DEEP CIRCULATION AND MERIDIONAL OVERTURNING: RECENT PROGRESS AND A STRATEGY FOR SUSTAINED OBSERVATIONS

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Abstract: *The deep circulation and meridional overturning circulation (MOC) strongly influence phenomena of direct interest to society, including climate change and variability, seal-level rise, temperature and rainfall patterns, global biogeochemical cycles and marine productivity. Observations of the deep ocean remain scarce, limiting our ability to understand and predict the deep and meridional overturning circulations, their response to changes in forcing, and the impact of changes in the deep ocean. However, substantial progress has been made in recent years, including quantitative estimates of the strength of the global overturning circulation; the first time series measurements of the Atlantic meridional overturning circulation; evidence for changes in temperature, salinity and carbon in the deep ocean; and a deeper understanding of the role of the deep ocean and MOC in low-frequency climate variability. These advances provide a guide to the design and implementation of a sustained observing system for the deep ocean and MOC.*

1. INTRODUCTION

Roughly half the world ocean volume lies below 2000 m. While Argo floats and satellite remote sensing have revolutionised our ability to measure the upper layers of the ocean, the deep ocean is beyond the reach of these tools and remains very poorly sampled. Growing recognition of the intimate link between the deep ocean and the evolution of climate has underscored the need for sustained observations of the "deep half" of the ocean.

The meridional overturning circulation (MOC) is a primary mechanism for the transport and storage of heat, freshwater and carbon by the ocean and therefore has a large impact on climate variability and change. The MOC is a three-dimensional circulation pattern that links each of the basins and spans the full-depth of the global oceans. Both wind- and buoyancy-forced circulations contribute to the MOC. The transport of properties by the MOC depends on the rate of overturning and the difference in property concentration between the upper and lower limbs of the overturning; in many locations, the horizontal gyres also contribute to the meridional transport of heat and other properties. Therefore observations of the MOC must extend throughout the full depth and breadth of the ocean basins to quantify changes in the MOC and to determine their cause and impact. This poses a significant challenge, given existing tools. Often it is necessary to rely on proxy techniques that allow the transport to be inferred from indirect, and more feasible, measurements.

Changes in the MOC have been linked to past climate variations and climate models suggest the MOC will both respond to and drive climate change in the future, including the possibility that a slow-down of the MOC could result in an abrupt change in climate (eg [1]). Model studies suggest that changes in sea surface height associated with a weakening of the MOC could roughly double the sea-level rise on the eastern seaboard of North America expected from thermal expansion and ice melt [2]. The deep ocean is also involved in climate variability, on time-scales from decades and longer (eg [3]).

Biological activity transfers nutrients and carbon to the deep ocean as settling particles. Upwelling of deep water as part of the MOC, particularly in the Southern Ocean, returns nutrients to the surface ocean to support phytoplankton growth [4]. Changes in the overturning circulation would therefore be expected to influence global primary productivity and ecosystem function [92]. Deep water is also rich in carbon and the efficiency with which the ocean sequesters carbon dioxide from the atmosphere depends on a balance between the outgassing from upwelled deep water and the physical and biological processes acting to transport carbon into the ocean interior [5]. The introduction of carbon-rich deep water into the surface layer will also affect the carbon saturation state, with implications for marine ecosystems.

While time series measurements are sparse in the deep ocean, there is increasing evidence of changes in properties and circulation. The changes make a significant contribution to changes in the overall heat content of the ocean, and therefore sea-level rise. Anthropogenic carbon dioxide is also beginning to accumulate in the deep ocean. Efforts to track the evolving ocean inventory of heat, freshwater, carbon and other climate-relevant quantities must include measurements of the ocean below 2000 m.

Many of the most urgent challenges society is facing cannot be addressed without understanding (and therefore observing) the deep ocean. These challenges include climate change, including the risk of abrupt change; cycles of floods and droughts driven by decadal variability; sea-level rise; the future of the carbon cycle; and food security.

2. RECENT PROGRESS IN OBSERVING AND UNDERSTANDING THE DEEP OCEAN AND MOC

Given that variations in the MOC have been linked to climate changes in the past, the response of the MOC to future climate change is an important issue. The previous generation of coupled climate models showed that the MOC slowed down, and in some cases collapsed, with enhanced greenhouse gas forcing [6]. More recent coupled climate models suggest that the Atlantic MOC is likely to weaken with climate change (by about 30-40%), but the response is not as dramatic as in the earlier projections (Fig. 1). The models that perform best when compared with observations all weaken gradually over the coming century. The figure also shows that there is large variation between the IPCC 4AR models in terms of the magnitude, variability and sensitivity to change of the MOC. The wide spread of results in Fig. 1 underscores the need for observations of the MOC, including time series, to test and improve climate models.

2.1 Observations of the MOC transport

Measuring the MOC is a difficult task. The MOC extends throughout the global ocean, reaches from the sea surface to the sea floor, and consists of both intense narrow boundary currents and broad flows in the ocean interior. In essence, measuring the MOC and associated heat and freshwater transport requires observations of the global, full-depth, three-dimensional, time-varying flow of the ocean. We do not yet have tools that allow us to do this directly.

