Overturning in the North Atlantic

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Abstract

The global overturning of ocean waters involves the equatorward transport of cold, deep waters and the poleward transport of warm, near-surface waters. Such movement creates a net poleward transport of heat that, in partnership with the atmosphere, establishes the global and regional climates. Although oceanographers have long assumed that a reduction in deep water formation at high latitudes in the North Atlantic translates into a slowing of the ocean's overturning and hence in Earth's climate, observational and modeling studies over the past decade have called this assumed linkage into question. The observational basis for linking water mass formation with the ocean's meridional overturning is reviewed herein. Understanding this linkage is crucial to efforts aimed at predicting the consequences of the warming and freshening of high-latitude surface waters to the climate system.

1. INTRODUCTION

Ocean waters are prone to overturning. Though generally stably stratified, with less dense waters situated above more dense waters, ocean surface waters are vulnerable to a host of processes that can quickly change their density. An exchange of heat or freshwater across the sea surface can increase or decrease surface water density such that the water column becomes more or less stable, respectively. Destabilization results in a local overturning of the waters. Such overturning is ubiquitous, as are the mixed layers of homogeneous water properties that result. Some mixed layers are ephemeral, lasting only until the warmth of the morning sun erases the signature of nocturnal overturning, whereas others persist from one season to the next. Mixed layers can be shallow or impressively deep, with the depth of mixing largely mapped to seasons and latitudes.

Local overturning, linked to exchanges of buoyancy across the sea surface, is of much interest not only for its role in heat budgets in the atmosphere and ocean, but also because it is considered the first stage in the process that creates the myriad of water masses that occupy vast regions of the ocean basins. These water masses, generally categorized by the depth at which they reside in the water column, have been a focus of physical oceanographic studies for decades and have been the cornerstone for our understanding of flow patterns at depth. In particular, the deep water masses formed via local overturning during winter in the high latitudes of the North Atlantic and in the Nordic Seas have received considerable attention because traces of their signature can be found globally (Lazier et al. 2001, Saunders 2001 and references therein).

The ocean's meridional overturning, the subject of this review, describes the movement of water in the meridional/depth plane. This two-dimensional overturning is understood to involve the bulk movement of upper, thermocline waters in one meridional direction and the movement of deep waters in the opposing meridional direction. In the North Atlantic, the upper waters move poleward while deep waters move equatorward; in the South Atlantic, these directions are reversed. These meridional movements are linked via downwelling at some locales, where surface waters are converted to deep waters, and via upwelling elsewhere for the transformation of deep to shallow waters. Conventionally, the meridional overturning circulation (MOC) has been connoted with the "ocean conveyor belt," which in turn has been linked synonymously with the thermohaline circulation. Today, neither linkage is safely assumed (Wunsch 2002, Lozier 2010). Instead, the MOC is identified by a mathematical definition: the zonally integrated volume flux as a function of latitude and depth. As shown in **Figure 1**, the calculation of zonally integrated volume fluxes results in streamlines in the meridional/depth plane that depict the northward (poleward) flow of surface waters across the equator, referred to as the upper limb of the overturning, and the southward (equatorward) flow of deep waters that were recently ventilated at high latitudes in the North Atlantic, referred to as the lower limb of the overturning. The summation of the total poleward (or equatorward) components of this overturning yields a single measure for the strength of the meridional overturning. Importantly, this description of the MOC is a simple definition of the flow field and, as such, does not presuppose a mechanistic cause for the overturning or its variability.

The crux of this review is the relationship between local overturning, which leads to the production of water masses, and the ocean's meridional overturning. The focus is restricted to the deep water masses formed in the high latitudes of the North Atlantic, where sufficient observations and studies over the past decades allow for such a review. The relationship between the local production of deep water masses and the meridional overturning has been assumed mutually causal for decades. With this causality, the strength of the meridional overturning depends upon the spread of dense water masses produced via local overturning at high latitudes in the North Atlantic: a larger/smaller production of water masses enhances/diminishes the magnitude of the
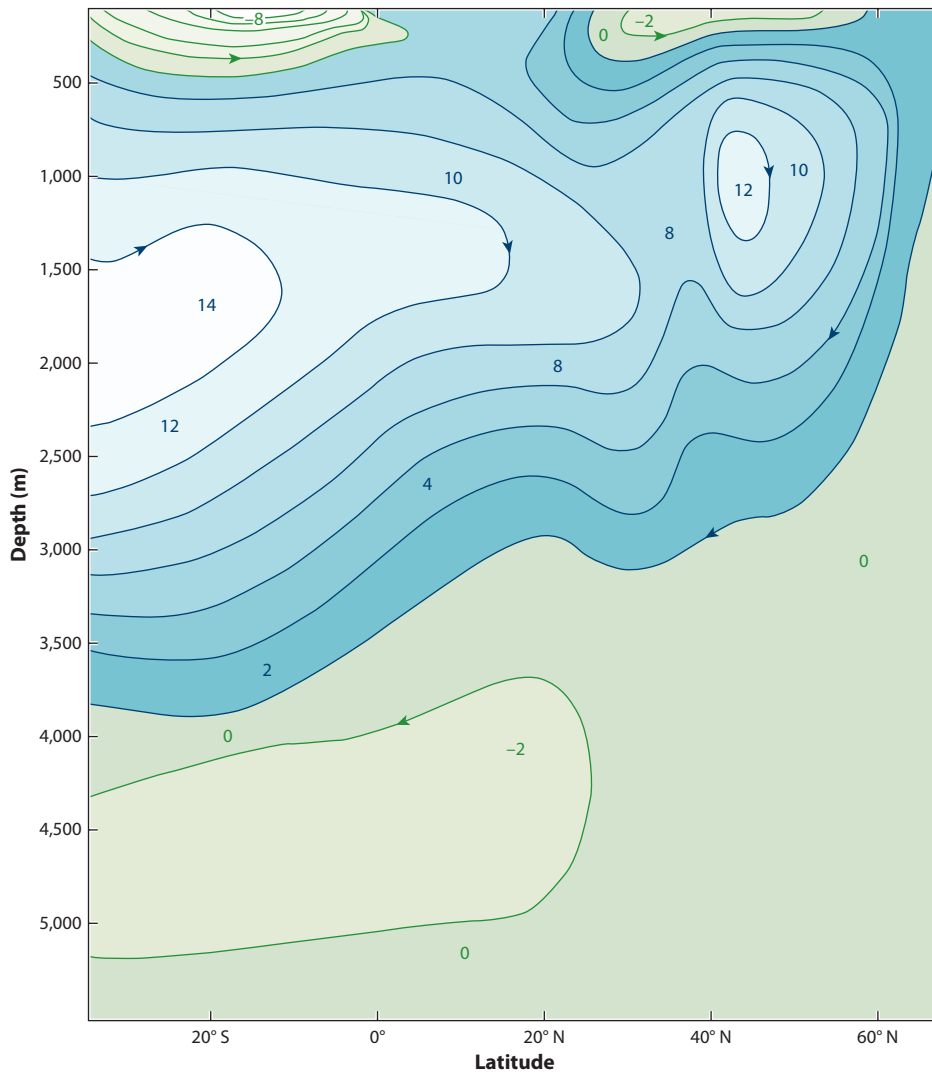
Figure 1

Meridional overturning circulation. The contoured field is volume flux (in Sv, 10^6 m^3 s^{-1}), calculated as the zonal integral of the meridional velocity obtained from a general circulation model. The focus of this review is on the clockwise overturning circulation comprising northward near-surface flow, downwelling in the high latitudes of the North Atlantic, and southward flow at depth. (Figure adapted from Wunsch 2002.)

overturning. Likewise, the return of surface waters as part of the upper limb of the overturning has been assumed to impact local overturning at high latitudes by weakening or strengthening the surface stratification, depending upon the salinity and/or temperature of the returning waters. This two-way relationship has been used to build feedback scenarios. For example, a freshening of the surface waters in the high-latitude North Atlantic is expected to inhibit the production of deep water masses, which in turn would slow the overturning, an action that would rob the high latitudes of the warmth delivered by the returning waters and hence encourage the resumption of overturning because the surface waters would tend to cool.
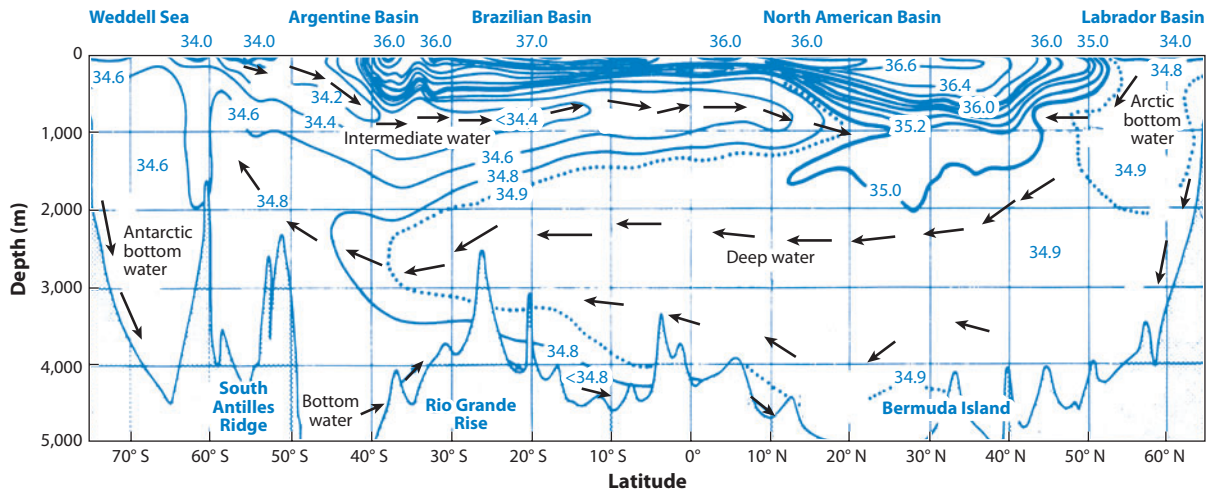
Figure 2

