and heat flux at several latitudes in the subpolar, subtropical, and tropical North and South Atlantic (Fig. 3).

Among the challenges in designing an improved observing system is the fact that AMOC variability is driven by a variety of processes at different timescales. For example at 26.5°N Ekman transport fluctuations dominate AMOC variability at sub-seasonal timescales ([52], [53] and [54]). However, at seasonal timescales baroclinic adjustment of the basin-interior circulation is more important that the Ekman driven fluctuations (Fig. 5). At decadal timescales, variability in Labrador Sea Water has been linked to the North Atlantic Oscillation (NAO), suggesting a role in decadal changes in the AMOC. It should be noted though that deep convection in 2008 was not related in a simple way to the NAO ([55] and [56]), which emphasizes the need for continuous monitoring of the AMOC at a number of latitudes to explore how this signal will propagate through the Atlantic.

A key requirement therefore, for the AMOC observing system is to make measurements for sufficiently long that we can establish the spectrum of variability at chosen latitudes and their meridional connectivity over climate relevant timescales. This will allow us to disentangle natural and anthropogenic forced variability in the AMOC and the global atmosphere-ocean energy flows on different timescales.

Which latitudes are crucial for monitoring the meridional evolution and connectivity of the AMOC appears dependent on the timescale of interest. References [57] and [49] show that in a range of models the AMOC has quite different timescales for its meridional coherence in the subpolar compared to the subtropical North Atlantic. Northward of 40°N the variability has a strong coherent decadal variability, while in the subtropical gyre higher frequencies dominate. These model analyses suggest that the AMOC must be monitored in the subpolar and subtropical North Atlantic to determine the meridionally coherent AMOC variability. Reference [40] shows that the horizontal subpolar gyre circulation and AMOC contribute about equally to meridional heat transport at 47°N and this does not change with increased horizontal resolution (S. Hüttl-Kabus and C. Böning, pers. comm.). References [40 and 58] show that in a global coupled climate model AMOC changes over several decades could be captured by two AMOC arrays: one in each hemisphere of the Atlantic. However, for interannual to decadal variability additional latitudes are crucial to capturing the AMOC evolution throughout the Atlantic.

Reference [59] argues that on timescales longer than a few years buoyancy forcing over the subpolar North Atlantic plays a dominant role in setting the strength of the AMOC at lower latitudes. Density anomalies originating from air-sea interaction in the Labrador or Nordic seas spreads southward. Hence, the importance of measuring and understanding how high latitude information propagates along the western boundary in the North Atlantic.

In the South Atlantic dynamic and buoyancy exchange processes, occurring in localized regions within the southwestern Atlantic and the Cape Basin, potentially alter the thermohaline circulation and associated mass, heat and freshwater fluxes ([60], [61], [62], [63], [64] and [65]).

The net buoyancy and heat transport from the South Atlantic to the North Atlantic depends on the ratio of the water mass contributions from the South Indian Ocean and from the South Pacific Ocean ([66]). The Drake Passage and the region south of South Africa are key locations for observing the Antarctic Circumpolar Current (ACC), ([67] and [68]). Heat, salt, mass, freshwater, nutrients and other oceanic properties are transported via the ACC and the Agulhas Current between the Atlantic, Pacific and Indian Oceans ([69], [70] and [71]), with consequences for the AMOC and global climate ([72], [73], [74], [75] and [76]). A May 2007 workshop gathered scientists from South America, Europe and US to discuss the design and implementation of an observational system to monitor the AMOC in the South Atlantic (*SA*MOC) ([77]). Among the key results of the workshop was that modelling results and existing observations indicated the need to increase observations not only in the Southern Ocean south of Africa and South America but also in the interior of the South Atlantic. Specifically it was recommended to expand and initiate new routine time series of boundary currents for the whole water column to be retrieved in near real-time (i.e. every three to six month).

In July 2007, the US CLIVAR AMOC Implementation Panel workshop was held to write the implementation strategy document for the AMOC. This US strategy identified three locations for monitoring of the AMOC in the Atlantic with a focus on basin-wide integrals of transport. In addition to the South Atlantic and subtropical North Atlantic lines already discussed, this panel strongly recommended instrumenting the subpolar North Atlantic lines indicated in Fig. 3. The subpolar gyre presents unique challenges due to the fine horizontal spatial scales and barotropic flows in that, which are less influential in the other regions ([28]). Observations of the net export of deep waters from the Labrador Sea area, for example, show wildly different values of Labrador Sea Water production. Numerical models also show disparities between deep-water formations, indicating processes in the subpolar gyre are not well understood and need further study.