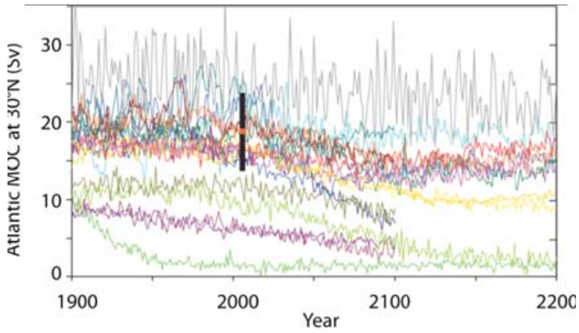

Figure 1. Evolution of the Atlantic meridional overturning circulation (AMOC) at 30°N in simulations with the suite of comprehensive coupled climate models from 1850 to 2100 using 20th Century Climate in Coupled Models (20C3M) simulations for 1850 to 1999 and the SRES A1B emissions scenario for 1999 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 [7].

Estimates of the global MOC have therefore relied on indirect measurements. Hydrographic sections provide most of the information we have about the deep ocean. These sections can be combined with simple dynamical statements (eg geostrophy and conservation of mass) to estimate the overturning circulation using inverse methods or similar techniques. Fig. 2 illustrates the global overturning circulation inferred from a recent calculation [8,9]. The figure shows the familiar overturning in the Atlantic associated with the formation and export of North Atlantic Deep Water (NADW), balanced by northward flow of intermediate water and bottom water. The figure also illustrates the near-global extent of the MOC, with deep water exported from the Atlantic circulating through the other ocean basins and returning in the upper ocean. (Fig. 8, discussed in Section 3, provides a different perspective of the global MOC.) To understand the dynamics, transport and variability of the MOC, it is not possible to restrict attention to the North Atlantic. In particular, water mass transformations taking place in the Southern Ocean play an important role by connecting the upper and lower limbs of the MOC and dense water formed along the margin of Antarctica plays an equal role with NADW in ventilating the abyssal ocean [10].

Observations of other flow pathways (eg the Indonesian Throughflow, the southern hemisphere "supergyre," and deep boundary currents) are needed for a full understanding of the MOC [11].

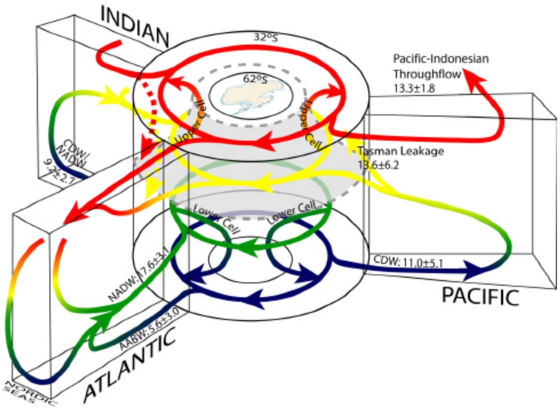

Figure 2: A schematic of the global meridional overturning circulation [8].

Hydrography-based estimates of the global MOC [8,12,13] are an impressive achievement, but have several weaknesses. They are usually based on a small number of widely-spaced sections taken at different times and rely on an assumption of a steady state ocean. Generally direct velocity measurements do not exist to use as a reference for geostrophic calculations, and even if they do, are often aliased with tides or inertial motions or are representative of different spatial scales. The solutions are underdetermined and the true uncertainty of the estimate can be difficult to estimate. Ocean state estimates, based on assimilation of a variety of observations into a dynamical ocean model, potentially overcome a number of these drawbacks (eg [14]). Perhaps most importantly, ocean reanalyses can provide estimates of the variability of the MOC with time, consistent with both dynamics and observations. However, ocean state estimation is in its infancy and issues remain with model error, uncertain forcing fields, the lack of observations (with known errors) available for use as constraints, and computational demands (resulting in reanalyses with either low spatial resolution, short duration, dynamically inconsistent assimilation approaches, or limited spatial domain) [14,15]. Ultimately our best estimates of the MOC are likely to be derived from high resolution, data-assimilating models, but there is some way to go before this goal is reached. In particular, deep observations are essential, both as constraints and for model validation. Reference [85] showed that assimilating observations of the MOC at 26.5N (see below) improved the representation of the upper and lower limbs of the MOC in an ocean state estimate over a latitude range of ±5 degrees of latitude of the observations.

While continuous, direct measurements of the global MOC are not feasible, new approaches have been developed to allow monitoring of the MOC at particular locations. One of the most exciting achievements in ocean observing in the last decade has been the first continuous, multi-year time series measurements of the Atlantic MOC.

The most ambitious example is the RAPID/MOCHA array at 26.5N in the Atlantic being carried out by the UK and USA [16-18]. Fig. 3 shows a 3.5 year time series of the transport of individual components of the MOC: the Gulf Stream at Florida Straits, interior flow in the upper ocean and Ekman transport. The mean overturning is 18.5 Sv, with a standard deviation of 4.9 Sv and a standard error of 1.5 Sv. The annual mean meridional heat transport is 1.3×10^{15} W, with a range from 0.1 to 2.5×10^{15} W; variability of the Ekman transport and geostrophic flow contribute roughly equally to the variability of heat transport [19]. The measurements reveal significant and unanticipated high frequency variability of the MOC on several time-scales, underscoring the need for both continuous sampling to avoid aliasing and for long time series to detect trends. A previous study which used a sequence of hydrographic snapshots to infer a decline in the strength of the AMOC [20] now appear likely to have resulted from aliasing [18]. The existence of a continuous time series is allowing new insights into the dynamics of the MOC, including identification of the mechanisms responsible for variability of the MOC on different time-scales (eg [21]). The demonstration that it is possible to directly and continuously observe the overturning circulation and meridional heat flux is a remarkable achievement.