Meridional cross section of salinity in the western Atlantic Ocean. (Figure adapted from Tchernia 1980, where it was reprinted from Merz 1925.)

This feedback scenario highlights an important aspect of the overturning circulation: The transport of heat accomplished by this circulation is of more consequence than the transport of water itself. In fact, interest in the meridional overturning largely stems from its expected influence on the meridional transport of heat. In partnership with the atmosphere, the ocean provides a poleward heat flux that offsets the radiation inequities imposed by the differential heating of Earth (Trenberth & Caron 2001, Ganachaud & Wunsch 2003). Without the fluid movement of heat from equatorial to polar latitudes, the temperature difference between the equator and poles is estimated to be ~110°C, rather than the more moderate 30°C that exists today (Gill 1982). Thus, successful predictions of climate change and climate variability depend crucially on an adequate understanding of the movement of these planetary fluids and their susceptibility to perturbations. For the ocean, nowhere is this truer than in the North Atlantic. As revealed by a recent study, the MOC in the subtropical North Atlantic is largely responsible for the oceanic poleward heat flux at 26.5° N (Johns et al. 2011), an amount that accounts for 70% of the ocean's global contribution and 25% of the total poleward heat flux. Thus, an understanding of how, when, and why overturning circulation in the North Atlantic might change is of prime importance.

The link between local and meridional overturning was grounded in the earliest observations of the ocean's property fields, where distinct temperature, salinity, and oxygen signatures of inter-mediate and deep water masses were traced from their source regions to points worldwide (Merz 1925, Wüst 1935; for a review, see Richardson 2008). The trace of those signatures was used to infer flow pathways, as illustrated in **Figure 2**—a choice that assumes an ocean flow field where advection dictates the spread of properties. With the spread of these deep properties so distinct from the distribution of surface properties, conjectures on the driving force for the deep flow focused on the density gradients that these water masses created. Thus, deep water masses were assumed to provide not only the tracers for the deep flow, but also the mechanism.

Though competing hypotheses for the forcing of the overturning persist (Kuhlbrodt et al. 2007, Visbeck 2007), it is generally recognized today that this circulation is not simply "pushed" by meridional density gradients. Instead the overturning circulation is likely a function of internal mixing supplied by tides and winds, remote and local wind and buoyancy forcing, and the impact

of eddies on all of these processes. Whereas theoretical and modeling studies have focused on ascertaining how these processes collectively drive the overturning continue apace, this review focuses on one question of immediate relevance: What is the impact of variable North Atlantic Deep Water (NADW) production on the ocean's meridional overturning? In other words, are changes in local overturning manifest in a temporally variable meridional overturning?

Though countless modeling studies have demonstrated the impact of deep water formation changes on the overturning circulation, the focus with this review is primarily on the observational evidence for such a linkage. This linkage was studied by Schott et al. (2004), who analyzed moored array observations off the Labrador coast for signatures of recently ventilated Labrador Sea Water (LSW) in the waters of the Deep Western Boundary Current (DWBC) off the continental slope in the western subpolar basin. In the intervening 8 years since this study, our conceptual understanding of the structure, coherence, and variability of the meridional overturning has advanced considerably, as has our understanding of deep water formation processes; thus, a new look at this question is timely. A reexamination is timely as well because the Arctic waters—source waters for the overflow waters that feed the North Atlantic and for the freshwater input into the Labrador Sea—are undergoing unprecedented change (McPhee et al. 2009). The global consequence of those changes depends in large part on their downstream communication via the overturning. As such, it is essential that we understand the nature of this communication. Fortunately, new observations in the North Atlantic over the past decade have facilitated a closer look at this linkage: those studies, along with complementary modeling studies, are reviewed herein. For reviews on other aspects of the MOC, interested readers are referred to (*a*) a monograph on the history of overturning schematics (Richardson 2008), (*b*) a recent review on observational and modeling estimates of MOC strength and structure (Cunningham & Marsh 2010), (*c*) an examination of the physical mechanisms supplying the energy required for overturning (Kuhlbrodt et al. 2007), and (*d*) a review on the contribution of the South Atlantic to MOC variability (Garzoli & Matano 2011).

2. SPREADING OF THE NORTH ATLANTIC DEEP WATERS

Although today oceanographers assimilate many thousands of observations of temperature, salinity, and sea surface height into ocean models to produce estimates of the ocean circulation (Bell et al. 2009, Wunsch et al. 2009, and references therein), just over 200 years ago a single temperature profile from the tropical waters was used to infer the ocean's meridional overturning (Warren 1981). In 1800, Count Rumford's interest was drawn to a record of temperature change with depth in the tropical Atlantic, taken by a sea captain of a British slave trader at the request of an English clergyman in 1751. These observations, recorded and then sent to the Royal Society in London, revealed deep ocean temperatures far colder than expectations based on local air temperatures. Recognizing that these deep tropical waters must have originated from a locale where surface waters were that cool, Rumford correctly surmised that ocean waters must overturn in the meridional plane. Essentially, from this single profile of temperature in the tropics, Rumford deduced that (*a*) cold waters descended from the surface near the poles, filling the global ocean as they spread equatorward, and (*b*) high-latitude regions were replenished with warm surface waters from lower latitudes.

It was not until the early part of the last century that the spreading Rumford imagined was revealed. Property signatures of the deep water masses spreading from the North Atlantic to the shores of the Antarctic continent were made abundantly clear from the first shipboard survey of the Atlantic during 1925–1927 onboard the research vessel *Meteor* (Wüst 1935, Richardson 2008). Meridional hydrographic sections showed NADW penetrating from the surface waters at high latitudes in the northern North Atlantic into the deep waters at lower latitudes. As discussed in
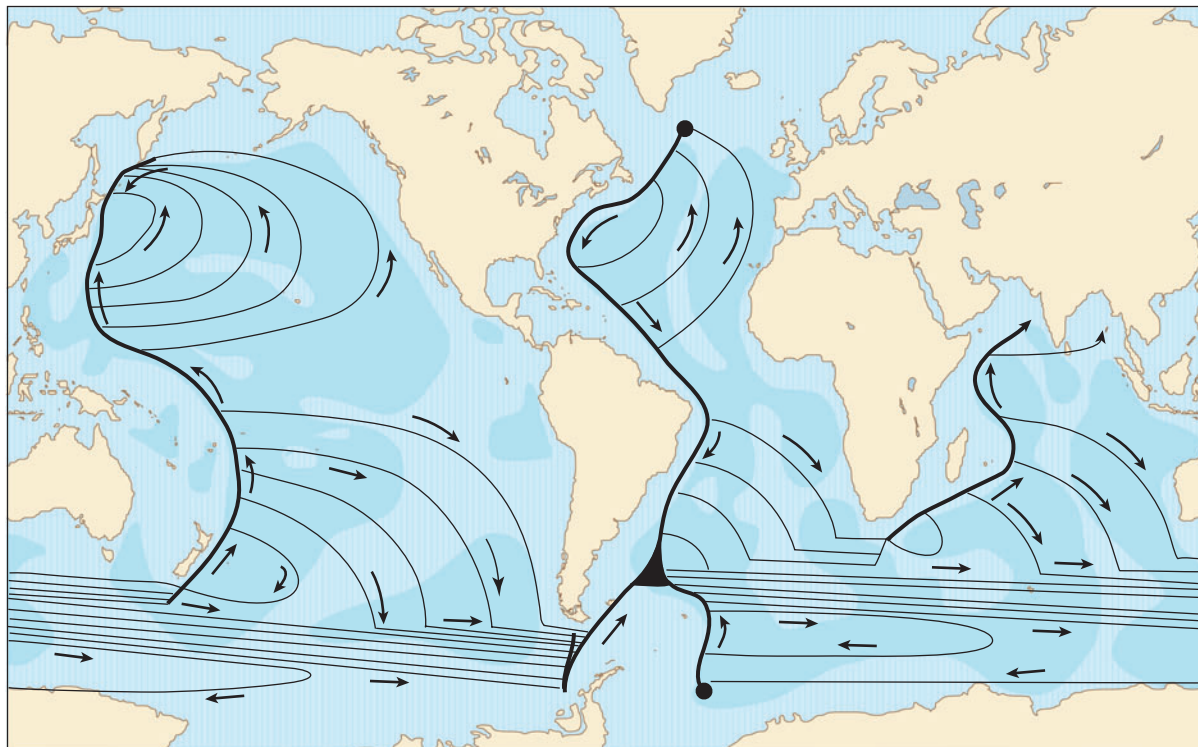
Figure 3