Therefore, based on the output of these earlier workshops and our (limited) understanding of AMOC meridional coherence, and building on existing observational programmes, the recommended latitudes for basin-wide AMOC monitoring are near 47°N in the North Atlantic, spanning subpolar gyre, 26.5°N in the North Atlantic subtropical gyre, and between 25-35°S in the South Atlantic subtropical gyre. These three arrays should enable estimates of the meridional heat flux convergence in the subtropics and divergence over the subpolar North Atlantic, and the transport of variability from the high and lower latitudes. We propose an array at Cape Farewell perhaps expanded to include the AR7 repeat line, a key pivot location in the sub-polar North Atlantic, to monitor the combined flux of the Denmark Strait and Faeroe Bank Channel overflows and the lower limb of the AMOC. Furthermore, in order to monitor for long-term, low frequency, climate trends in the AMOC we recommend the continuation of existing long-term western boundary measurements along the Labrador coast, along the coast of New England (Line W, Wave arrays), in the subtropical North and South Atlantic (WBTS, MOVE and SAM (Sensor Arrays and Multichannel Signal Processing) arrays). Additionally choke point fluxes by the Antarctic Circumpolar Current (ACC) in Drake Passage and south of Africa must be maintained and/or expanded in order to better quantify South Atlantic water mass changes and their impact on the AMOC. Equatorial exchanges will be quantified between the South and North Atlantic by the arrays in each hemisphere. These measurements should also be complimented by continuous monitoring of the Nordic Seas overflows across the Greenland-Iceland-Scotland Ridge and the compensating northward flow of Atlantic Water; production and export fluxes from the Labrador Sea; and continuous measurements of AABW in the Southern Ocean.

As noted in the introduction, while the AMOC is often discussed in terms of the large-scale, circulation with deep water originating in the North Atlantic Ocean, surface water also sinks into the abyssal ocean around Antarctica (e.g. [19]). There is substantial evidence indicating that the volume of abyssal water formed around Antarctica is of similar magnitude to its more commonly described North Atlantic limb (e.g. [16]) and bottom water of Antarctic origin has been shown to warm (e.g. [78], [79], [80], [81] and [82]) and freshen ([83] and [82]) over the last decade. These changes could suggest a change in the AABW limb of the overturning circulation as suggested by thermocline tilt changes observed in the North Atlantic ([84]) and North Pacific ([85]). Atlantic AMOC observing systems should measure this circulation, especially in the South Atlantic.

4.1. Readiness and Challenges

The scientific rationale for general AMOC monitoring has been extensively addressed. Less well developed are arguments for observing particular latitudes, and the choices here are largely pragmatic – building on existing systems. Many elements of the thermohaline circulation are being actively monitored using a variety of in situ observational techniques. However, the challenge is to fund and deploy much larger basin-wide systems incorporating these measurements, to monitor the total circulation and the meridional heat flux. Very few preliminary modelling studies have been done to assess what latitudes and what observations might be required at those latitudes to recover the AMOC and the meridional heat flux and much more work in this regard is required. These should be a necessary though not sufficient requirement for the community to endorse specific latitudes and these studies are urgently required. This will also result in specific proposals for monitoring that can be examined in detail and around which different groups can coalesce to support the necessary observations.

In situ sensors, mooring technology and developing in situ vehicles such as gliders are likely to achieve the required measurements. For interior temperature measurement full-depth Argo floats will help with the calculation of the meridional heat flux. The biggest technological challenge is to transmit data from the monitoring systems on timescales of one to six months for seasonal forecasting and climate model assimilations. The one-month delivery time does allow the observations to be used for seasonal forecasting problems, providing a data product, useful in the short term, before the interannual and decadal records are available. Therefore, it is recommended to develop new cost effective technology to allow near real-time observations over the full depth of the ocean.

5. CONCLUSION

Presently in situ observations provide only a partial view of the AMOC. The Atlantic Meridional overturning and Heat Flux array at 26.5°N provides a prototype for the continuous monitoring of the vertical strength and structure of the AMOC. We propose to deploy additional arrays 47°N, 16°N, 25°S and 34°S, modifying the observational strategy at 26.5°N in the light of modelling studies and prior analysis of in situ observations. In addition we propose an array at Cape Farewell expanded to include the AR7 repeat line, a key pivot location in the sub-polar North Atlantic, monitoring the Denmark Strait and Faeroe Bank Channel overflows and the lower limb of the AMOC.

A wide range of coupled climate models forecast a slowing of the AMOC over the coming decades. The zonal section arrays will provide fundamental benchmark observations of the AMOC throughout the Atlantic consisting of a set of unambiguous dynamical constraints. These constraints are fundamental to verifying assimilation schemes and coupled climate model hindcasts. The arrays also measure the full spectrum of large-scale ocean variability and this is critical initialization information to improve the decadal forecasting skill of climate models.

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