The RAPID/MOCHA strategy for monitoring the AMOC consists of the following elements. The Gulf Stream transport through the Florida Straits is measured using electromagnetic measurements from a submarine cable. Tall moorings measure the transport of the western boundary current (the Antilles Current and the deep western boundary current (DWBC)). Dynamic height and bottom pressure moorings on either side of the deep basins and on either side of the mid-Atlantic ridge allow the pressure difference across the deep basins to be determined, from which the net transport can be derived using the geostrophic relationship. The Ekman transport is calculated from satellite scatterometer winds. The design was tested and refined using output from eddy-permitting ocean circulation models [22,23]. The fact that the sum of the individual components approximately conserves mass provides additional confidence that the transport estimates are robust [18].

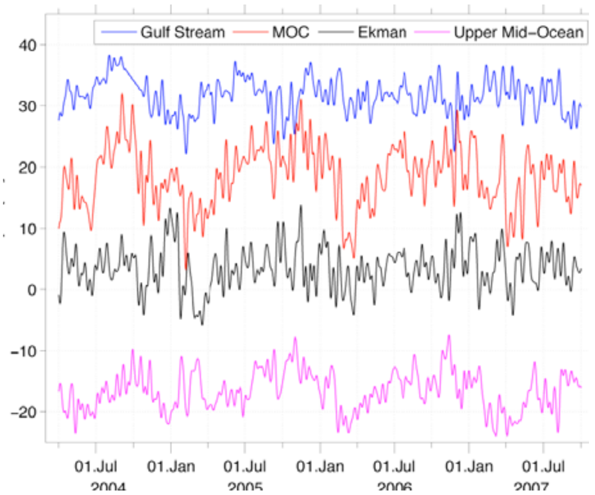

Figure 3. Twice daily time series of Florida Straits transport (blue), Ekman transport (black), upper midocean transport (magenta) and overturning transport (red). Transports in Sv, positive northward. Florida Straits transport is based on electromagnetic cable measurements. Ekman transport is based 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 [17]. 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.

The end-point monitoring approach has also proved effective at 16N in the Atlantic in the Meridional Overturning Variability Experiment (MOVE), where the time series of North Atlantic Deep Water export is now more than nine years long [24,25]. Flows in the eastern basin contribute little to the net transport. The near-rectangular geometry of the western Atlantic basin allows the MOC to be monitored with a small number of instruments and thus is very cost-effective. As found at 26.5N, the transport of the lower limb of the MOC is highly variable on short time-scales (Fig. 4). Despite the large high frequency variability, the time series is of sufficient duration to detect a significant (at 85%) weakening trend, corresponding to a 3 Sv reduction in the NADW export over the duration of the record. The weakening of the MOC is consistent in magnitude with internal variability in the FLAME model and with the MOC reduction projected from a coupled model initialised with SST [26].

The array design studies of [22,23] also identified locations where the end-point monitoring approach will not work. If barotropic flows make a significant contribution to the mass and heat transport, they need to be measured. Where western boundary currents are broad (eg over sloping topography), extensive and expensive moored arrays may be required. Complex bathymetry and barotropic flows in the ocean interior also need to be resolved, for example in the subpolar gyre where the gyre circulation makes a significant contribution to the net heat flux. For accurate estimates of property transports, these measurements need to be horizontally coherent to capture the correlations of velocity and temperature that are responsible for heat transport.

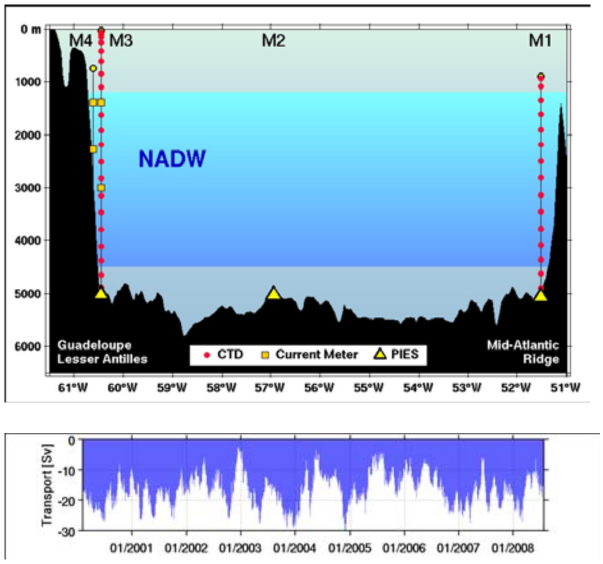

Figure 4. Top – MOVE section with endpoint moorings and PIES. Bottom – Absolute internal plus continental slope transport of NADW through the MOVE section from end-point moorings with density sensors. The long-term mean is 14.9Sv (southward). [25]

Basin-integrals of the MOC have only been directly and continuously observed at 26.5N and 16N in the Atlantic. But measurements of components of the MOC of more than one year duration have now been made at several locations, in particular in dense overflows and along the deep western boundary current carrying NADW southward in the deep limb of the AMOC [16,19,27,28]. These measurements have generally spanned the overflow or deep western boundary current, but not the flows in the interior of the basin. The presence of recirculation gyres offshore of the DWBC [29], usually not resolved by the moored arrays, often makes it difficult to use these measurements to infer the strength (or throughflow) of the MOC [28]. However, they do provide robust estimates of a primary pathway of the MOC. The DWBC estimates can be combined with measurements in the ocean interior (eg hydrographic sections) to estimate the MOC and net meridional transport. They also provide valuable constraints for ocean state estimates and for the testing of ocean models.