The abyssal flow as theorized by Stommel (1958). Water mass source regions in the northern North Atlantic and Antarctica are denoted by black dots. These water masses spread equatorward by western intensified boundary currents (*thick lines*) that feed a poleward interior circulation (*thin lines*). (Figure adapted from Lozier 2010, where it was reprinted from Stommel 1958.)

the excellent review of meridional overturning schematics mentioned above (Richardson 2008), early oceanographers added arrows to the contours to indicate flow along the strikingly visible property "tongues." Furthermore, some of the first plan views of these property fields revealed an interesting asymmetry: the spreading of the deep waters was concentrated along the western boundaries of the basin (Richardson 2008). It was not until the midcentury mark that Henry Stommel (1958) formulated a theory for the abyssal circulation that accounted for the asymmetrical supply of NADW along deep western boundary currents. This theory, based on steady-state potential vorticity dynamics, required an equatorward-flowing deep western boundary current to offset a poleward transport of water in the abyssal interior (**Figure 3**). Though there has never been evidence of poleward interior transport in the North Atlantic or elsewhere, clear and convincing evidence for deep western boundary currents filled with recently ventilated waters from the northern North Atlantic has long been abundant (Pickart 1992, Smethie et al. 2000).

3. LINKAGE BETWEEN WATER MASS VARIABILITY AND DEEP WESTERN BOUNDARY CURRENT TRANSPORT CHANGES

Starting in the early 1980s, studies suggested that meridional overturning changes could drive climate fluctuations (Broecker & Peng 1982, Broecker 1991, and references therein) on millennial timescales. Furthermore, studies during the 1990s raised the possibility that meridional

overturning changes could cause climate change on decadal, or rapid, timescales (Stocker & Wright 1991, Rahmstorf 1994). Thus, with anthropogenic warming continuing apace in the twentieth century and a projected continuation into the next century (Intergov. Panel Clim. Change 1990), concerns mounted that the diminishment of deep water production in the North Atlantic would lead to rapid climate change through the slowing of the meridional overturning. Deep water formation is difficult to quantify because the time and locale of production are highly variable from winter to winter; thus, quantification efforts focused instead on the properties and transport of the DWBC in the North Atlantic. A measure of the DWBC was considered essentially a shortcut to a measure of the MOC: although the upper limb of the MOC was considered inextricably linked to the much more energetic wind-driven circulation, the lower limb was considered to be channeled through the DWBC. Thus, variable DWBC transport and properties were believed to reflect changes in MOC transport and properties, which in turn were understood to result from changes in deep water formation.

An opportunity to assess the linkage between deep water formation variability and DWBC changes was afforded by the deployment of a moored array east of the Grand Banks at 43° N during 1993–1995 (Clarke et al. 1998, Meinen et al. 2000) and then again, with a modified design, from 1999 through 2001 as part of the World Ocean Circulation Experiment (Schott et al. 2004). Both experiments enabled the computation of transport and property time series at a location considered to be the crossroads of the deep North Atlantic, where recently ventilated, cold waters from the north transited from the subpolar regions to the subtropics, passing by the relatively warm waters of subtropical origin carried within the northward-flowing North Atlantic Current. In an extensive analysis of the time series from these two deployments, Schott et al. (2004) found that the transports of LSW over these two time periods were remarkably similar despite the large differences in convective activity in the Labrador Sea during the two time periods: the earlier time period was marked by strong convective activity, while LSW production was extremely weak during the latter time period (Lazier et al. 2002). This result raised questions about the responsiveness of the MOC to changes in deep water production; however, the linkage could not be conclusively ruled out because of increasing indications that the DWBC was not the sole conduit for the passage of deep waters to the lower latitudes (Schott et al. 2004).

4. LAGRANGIAN VIEW OF SUBPOLAR TO SUBTROPICAL EXPORT

Doubts about the DWBC's role as a unique pathway for the deep waters of the northern North Atlantic were brought to the fore with analyses of profiling floats released in the Labrador Sea during the 1990s. Of approximately 200 profiling floats released in the central Labrador Sea as part of the Labrador Sea Deep Convection Experiment (Lab Sea Group 1998), none were exported to the subtropical region within the DWBC (Lavender et al. 2000). Although it might be surmised that the floats were never part of the DWBC system because they were placed in the interior of the Labrador Sea, a second study purposely placed 15 floats within the DWBC at the depth of the LSW; after 2 years, all of these floats were detrained from the DWBC, and none were exported to the subtropical basin via the DWBC conduit (Fischer & Schott 2002). Fairly, concerns were raised about the legitimacy of these profiling floats as indicators of deep flow pathways, because periodic surfacing (nominally every 10 days) exposed the floats to strong surface currents that could easily displace a float from its pre-ascent position (Getzlaff et al. 2006).

To further explore the pathways of recently ventilated waters from the subpolar gyre to the subtropics, a RAFOS (Rossby et al. 1986) float study was designed to explicitly test whether the DWBC was the primary conduit for the subpolar to subtropical export of LSW (Bower et al. 2009). As part of this program, six floats were released four times each year for 3 years within the

southward-flowing boundary current near Orphan Knoll off the Labrador coast. Two deployment depths were selected to capture the expected range of LSW convective activity: 700 and 1,500 m. The trajectories of these RAFOS floats confirmed suspicions raised earlier by the profiling float studies mentioned above as well as by tracer studies (Rhein et al. 2002, Kieke et al. 2006): Very few RAFOS floats entered the subtropical gyre via the DWBC; instead, the dominant pathway to the subtropics was via the interior, generally confined to the west of the Mid-Atlantic Ridge. Because these observational floats were necessarily limited in number and lifetime, this study was complemented by the simulation of float trajectories within an eddy-resolving ocean general circulation model (Böning et al. 2006).

As seen in **Figure 4**, the observed and simulated floats, all launched at a common site near Orphan Knoll, trace multiple entry points from the subpolar DWBC into the subtropics. The pathways essentially map a large-scale anticyclonic recirculation (**Figure 5**) believed to result from eddy-driven mean flow (Lozier 1997). These deep recirculations were originally identified from an analysis of historical hydrographic data (Lozier 1997) and later confirmed by a modeling study that demonstrated the absence of these recirculations in models that do not adequately resolve mesoscale eddies (Gary et al. 2011). Quantification of the transport associated with the interior pathways shows that they, not the DWBC, dominate the transport of deep water to the subtropics. Concerns that isobaric floats do not adequately mimic three-dimensional pathways (Getzlaff et al. 2006) were addressed in a recent study that showed a remarkable similarity between two- and three-dimensional pathways in eddy-resolved, time-varying flow fields (Bower et al. 2011). Interestingly, this study found that although the DWBC is not the dominant pathway, it appears to be the fastest track for the advection of deep water property signals to arrive in the subtropics, as previously suggested (Molinari et al. 1998). Thus, although it is clear that DWBC transport variability downstream of the subpolar gyre cannot be used as a measure of the export of deep subpolar waters to the subtropics, or the lower limb of the overturning circulation, observations of property changes within the DWBC will generally reflect upstream source water changes earlier than other locales in the subtropics. However, it is noted that recirculations create considerable mixing between boundary current and interior waters such that the age of boundary current waters is measurably larger than that expected based on advection along the boundary from the subpolar to subtropical region (Watts 1991). Furthermore, tracer age contours in the subtropical basin are more closely perpendicular than parallel with the western boundary (Smethie et al. 2000), consistent with evidence from the observed and modeled float studies (Bower et al. 2009, Gary et al. 2011) that reveal interior pathways. Finally, the float and tracer studies collectively suggest that source water changes alone do not dictate water mass age or properties. In illustration, Lozier (1999) showed that deep waters age most rapidly (as measured by tritium-He[3] gradients) along the DWBC at the depth where the spatial extent of these eddy-driven recirculations is largest.