Few long-term current measurements have been made of the DWBCs in the other ocean basins, where estimates of the strength of the MOC still vary widely [12,13,30,31]. Exceptions include the current carrying Antarctic Bottom Water (AABW) northward into the Argentine Basin [32], the flow entering the Perth Basin [33] and the Pacific DWBC at 30S [34]. A recent study has directly measured for the first time the mean transport of the DWBC carrying AABW northward on the eastern flank of the Kerguelen Plateau (Fig. 5, [35]. Two-year mean flows of more than 20 cm s^{-1} were found at 3500 m depth, carrying 12.3 Sv northward (standard error of 1.2 Sv, standard deviation of 5.6 Sv), indicating that the Kerguelen DWBC makes a significant contribution to the global MOC.

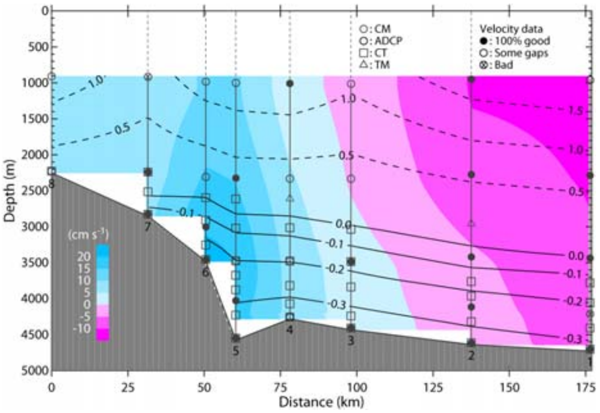

Figure 5. Kerguelen DWBC mean sections of the velocity perpendicular to the mooring array (shading; positive northwestward) and potential temperature (contours) over the two-year deployment. Also shown is a schematic diagram of moorings. CM, CT and TM denote current meter, conductivity-temperature recorder and thermistor.[35]

2.2 Influence of the deep ocean and MOC on global biogeochemical cycles

The MOC plays an important role in the global cycles of carbon, nutrients and other properties. Biological processes tend to transfer carbon and nutrients from the surface to the deep ocean. As a result, the deep ocean accounts for more than half of the natural oceanic carbon inventory. Mixing and the upwelling limbs of the MOC return carbon and nutrients to the surface layer, where nutrients can support phytoplankton growth and the introduction of carbon-rich deep water to the surface layer affects air-sea exchange and the chemistry (eg pH) of the upper ocean. For example, models suggest that nutrients upwelled and exported by the Southern Ocean support 75% of global primary production north of 30°S [4]. Changes in the MOC would therefore be anticipated to have an impact on biological productivity, food security and the ocean uptake of CO2. Atmospheric observations and coarse-resolution ocean model studies have suggested that the carbon sink in the Southern Ocean has "saturated" in recent decades, as a result of an increase in strength of the overturning circulation (and hence increased outgassing of natural carbon from the deep ocean) in response to stronger winds [5].

The sinking of surface waters in the downwelling limbs of the MOC transfers anthropogenic CO2 to the deep ocean. While most of the oceanic inventory is found in the upper ocean, anthropogenic CO2 is beginning to invade the deep sea in deep water formation areas. For example, Fig. 6 shows that anthropogenic CO2 is present in the deep waters of the North Atlantic. Anthropogenic CO2 has also been observed in deep waters formed in the Southern Ocean [36-38]. As the deep ocean burden increases with time, it will become increasingly important to measure the deep ocean to track the evolving inventory of anthropogenic CO2, particularly near the deep water formation zones and export pathways. Estimating anthropogenic CO2 in the ocean depends on empirical techniques, many of which rely on simultaneous measurements of other tracers, such as CFCs [39]. Therefore it is essential that hydrographic sections include transient tracers such as CFCs and SF6 as well as measurements of the carbon system.

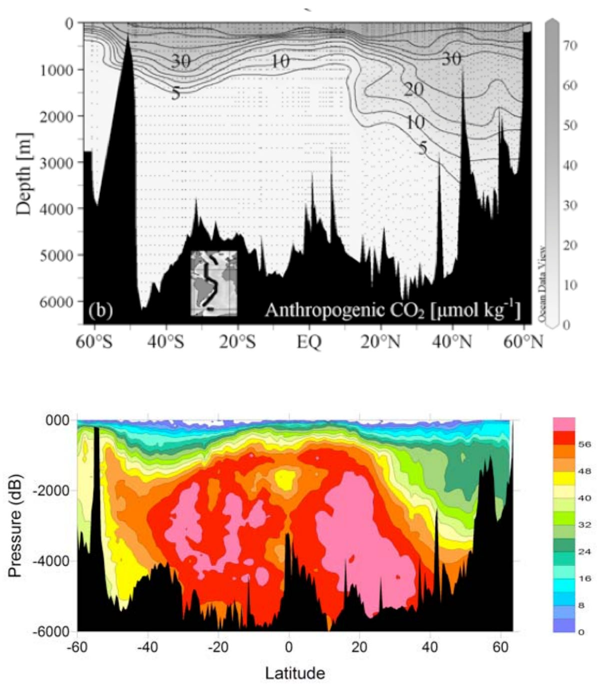

Figure 6. Top: Anthropogenic CO_2 *levels along a cross section in the Atlantic Ocean (see insert) showing appreciable levels at depths greater then 2000 m in the western basin of the North Atlantic (from[40]). Bottom: Chlorofluorocarbon-12 (CFC-12) age cross section for a Merdional section in the North Atantic (nominally 20 W).*