In sum, the Lagrangian view of the North Atlantic over the past decade has provided evidence that monitoring the DWBC in the subtropical basin is insufficient as a monitor of transport changes within the deep limb of the MOC. Additionally, this Lagrangian view has reinforced a growing appreciation for the contribution of eddies to the pattern of the deep velocity and
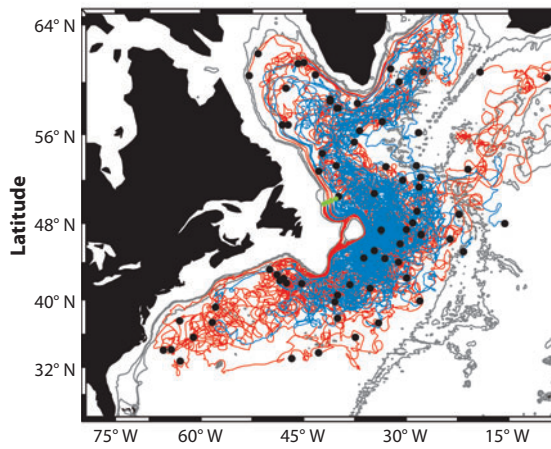
Figure 4

Trajectories of (*a*) 2, (*b*) 5, and (*c*) 10 years' duration for 72 synthetic floats at 700 m (*red*) and 1,500 m (*blue*), selected from an ensemble of 7,280 15-year trajectories computed using the three-dimensional model velocity field from an ocean general circulation model. Observational trajectories (*yellow*) are shown in panel *a* for comparison. All floats share the same launch location (*green line*) at Orphan Knoll in the subpolar North Atlantic. The endpoint of each synthetic float trajectory is marked with a black dot. Isobaths are shown in gray for 0, 700, 1,500, and 3,000 m. (Figure adapted from Bower et al. 2009.)
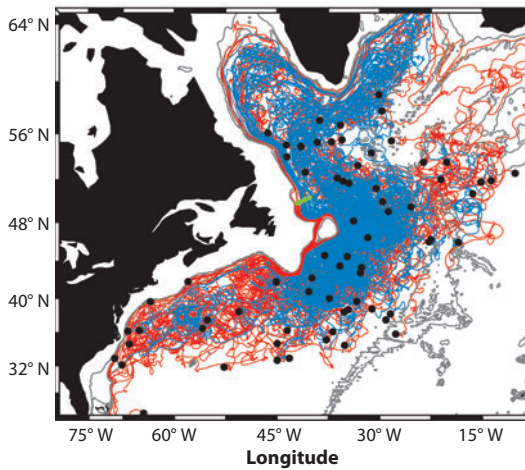
a 2 years after launch
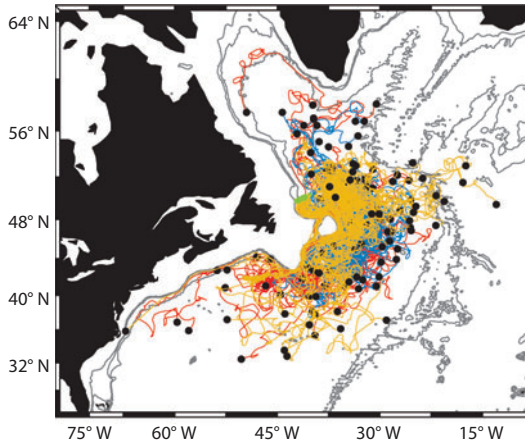
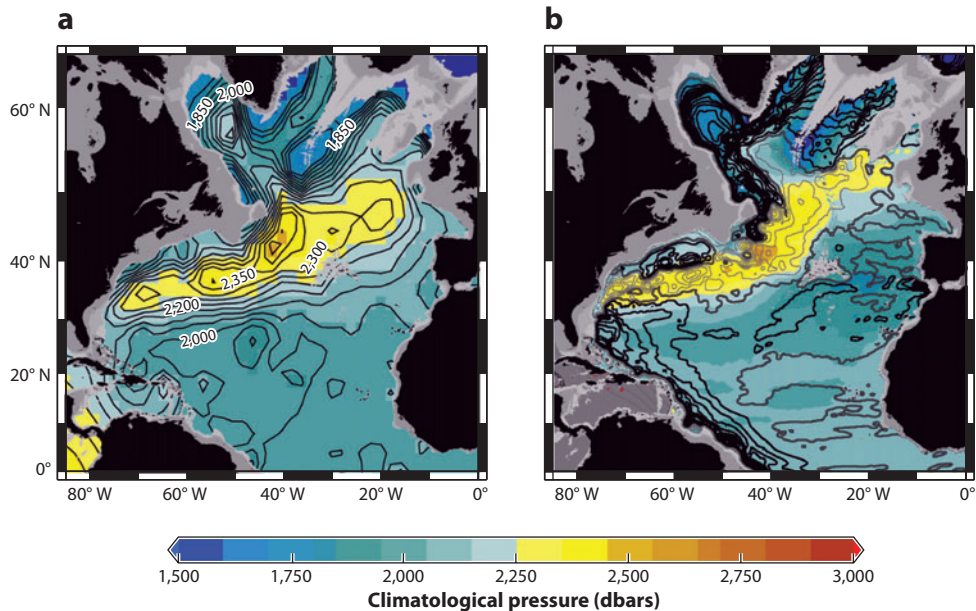**b** 5 years after launch

c 10 years after launch

Figure 5

(*a*) Climatological pressure on a deep isopycnal ($\sigma_2 = 36.95$, ~2,300 m in the subtropical basin) created from historical hydrographic data, contoured at 50-dbar intervals. The isobars approximate flow lines with the assumption of geostrophy, and the closed isobars trace an anticyclonic recirculation to the south of the Gulf Stream/North Atlantic Current with the assumption of a deep level of no motion (Lozier 1997). (*b*) Climatological pressure as in panel *a*, but created using output from an eddy-resolving general circulation model on $\sigma_2 = 36.98$, and the overlaid contours are the model's time-mean streamfunction with 1,000 m² s⁻¹ intervals. Thick black lines are positive values, and thinner gray lines are negative values. (Figure adapted from Gary et al. 2011.)

property fields. Though eddies have been understood to detrain and entrain fluid from deep boundary currents (Bower & Hunt 2000) and even to constitute the whole of the deep western boundary current at 8° S in the South Atlantic (Dengler et al. 2004), there is now an appreciation that eddies can drive the mean flow. As will be discussed below, the contribution of eddies also extends to the transformation of convected waters, further challenging our understanding of water mass production and its linkage to water mass export.

5. TRANSBASIN MEASURES OF MERIDIONAL OVERTURNING CIRCULATION VARIABILITY VIA HYDROGRAPHIC SURVEYS

For a full accounting of the MOC and its variability, it has been understood that transbasin measurements of transport are necessary. Because the ocean's velocity field has historically been more difficult to measure than its property fields, the historical database of temperature and salinity observations far outweighs that for velocity. As such, attempts to understand MOC variability over the modern observational record have had to rely on indirect estimates assessed from hydrography. In brief, reconstruction of the density field from measures of the local temperature, salinity, and pressure fields allows for a computation of the geostrophic shear, which yields a measure of geostrophic velocities as a function of depth once a reference velocity is known. To calculate changes in the meridional overturning, the only choice for many years was to use repeat hydrographic zonal sections.
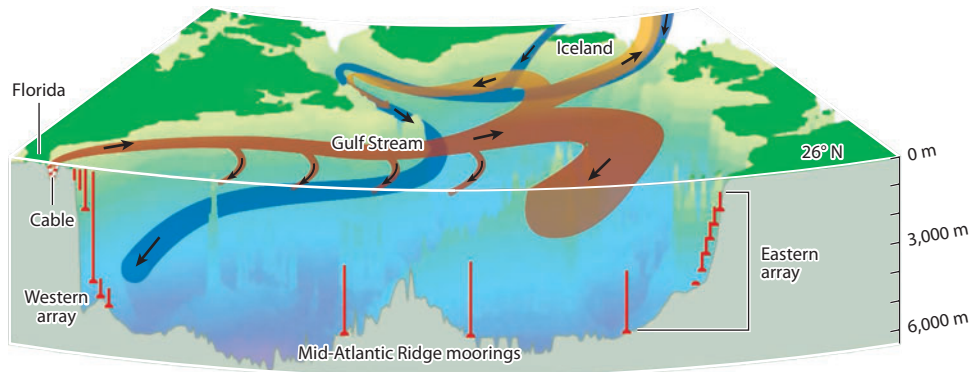
Figure 6

Schematic of the RAPID/MOCHA array at 26° N. The overturning circulation comprises the Gulf Stream transport through the Florida Straits, directly measured via electromagnetic cables; the Ekman transport, estimated from QuikSCAT winds; and the midocean geostrophic transport, estimated from the moored array instruments. (Figure adapted from Church 2007.)