CFC-12 ages greater then 50 years are not reliable, but those less then that suggest that water has ventilated on these time-scales and should contain measureable anthropogenic CO_2 *(From [41,[42)*

2.3 Influence of the deep ocean and MOC on low-frequency climate variability

Seasonal and interannual climate variability is largely independent of the deep ocean and MOC. But as the time-scale of climate variability increases, the deep ocean becomes an increasingly important player. Multidecadal variations in Atlantic sea surface temperature (SST) have been linked to a wide range of phenomena of direct interest to society, including regional climate anomalies, persistent drought, hurricane frequency and fisheries production (see [43,90,94] and references therein). Recent studies provide evidence that the deep ocean and MOC are intimately involved in the dynamics of decadal and longer climate phenomena [3]. In particular, recent work (eg [44] supports the conclusion of [45] that at these time-scales the ocean tends to drive the atmosphere, and therefore ocean observations may offer some potential predictability. Estimates of the potential predictability of decadal variability tend to be large where the MOC is significant, in the North Atlantic and Southern Ocean [3]. While our dynamical understanding of low-frequency climate variability remains incomplete, a number of studies have concluded that advection of salinity anomalies by the MOC results in decadal variability of the MOC and its heat transport, and therefore in anomalies of sea surface temperature that drive decadal variability in the overlying atmosphere.

Decadal predictions would be of great value to society, for example by providing advanced warning of periods of drought. Improvements in this young field will require a more complete understanding of the dynamics of the MOC and deep ocean and their links to the atmosphere. An important point is that climate prediction at these time-scales becomes a joint initial value/boundary value problem, requiring accurate data with which to initialise the climate state, in particular the ocean [3]. Sustained observations of the deep ocean and MOC are needed to make progress on decadal prediction [46]. Preliminary studies at the Met Office Hadley centre have shown that temperature observations below 2000m improve decadal forecasts of future ocean heat content change [47,48].

2.4 Observations of change in the deep ocean

The lack of time series measurements has in the past prevented studies of change in the deep ocean. Recent analyses of data collected by the repeat hydrography program [49] is starting to reveal larger than anticipated signals of change in the deep ocean. The changes in deep ocean properties indicate that at least in some regions the deep ocean can respond rapidly to changes in surface climate.

The Antarctic Bottom Water (AABW) exported from the Southern Ocean to ventilate the abyss of each ocean basin has warmed in recent decades [50-54,89]. An example from the Atlantic is shown in Fig. 7. The changes in deep ocean temperature are sufficient to account for a significant fraction of the global energy imbalance [48,52,55]. Reference [52] estimated that the deep ocean could add an additional 2-10% to the upper ocean heat content trend and is likely to grow in importance as the anthropogenic warming signal propagates to increasing depth with time. These new studies complement previous results [55,56,87], indicating significant warming between 700 and 3000 m in the North Atlantic Ocean. Such abyssal and deep changes appear to make a substantial contribution to rising ocean heat content and hence sea level changes (e.g. [57]).

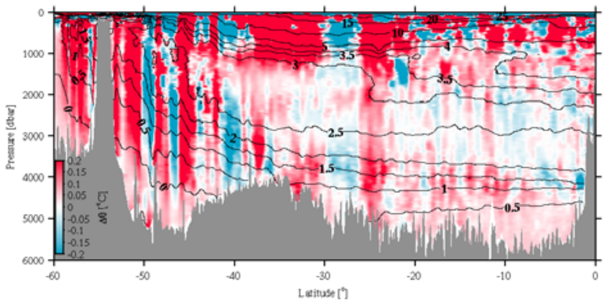

Figure 7. Differences in potential temperature, ΔΘ [°C], in the western South Atlantic resulting from subtracting WOCE section A16 data taken in 1985 (and A23 in 1995 in the Scotia Sea, south of 54°S) from 2005 reoccupation data taken by the U.S. CLIVAR/CO2 Repeat Hydrography Program. Values of ΔΘ are color contoured (inset color bar) from –0.2°C to +0.2°C to accentuate deep changes. Mean theta is contoured (black lines) at 0.5°C intervals below 15°C, and 5°C intervals above 15°C. Abyssal warming in the Scotia Sea, Argentine Basin, and Brazil Basin reaches 0.04°C, equivalent to 0.5 W m^{-2} *heating along the section to account for the warming at pressures exceeding 3000 dbar. After [50].*

The possibility that increased freshwater input to the high latitude ocean could cause a slowing of the thermohaline circulation, driving an abrupt change in climate, has focused considerable interest on the high latitude freshwater budget [1]. Changes in upper ocean salinity have been observed in each of the ocean basins, with an increase in salinity in the subtropical evaporation zones and a decrease at higher latitudes that is consistent with a more vigorous hydrological cycle and increased supply of melt water at high latitudes [58]. Numerous studies documented a freshening of North Atlantic Deep Water between the mid-1960s and the mid-1990s, when the North Atlantic

Oscillation (NAO) evolved to an extreme positive state (e.g. [59]). The freshening reversed in the mid-1990s. Weakening of westerlies associated with the NAO decline in the mid-1990s to mid-2000s caused a reduction of convection intensity in the Labrador Sea, a slowing and contraction of the subpolar gyre, and the northward advance of warm saline subtropical waters [60-64]. The NAO-induced upper ocean changes were rapidly transferred to deeper levels, causing an increase in temperature and salinity of Labrador Sea Water (LSW) and the deep waters[65-67].