Such a choice was made by Bryden et al. (2005) using five repeat surveys at 25° N from 1957 to 2004. This study showed that the overturning had slowed by 30% over the period of the surveys, an astounding and unanticipated change over such a relatively short time. However, an assessment of transports at 48° N using five repeat World Ocean Circulation Experiment sections and air/sea heat and freshwater fluxes as input to an inverse box model yielded no significant trend in the meridional overturning at that latitude (Lumpkin et al. 2008). Given the expectation of an overturning circulation that extends across the Atlantic basin, these results were difficult to reconcile with those of Bryden et al. (2005). However, for the later study, the time period assessed was 1993–2000, much shorter than that at 25° N. Thus, claims of consistency, as well as those of inconsistency, were evasive from these separate MOC measures. Importantly, the Lumpkin et al. (2008) study demonstrated the sensitivity of MOC reconstructions that lack some direct transport measures: (*a*) Reconstructions based solely on hydrography are sensitive to the choice of reference level and reference velocities, and (*b*) those based on air/sea fluxes are sensitive to the specific flux data set chosen.

6. CONTINUOUS MEASURE OF MERIDIONAL OVERTURNING CIRCULATION

In response to studies suggesting that rapid changes in climate occurred during the Holocene on decadal timescales, and in recognition of the fact that the modern atmosphere was warming at an unprecedented rate with unknown consequences for the ocean and its overturning, a UK/US observational program named RAPID/MOCHA (Rapid Climate Change/Meridional Overturning Circulation and Heatflux Array) was established in the middle part of the last decade (Cunningham et al. 2007). Thus, over 200 years after Count Rumford surmised the existence of the ocean's meridional overturning, an observational system was put in place to provide the first continuous measure of the MOC. The RAPID/MOCHA program comprises instruments deployed along a section at 25° N stretching from the North American continent to the west coast of Africa. **Figure 6** shows the measurement system that was designed to estimate the total overturning and heat flux at that latitude. The overturning is computed from the sum of the directly measured Gulf
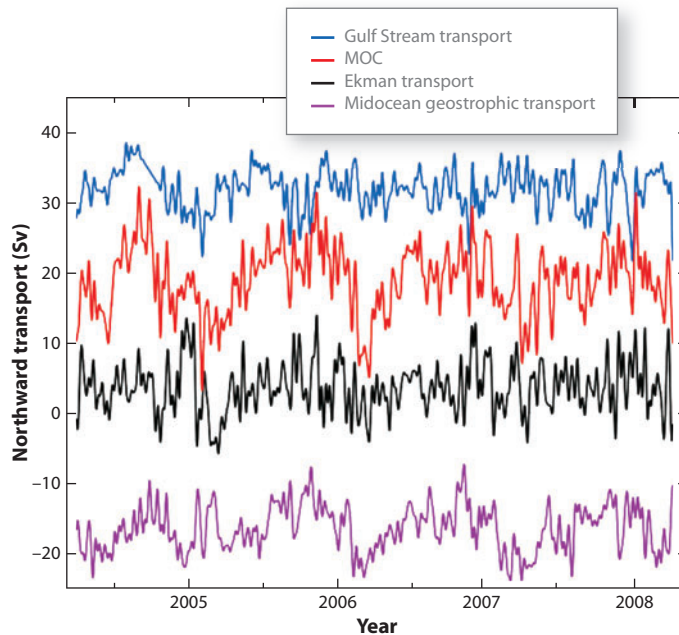
Figure 7

Time series of the meridional overturning transport at 26° N from the RAPID/MOCHA array. The
meridional overturning circulation (MOC) is computed from the sum of the Gulf Stream transport through
the Florida Straits, directly measured via electromagnetic cables; the Ekman transport, estimated from
QuikSCAT winds; and the midocean geostrophic transport, estimated from the moored array instruments.
(Figure adapted from Rayner et al. 2011.)

Stream transport through the Florida Straits, the Ekman transport estimated from QuikSCAT
winds, and the midocean geostrophic transport estimated from the moored array measurements.

After just 1 year of measurements, our conceptual understanding of overturning variability
changed dramatically. As seen in **Figure 7**, the overturning strength changed sixfold from April
2004 to April 2005, from a minimum of ∼5 Sv to a maximum of ∼30 Sv. To place this change
in context, recall that a prior study based on synoptic hydrographic surveys had estimated an
overturning decline of 30% over the course of almost 50 years (Bryden et al. 2005). Clearly,
with the demonstrated intraseasonal variability, synoptic sections were now understood to be
inadequate to capture measures of interannual transport variability. The continuation of the time
series reveals a strong seasonality (Rayner et al. 2011) that dominates the record; a removal of this
signal will, in time, likely reveal interannual changes.

Unfortunately, the strong intraseasonal variability of the MOC revealed by the
RAPID/MOCHA array seriously constrains our ability to re-create MOC variability over the
modern observational period, because synoptic hydrographic sections are the only past transbasin
measurements. Furthermore, as detailed in a recent review by Cunningham & Marsh (2010),
modeling estimates have not been able to help in this regard: There is currently no consensus
on the strength of the MOC in assimilation/reanalysis products, and ocean general circulation
models are in disagreement about the strength and variability of the MOC. Indeed, an active area
of research within the climate modeling community is focused on the cause for such wide ranges
of MOC estimates from state estimates that are drawing from the same observational databases
(U.S. Clim. Var. Predict. Program 2011). Proxy measures of the overturning derived from satellite

altimetry and Argo float data are promising, but to date are limited to latitudes of steep topography on the western boundary (Willis 2010) and are of limited duration to provide a temporal context of decades. Thus, to date, direct MOC observations are limited to one latitude (26° N), and past measures of change remain elusive.

7. COHERENCE OF MERIDIONAL OVERTURNING CIRCULATION ACROSS THE ATLANTIC

In addition to questions about the representativeness of past synoptic sections as a measure of MOC variability, recent studies have also raised questions about whether MOC variability measured by the RAPID/MOCHA array is representative of changes at other latitudes in the Atlantic. This issue of representativeness was explored in a recent study (Bingham et al. 2007) using a selection of models, including a coupled atmosphere-ocean model and ocean general circulation models. Although MOC variability over the course of years was coherent within the subtropical gyre and within the subpolar gyre in the North Atlantic, there was little to no coherence across the gyre-gyre boundary near 40° N (**Figure 8**). The authors attribute this lack of coherence to the dominance of higher-frequency variability in the subtropical basin and lower-frequency variability in the subpolar basin. They surmise that variability in overturning due to deep water formation is reflected in the subpolar gyre, while such variability is obscured by higher-frequency variability in the subtropical gyre. These modeling results are consistent with a more recent study (Baehr et al. 2009) that uses output from a coupled climate model to correlate the annually averaged and zonally integrated mass flux at the latitude of the RAPID/MOCHA array with the same measure at all depths and at latitudes to the south and to the north. In brief, the correlation drops significantly outside the subtropical basin. Thus, this modeling study suggests that the MOC variability measured by the RAPID/MOCHA array cannot safely be assumed representative of MOC variability outside the North Atlantic subtropical basin.

Such gyre-gyre differences in MOC variability, suggested in the aforementioned modeling studies, were revealed in a recent observation-based study. Using the collection of historical hydrographic data gathered in the North Atlantic from 1950 to 2000 to initialize an ocean general circulation model, Lozier et al. (2010) assessed MOC variability as a function of latitude. Because of the limits of data density, the study was restricted to a comparison of two time periods: a low-North Atlantic Oscillation (NAO) time period (1950–1970) and a high-NAO time period (1980–2000). These time periods were chosen because the NAO is the dominant mode of climate variability in the North Atlantic during the winter months (Hurrell 1995): High-NAO periods are marked by stronger westerlies across the basin and by increased sensible and latent heat fluxes across the subpolar air/sea interface (Visbeck et al. 2003), all of which can impact ocean circulation. In brief, the Lozier et al. (2010) analysis revealed opposing changes for the subpolar and subtropical gyres: As shown in **Figure 9**, the subtropical basin's overturning weakened over this time period, while the subpolar basin slightly strengthened. As with the modeling study mentioned above (Bingham et al. 2007), property changes coincident with these transport changes revealed much higher variability for the subtropical gyre compared with the subpolar gyre. Owing to the link of the changes with the NAO index, the authors suggested that these changes were strongly influenced by climate variability.

A novel modeling study of an ocean general circulation model provides the needed context for the observed and modeled lack of coherence between the subtropical and subpolar gyre (Biastoch et al. 2008a). In a comparison of two model runs, one where the model was forced with interannually varying winds and climatological buoyancy and another where the model was forced with interannually varying buoyancy fluxes and climatological winds, stark differences in the pattern of MOC
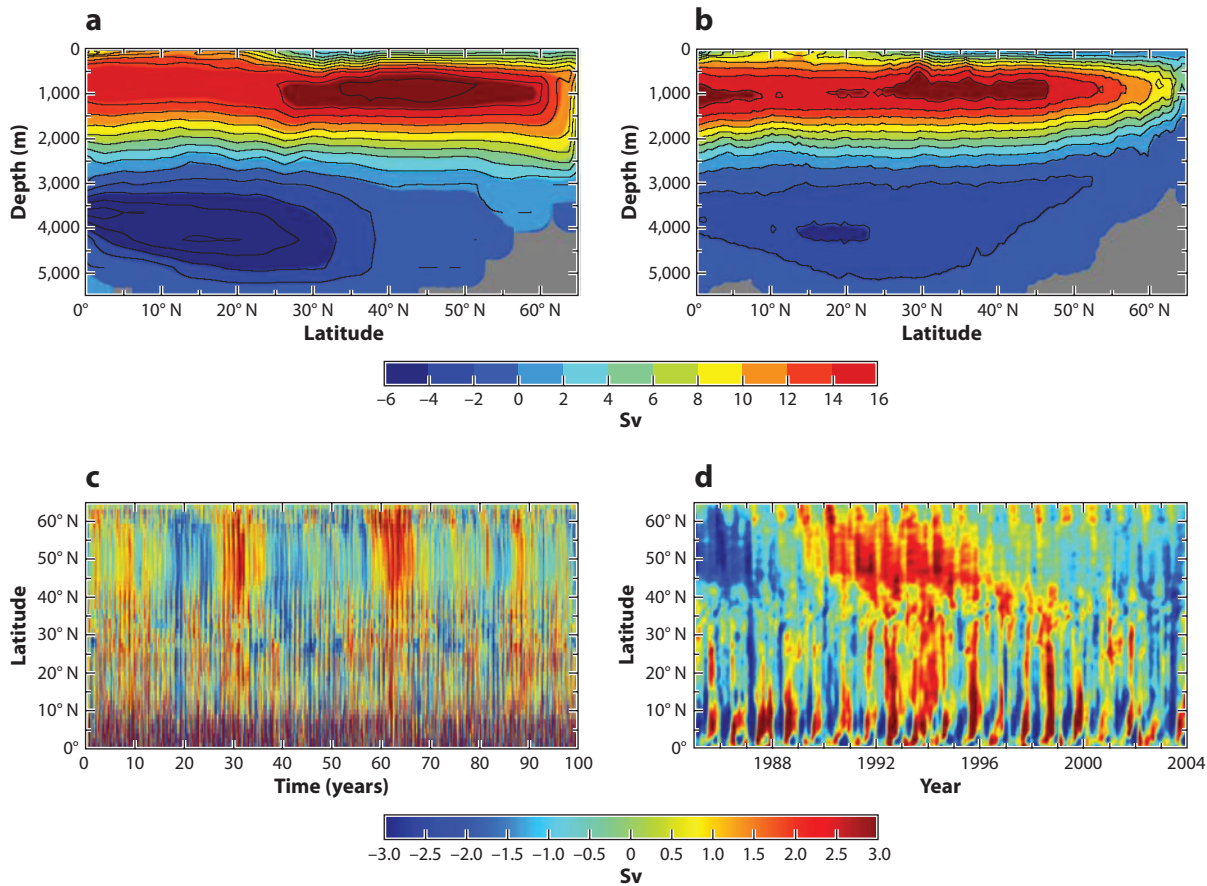
Figure 8

The time-averaged meridional overturning streamfunction (measured in Sv, 10^6 m^3 s^{-1}) in the North Atlantic for (*a*) a coupled atmosphere-ocean climate model and (*b*) an ocean general circulation model, along with the northward transport anomaly between 100 and 1,000 m as a function of latitude and time for (*c*) the coupled model and (*d*) the ocean-only model. (Figure adapted from Bingham et al. 2007.)

variability resulted. Specifically, when winds were variable, the MOC variability showed gyre-scale structure in its response; when buoyancy forcing was variable the basin showed a uniform response, i.e., the classical overturning response was recovered. Importantly, when both interannual winds and buoyancy forcing were applied, MOC variability was not coherent across the basin; rather, the structure mimicked that found in the runs with interannually varying winds. Thus, it appears that changes in wind forcing impose a strong constraint on MOC variability on interannual to decadal timescales. Changes in the dominant winds over the North Atlantic create changes in the thermocline thickness of the gyres, changes that alter the zonal density gradient and hence the meridional velocity (Lozier et al. 2010). With these collective studies, the linkage between deep water formation and MOC variability measured outside of the subpolar basin becomes all the more tenuous.

8. INFLUENCE FROM THE SOUTH ATLANTIC

Two recent studies focused on the Agulhas leakage have further weakened the link between deep water formation and basin-wide MOC variability by adding another mechanism in support of
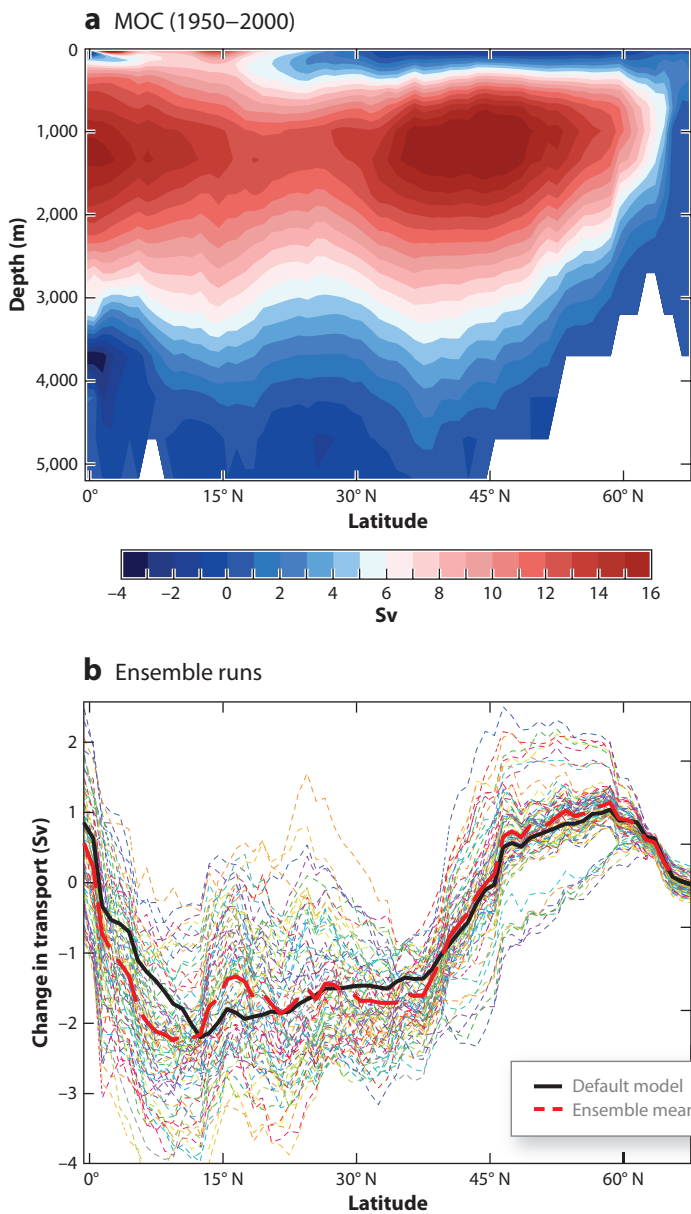
a MOC (1950–2000)

b Ensemble runs

Default model
Ensemble mean

Figure 9

(*a*) Estimate of the mean meridional overturning circulation (MOC) streamfunction (measured in Sv, 10^6 m^3 s^{-1}) evaluated from an ocean general circulation model initialized with historical hydrographic data averaged from 1950 to 2000. (*b*) 80 ensemble estimates of the MOC change (Sv), evaluated from 100 to 1,300 m from 1950–1970 to 1980–2000. (Figure adapted from Lozier et al. 2010.)

gyre-specific MOC changes. Long recognized as an important return pathway for surface waters returning to the northern North Atlantic as part of the upper limb of the overturning circulation, the Agulhas current rounds the Cape of Good Hope to enter the South Atlantic. As it makes the turn, the current sheds large eddies that leak away from the boundary and into the interior. Comparing assessments of MOC variability from an ocean general circulation model with and without a nested grid around the Agulhas region with resolution sufficient to resolve the Agulhas eddies (**Figure 10*a***), Biastoch et al. (2008b) showed that MOC variability is higher when these eddies are resolved. Notably, this change in variability is most pronounced in the South Atlantic, yet some impact is evident in the North Atlantic (**Figure 10*b***). A second experiment assessed the impact of deep water formation on MOC variability across the entire Atlantic basin: not surprisingly, the largest impact was in the subpolar region, with decreasing influence at latitudes farther south (**Figure 10*b***). Importantly, in both cases, the impact of wind forcing—dominant over the variability created by the Agulhas eddies and by deep water formation—was effectively removed from these assessments through the subtraction of the time series from a control run that included wind forcing. Clearly, this study adds to the nascent recognition of gyre-specific or perhaps even latitude-specific MOC variability that is the result of a number of mechanisms.