While measurements are sparse in the Southern Ocean, several recent studies have detected changes in the salinity of Antarctic Bottom Water [51,68-73]. The Ross Sea and Adélie Land regions supply about 40% of the total input of AABW [10]. Most of the AABW exported from both sources passes through the Australian Antarctic Basin, making it a good place to monitor changes in properties of the AABW formed in the Indian and Pacific sectors. The deep T-S relationship has changed throughout the basin in recent decades, with a shift toward fresher and lighter bottom water observed in the deepest 1000 m of the water column [73]. [70,74,88] suggest that the most likely source of the additional freshwater is basal melt of glacial ice in the Pacific sector. Enhanced basal melting there has been linked to warmer ocean temperatures [75]. In contrast, in the Weddell Sea the situation is ambiguous, with freshening of bottom water in the west [76] and a slight increase in the salinity of deep water in the east [54].

The evidence from the North Atlantic and the Southern Ocean suggests that the dense water sinking in both hemispheres is responding to changes in the high latitude freshwater balance, and is rapidly transmitting this climate signal to the deep ocean. However, in only a few places are the observations sufficiently frequent to avoid aliasing of interannual variability. Expanded arrays of continuous measurements of deep ocean properties are needed to better understand the MOC and its response to changes in forcing.

3. A STRATEGY FOR SUSTAINED OBSERVATIONS

The deep ocean remains essentially unmeasured by the present ocean observing system, at least in a continuous sense. Most of our information comes from deep hydrographic sections, few of which have been repeated to allow assessments of change. Repeat sections are often separated in space by 1000s of km and in time by years or decades and hence are prone to aliasing. Continuous time series spanning a few years have been obtained in a few current systems, most in the dense overflows and DWBC of the North Atlantic. Our present understanding and observations of the deep ocean and MOC are inadequate to carry out a rigorous process of setting priorities and evaluating trade-offs. No systematic observing system design studies have yet been carried out for the global MOC and deep inventory (indeed, further advances are likely needed before such tools are able to be used with confidence for array design studies [15]. Nevertheless, substantial progress has been made in recent years, as summarised below and in [17] and [42] (for example, Table 1 of [17] lists 25 individual contributions measuring components of the Atlantic MOC). A challenge for the community in the coming years is to make the transition from a collection of observing elements to an integrated, coherent observing system. New technologies are also needed. In the following we outline a strategy for initial steps towards this goal.

The scientific challenges to be addressed with deep ocean observations require measurements of both transport and inventory. The sampling needs of each are different and it is useful to consider them in turn when designing a strategy for sustained observations of the ocean.

Sustained time series measurements of the transport of the MOC and deep currents rely on use of a combination of approaches. Recent experiments like RAPID/MOCHA in the North Atlantic provide a template for a cost-effective monitoring array, including the following elements.

- *Boundary Currents:* Much of the transport of the MOC is carried in narrow boundary currents and therefore direct velocity measurements are needed there. Both the surface-intensified but deep-reaching western boundary currents of the subtropical and subpolar gyres, and the deep western boundary currents that dominate the abyssal flow need to be measured. Boundary current transports can be observed using current meter arrays incorporating point-measurements and profiling acoustic Doppler current profilers (ADCPs), cables, pressure gauges and pressure-equipped inverted echo sounders (PIES).
- *Interior flow:* The full-depth volume transport in the interior of deep basins can be inferred from deep hydrographic measurements near the end-points (from moorings, ships or in some cases PIES), using the geostrophic relationship. Additional measurements are needed over the sloping topography at the basin boundaries or mid-ocean ridges. (Note, however, that estimates of the transport of properties (eg heat, freshwater, carbon) require knowledge of the covariance between

velocity and concentration and cannot, in general, be made from end-point measurements alone. In these cases, the only technique available to measure fluxes over the full ocean depth is repeat hydrography (or PIES, for heat and freshwater transport, in those locations where proxy methods like the Gravest Empirical Mode [77] apply).)

- *Ekman transport* can be estimated from satellite scatterometer measurements of wind stress (and therefore scatterometers are an important part of an MOC observing system).
- *Altimetry and gravity* measurements from space provide additional constraints on the flow and are useful for monitoring the MOC (as well as changes in ocean mass relevant to ocean-cryosphere interaction) [93].
- *Synthesis:* analysis approaches such as inverse methods or state estimation are often required to combine the observations in a consistent manner, in particular where observations resolve only a component of the MOC.

Measurements of the evolving inventory of heat, freshwater, carbon and other properties rely heavily on deep repeat hydrography [49]. Hydrographic sections remain the only tool available to sample the deep ocean over broad scales and the only way to collect samples for biological and biogeochemical analyses. The signal of change will appear first and be most prominent near the dense water overflows and along the main pathways of the deep circulation, hence these areas need to be sampled more frequently. Moored instruments provide the only means to obtain continuous time series of ocean currents and water properties and are therefore a key part of the armoury, despite the relatively high cost and therefore limited spatial distribution. Altimetry and gravity measurements provide integral constraints on ocean heat content. Acoustic tomography/thermometry also provides useful integral constraints on ocean heat content [78]. However, each of these tools has limitations and as a result, we are still not in a position to accurately measure changes in full-depth ocean heat content and other properties over most of the ocean. New technologies, as described below, are urgently needed to allow routine sampling of the deep ocean and estimation of a true global integral of ocean heat and freshwater content from the surface to the sea floor.