9. LINKAGE BETWEEN MERIDIONAL OVERTURNING CIRCULATION CHANGES AND DEEP WATER PRODUCTION IN THE SUBPOLAR GYRE

Given the apparent diminishment of the impact of NADW changes on MOC variability in the South Atlantic and the subtropical North Atlantic, we retreat from the expectation of finding a basin-wide response to deep water formation changes and ask instead whether overturning in the subpolar North Atlantic can be directly linked to deep water formation. To answer this question, we examine the water mass formed via open ocean convection in the North Atlantic (the LSW) and the water masses that form in the Nordic Seas and flow across sills into the open Atlantic (known collectively as the lower NADW). LSW, the overflow waters, and the entrainment of warmer waters into the overflow waters have traditionally been considered to contribute equally to the total overturning volume (Schmitz 1996).

Motivated by studies that show the expected basin-wide response to deep water formation variability obscured by vigorous wind-driven variability (Eden & Willebrand 2001, Jayne & Marotzke 2001, Shaffrey & Sutton 2004), Böning et al. (2006) found that the strength of DWBC transport downstream of the Labrador Sea, at 53° N, was a strong indicator of convective activity in the Labrador Sea. In brief, within the ocean general circulation model they used to simulate the North Atlantic circulation, the transport of deep components of the DWBC was strongly correlated with the production of LSW, with a lag of 1–2 years. Thus, the authors suggest that a measure of the DWBC at the exit of the Labrador Sea can serve as an indicator of thermohaline-induced MOC variability whose signature in other parts of the Atlantic is masked by either wind-driven variability or South Atlantic circulation variability.

Clearly, such a measure is desirable as a metric of basin-wide MOC variability; however, several studies have cast doubt on whether the transport and property changes of LSW measured in the subpolar DWBC are a good measure of the production of LSW from year to year (Straneo 2006, Pickart & Spall 2007). As pointed out by Straneo (2006), the causal link between deep water formation and overturning has been called into question as more has been learned about the constraints on the spreading of deep water away from its formation sites (Send & Marshall 1995, Spall & Pickart 2001, Spall 2004) and about the role of eddies in the production of LSW. Essentially, the compilation of studies over the past 5–10 years yields a description of LSW
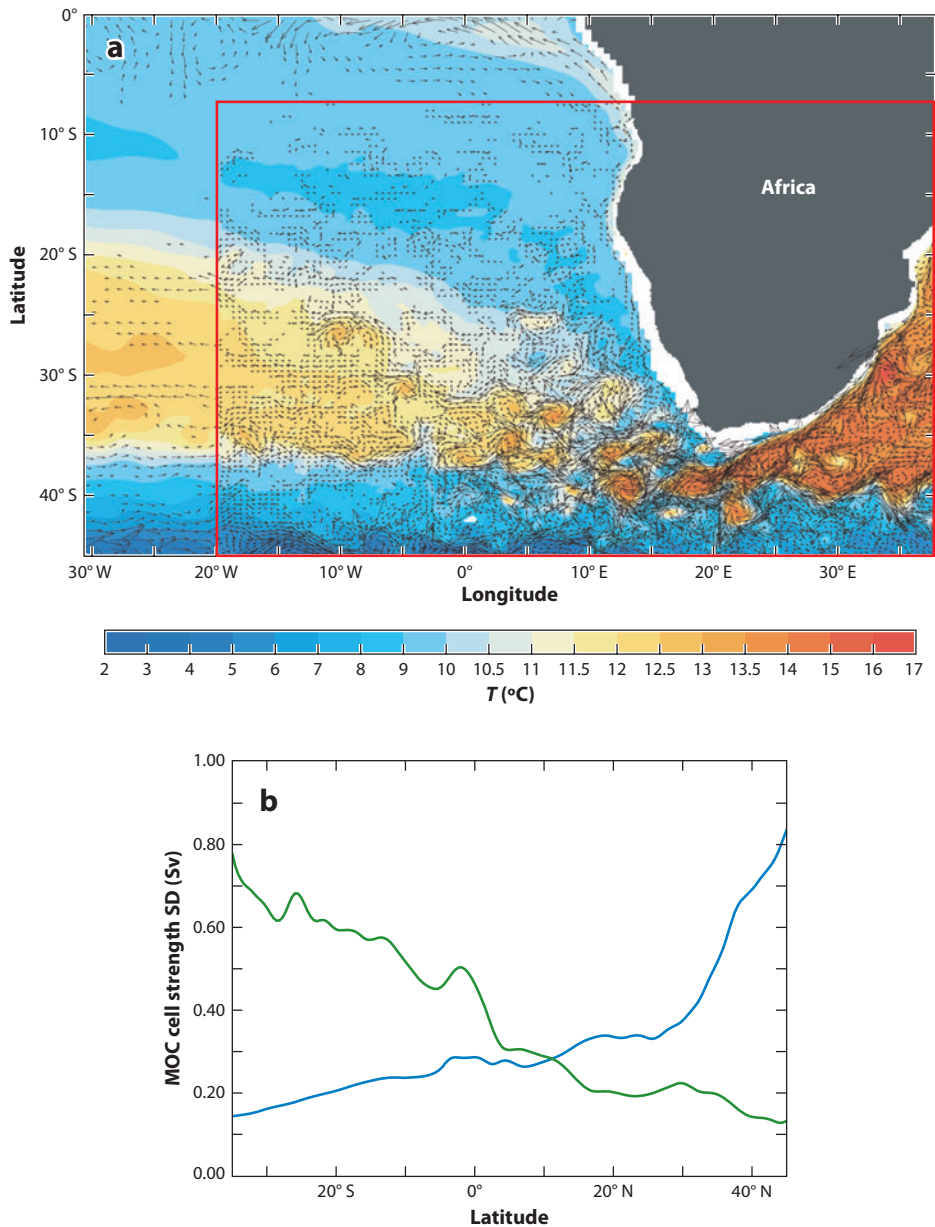
Figure 10

(*a*) Velocity vectors averaged over a 5-day period in 2004 in the Agulhas region superposed on the
temperature (in color) at 450 m in a high-resolution (0.1°) nest within a global ocean model resolved at 0.5°.
(*b*) Green line: Difference in the standard deviation of overturning strength as a function of latitude between
two experiments, one with and one without an Agulhas nest, showing the effect of the Agulhas-induced
variability. Blue line: Difference in the standard deviation of overturning strength as a function of latitude
between two experiments, one with interannually varying heat-flux forcing and climatological wind and
freshwater forcing and the other with all interannually forced fields, showing the effect of North Atlantic
Deep Water formation variability. Abbreviation: MOC, meridional overturning circulation. (Both panels
adapted from Biastoch et al. 2008b.)

production that is, at its simplest, portrayed by the schematic in **Figure 11**, in which LSW (or, in general, any convected water mass) fills the depths of the interior basin (bottom layer) and a two-layer boundary current rims the basin. Given that the properties of the deep interior are (in the case of LSW) colder and fresher than the properties of the surrounding deep boundary current, an eddy-driven property exchange densifies the boundary current, inducing a vertical mass flow from the upper to the lower layer. Thus, at the exit of the Labrador Sea, the deep boundary current carries colder and fresher water than it did at its entry, as well as a larger transport in part due to the increased thickness of the deep boundary layer at its exit (Straneo 2006).

In this scenario, as opposed to deep waters spreading from their formation sites, it is relatively easy to understand that the properties and transport variability within the boundary current are not the sole function of deep water formation properties. The boundary current transport, the property gradients between the interior and the boundary current, and the strength of the eddy field all play a role in setting the exit transport and properties, leading Straneo (2006) to conclude that "quantities such as overturning and water mass transformation are not trivially related and must not be taken as synonyms." Observational studies in support of this conclusion include an analysis of hydrographic sections across the Labrador Sea from 1990 to 1997 that reveals minimal impact of wintertime convection on the measures of MOC in the Labrador Sea, despite the fact that convective activity in that basin was the strongest ever recorded during that time period (Pickart & Spall 2007). An analysis of over 200 PALACE (Profiling Autonomous Lagrangian Current Explorer) floats in the Labrador Sea provides observational evidence for a strong eddy heat flux between the interior and the boundary current that may significantly impact interannual variability of the LSW properties exported from the basin in the DWBC (Palter et al. 2008). Finally, a study of a moored array at 53° N (Dengler et al. 2006) found a strengthening of the Deep Labrador Current over the time period of a well-studied decrease in convective activity, causing the authors to conclude that another mechanism must be responsible for the transport variability.