Specific recommendations:
The initial strategy for sustained observations of the MOC and deep ocean is summarised in Fig. 8. Further detail is available in [11,16,42,49]. Fig. 8 also illustrates the complex global network of deep boundary currents, basin-scale gyres, and interbasin exchanges that make up the MOC.

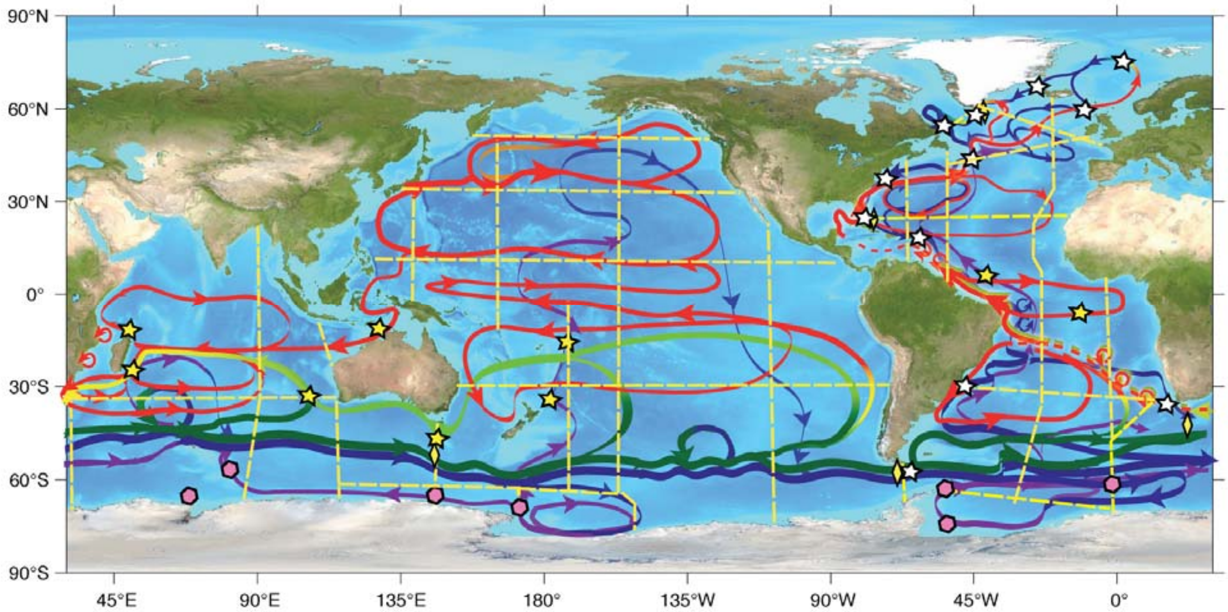

Figure 8. Schematic of the world ocean meridional overturning circulation, with observing system elements overlaid. Red is surface flows, blue and purple are deep flows, and yellows and greens represent transitions between depths. The proposed observing system is overlaid: repeat hydrography (dashed lines), moored arrays (stars), moored arrays to measure the AABW component of the global MOC (hexagons) and carbon moorings (diamonds). For clarity, some components of the proposed observing system are omitted (eg floats and broad-scale mooring array, see [42].) Base map from S. Speich, adapted from R. Lumpkin.

To understand the response of the MOC and associated property transports to changes in forcing, measurements are needed at several latitudes to allow the meridional coherence of the MOC to be assessed and understood. The partitioning of the meridional heat transport between the overturning and horizontal gyre circulations, for example, differs strongly with latitude [79]. Model studies suggest that the meridional coherence of the AMOC has different timescales at different latitudes, with stronger decadal variability in the subpolar regime and stronger high frequency variability in the subtropics [80,81]. Other model studies suggest that measurements at a single latitude in each basin of the Atlantic might be sufficient to detect MOC changes on multidecadal scales, but that measurements at additional latitudes are needed to capture interannual to decadal variability [79,86].

Based on these results, basin-wide monitoring of the Atlantic MOC and meridional heat and freshwater transport is recommended at a minimum of three latitudes: 47N, 26.5N and between 25-35S. At 26.5N, the RAPID/MOCHA array needs to be maintained. At 47N and 26.5N, interior measurements of water properties and velocity are needed, as well as boundary arrays and end-point monitoring.

The basin-wide monitoring needs to be complemented with measurements of key components of the MOC and deep circulation. Existing long-term measurements of dense overflows and boundary currents in the Atlantic must be continued (see Fig. 3 and Table 1 of [16] for the location of these measurements). A new array is needed at Cape Farewell to measure the combined flux of the Denmark Strait and Faroe Bank Channel overflows [82]. Monitoring of the boundary currents in the South Atlantic needs to be enhanced [42]. The Southern Ocean chokepoint sections and Indonesian Throughflow need to be monitored to determine the influence of interbasin exchange on the MOC [11,83,84]. Dense water formed in the Southern Ocean plays a roughly equal role in ventilating the deep ocean [9,10] and therefore the southern hemisphere dense overflows and boundary currents carrying ventilated water northward also need to be measured for a complete understanding of the global MOC [91].

Repeat hydrography will remain the backbone of the broad-scale deep ocean observing system [49]. The recommended repeat hydrographic lines are shown in Fig. 8. On each section, top-to-bottom measurements of temperature, salinity, oxygen, carbon, nutrients and transient tracers are needed. More frequent sections are recommended near the dense water overflows and boundary currents, where the signal of change is evolving more rapidly (see [49] for the rationale and recommended sampling frequency for specific sections).

The repeat hydrography program, while essential, is still far from adequately sampling the deep ocean, given the infrequent sampling in space and time. Acoustic thermometry is a valuable and cost-effective complement to deep hydrography, capable of providing basin-wide integrals of heat content that include the deep ocean [78].

In addition to the importance of maintaining the existent observing systems for deep ocean velocity, heat, salt, and carbon there is a critical need to develop new, cost-effective, technologies for observing the deep ocean. Profiling floats capable of deeper profiling would allow broad-scale, sustained sampling of deep ocean properties for the first time. As well as the technological advances necessary to achieve this, design studies are needed urgently to determine the appropriate investment and deployment strategy for deep floats. Deep gliders could also make an important contribution. Near-continuous time series are needed to avoid aliasing and to determine the spectrum of deep variability. Development of inexpensive, long-term moorings with the ability to transfer data to the surface (eg using expendable data capsules, acoustics or other means) is needed to allow time series to be measured in remote ocean locations [42]. It is not yet possible to measure properties other than temperature, salinity and oxygen from a mooring. Development of new sensors and platforms to measure carbon and other biogeochemical parameters is essential to improve our ability to track the evolving ocean inventory of carbon and acidification.

An observing system for the MOC also depends heavily on elements of the global ocean observing system covered in detail by other CWPs and PPs, including Argo, boundary current measurements and satellite remote sensing (eg altimetry, gravity, infrared and microwave SST, scatterometer and cryosphere).

The strategy outlined above and illustrated in Fig. 8 is a first step, guided by (incomplete) existing knowledge of the MOC and deep ocean and constrained by what is feasible. Rigorous observing system design studies are needed to refine the strategy.

4. SUMMARY OF RATIONALE AND RECOMMENDATIONS

Sustained observations of the deep ocean are needed to address key uncertainties that limit our ability to provide the knowledge needed by society to respond effectively to climate change and variability. In particular, deep observations are needed:

- To determine the transport (mass, heat, salt, and carbon), variability, dynamics and climate influence of the MOC. This deeper understanding of the nature of the MOC is required to provide more accurate projections of future climate.
- To close the planetary energy budget. Heat storage by the deep ocean makes a significant contribution to the overall heat budget of the Earth.
- To determine rate and mechanisms of sea-level rise. Estimates of sea-level that do not take the deep ocean into account will tend to underestimate the rate of sea-level rise; changes in sea-level associated with future changes in the MOC may produce regional anomalies in sea-level of comparable size to the rise due to thermal expansion and melting of ice.
- To determine the global budgets of carbon and nutrients, their sensitivity to change and the impacts of changing ocean chemistry on deep-sea biota. The ability of the ocean to store carbon dioxide is a strong function of the MOC, including both sequestration of anthropogenic CO2 in deep water formation areas and release of natural CO2 in upwelling regions. Changes in the MOC would alter the ocean sink of CO2 and the overall biological productivity of the ocean, through changes in nutrient supply.
- To constrain ocean state estimates. The lack of observations below 2000 m to constrain ocean state estimates limits the ability of ocean reanalyses to simulate important ocean quantities like meridional heat flux.
- To initialise decadal climate forecasts. The deep ocean becomes increasingly important as the time-scale of interest increases; initialising with deep ocean observations increases the skill of decadal and multi-decadal forcasts.
- To understand the dynamics and nature of the global-scale ocean circulation, including the response to forcing and modes of variability. Much of the deep ocean remains poorly sampled and therefore largely unknown.
- To test and develop models, proxies and satellite data. Present models vary widely in their representation of the MOC and the deep circulation, but the lack of deep observations makes it difficult to identify model flaws. Proxy techniques based on integral measures of ocean properties (sea surface height, gravity) are becoming more useful and more widely used, but require deep observations for their development and validation.

Sustained observations of the deep ocean remain a significant challenge. However, recent advances provide some guidance for the design of a deep ocean observing system. Recommendations for deep ocean observations include:

- Maintain and build on established sites and technologies.
- Deploy moored arrays in key deep boundary currents and passages.
- Exploit the end-point monitoring approach for cost-effective measurements of basin-scale, full-depth flows, where possible. Recognise that heat and freshwater flux generally require observations in interior (eg from PIES or repeat hydrography).
- Repeat full-depth hydrography with tracers (with more frequent measurements near dense water outflows).
- Develop and deploy inexpensive moorings (eg using data capsules) to measure deep ocean properties on basin scales.
- Expand the use of acoustic tomography/thermometry, which provides valuable integral constraints on ocean heat content, including the deep ocean, but remains underexploited.
- Maintain satellite observations (altimeter, gravity), which measure integrals of the water column and are therefore an important component of a deep ocean observing system.
- Carry out further observing system evaluation studies to refine the design of the deep ocean observing system.
- Enhance the coordination of deep ocean studies, to ensure resources are deployed as effectively as possible.

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