The linkage between variable production of overflow waters from the Nordic Seas and downstream MOC variability has been decidedly less studied and thus remains uncertain. Establishing this linkage is complicated by the strong imprint of wind forcing on the transport of overflow waters across the Greenland-Scotland Ridge (Olsen et al. 2008). Interestingly, this observational and modeling study reveals that barotropic and baroclinic contributions from wind forcing compensate to produce a remarkable stability in the overall transport of the Nordic overflow waters into the North Atlantic over the past 50 years. Thus, downstream measures of MOC variability must be attributed to mechanisms other than the production of these deep waters. However, assumptions that a measure of the deep DWBC transport is a collective measure of the overflow water variability fail for the same reason as they do for LSW: the strong possibility of interior pathways in the North Atlantic for the overflow waters. A recent study (Holliday et al. 2009) that reveals a disconnect in the overflow water transport around Cape Farewell offers the hypothesis that the transport divergence can be explained by interior pathways for some portion of the overflow waters. In support of this hypothesis, deep floats within an ocean general circulation model also show interior pathways that lead to the subtropics from the subpolar gyre (Lozier 2010).

10. THE OTHER SIDE OF CAUSALITY: MERIDIONAL OVERTURNING CIRCULATION UPPER LIMB

The bulk of this review has focused on the impact of deep water formation on MOC variability, although (as mentioned earlier) the linkage between the two has been assumed mutually causal: the warm and salty Gulf Stream and North Atlantic Current surface waters are believed to be
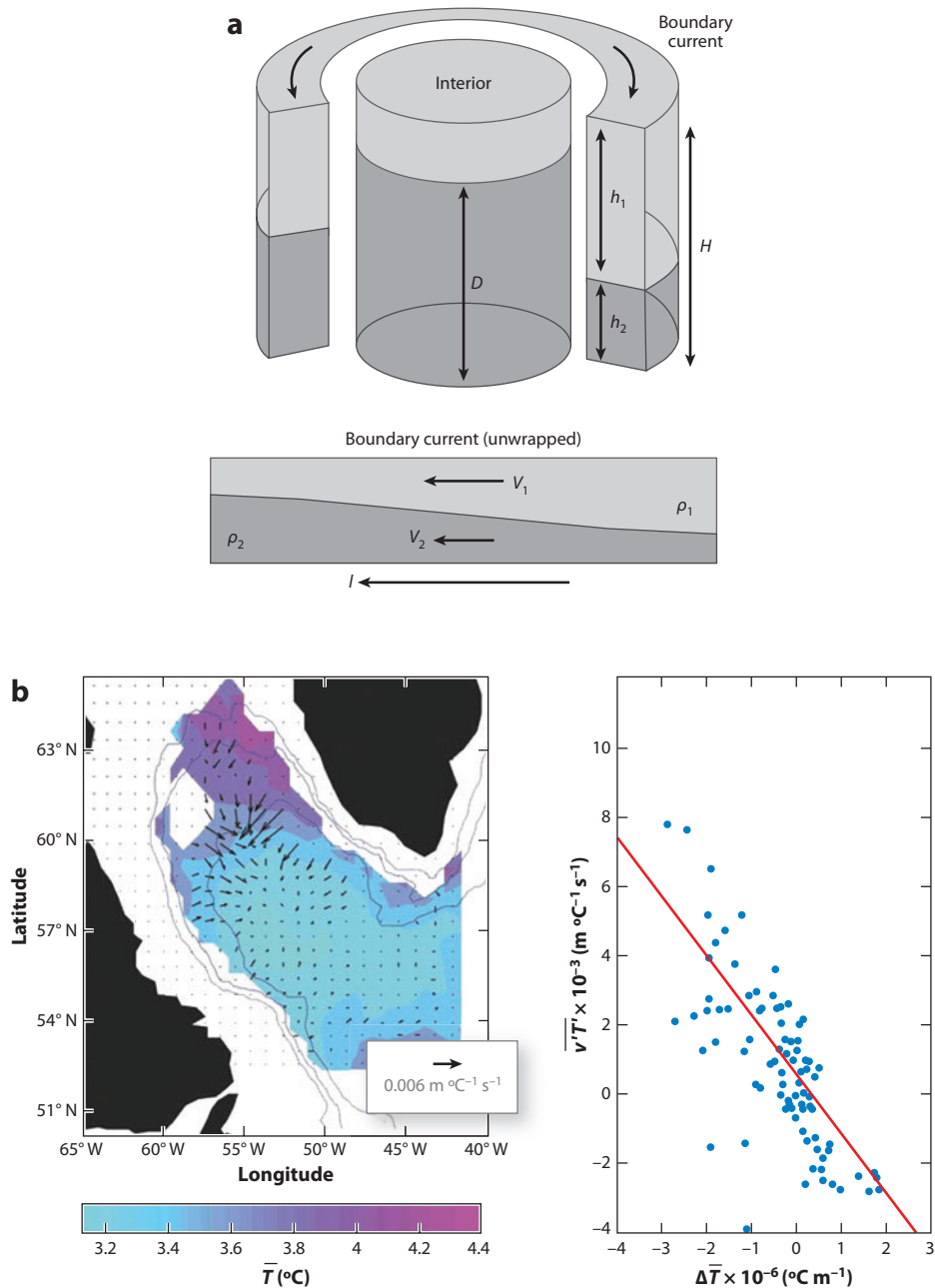
Figure 11

(*a*) Schematic of a two-layer idealized model for a convective basin: *h* represents the thicknesses of the upper and lower layers, *H* the total water depth, *V* the velocity of the layers, *D* the thickness of the dense water in the interior, *l* the along-boundary distance, and *ρ* the density. (*b*) (*Left panel*) Cross-stream eddy heat fluxes in the Labrador basin superposed on the mean temperature field (in color) at 700 m computed from profiling floats. (*Right panel*) Cross-stream eddy heat fluxes as a function of the mean temperature gradient. The relationship indicates that eddies contribute to the exchange of heat between the boundary current and the interior. (Panel *a* adapted from Straneo 2006; panel *b* adapted from Palter et al. 2008.)

the source waters for the Nordic Sea deep waters. With this expectation, the upper limb of the
MOC is identified with the throughput between the subtropical and subpolar gyres in the North
Atlantic. Such throughput, associated with the much-evident tilt of the surface isotherms from
the southwest to the northeast across the midlatitudes of the North Atlantic, however, is not
apparent from the pathways of surface drifters released in the North Atlantic from 1990 to 2002
(Brambilla & Talley 2006). An inspection of those surface drifters launched within the subtropical
gyre showed that only 1 out of 273 launched in the subtropics made the transit to the subpolar
gyre (**Figure 12**).

Brambilla & Talley (2006) suggested several possible reasons for the lack of subtropical to
subpolar pathways for these surface drifters: limited sampling by the drifters, limited drifter life-
time, inhibition by the Ekman velocity field, and inability of surface drifters to follow the three-
dimensional velocity field. Additionally, a follow-on study (Hakkinen & Rhines 2009) suggested
that temporal variability of the surface throughput could explain the lack of throughput during
the time period studied by Brambilla & Talley (2006). Recent studies to investigate these probable
causes included one (Rypina et al. 2011) that used a dynamical system approach to show that a
strong barrier exists between the surface waters of the subtropical and subpolar waters, as well as
another (Burkholder & Lozier 2011) that analyzed the gyre-gyre exchange in an ocean general
circulation model. In this latter study, surface waters of the subtropical waters were not advected to
the subpolar gyre under any circumstance: Both the mean Eulerian velocity field and the simulated
Lagrangian pathways show that the near-surface field is dominated by a southward Ekman flow.
Simulated floats placed below the Ekman layer, with sufficient time for the transit and in sufficient
number to avoid a sampling bias, reveal the expected throughput. Interestingly, floats launched in
the range of 400–900 m in the subtropical basin, not just below the Ekman layer, had the highest
probability of entering the subpolar gyre, though this does not necessarily mean that the largest
fraction of the throughput comes from that depth. In sum, the Burkholder & Lozier (2011) study
has made clear that the near-surface waters of subtropical origin recirculate almost wholly within
the subtropical gyre and, as such, do not contribute to the throughput to the subpolar gyre as part
of the upper limb of the MOC. Clearly, a view of the upper limb of the overturning that involves
surface waters needs revamping.

11. SUMMARY

A composite of the studies reviewed herein reveals an MOC with a tenuous link to the production
of deep water masses via local overturning at high latitudes in the North Atlantic. However, what
led to the establishment of the linkage in the first place is what keeps the oceanographic community
from severing it completely: undersampling. The deep ocean remains vastly undersampled, partic-
ularly so with respect to measures appropriate for the calculation of MOC variability. Starting with
the single temperature profile from which Count Rumford deduced the meridional overturning,
oceanographers have added only piecemeal to deep ocean observations over the decades, a pace
primarily attributable to the inaccessibility and inhospitable nature of the abyss. Slowly, however,
new measurements have added to our emerging understanding of the deep ocean velocity and
property fields. Today we have a much greater appreciation for the impact of wind and eddies on
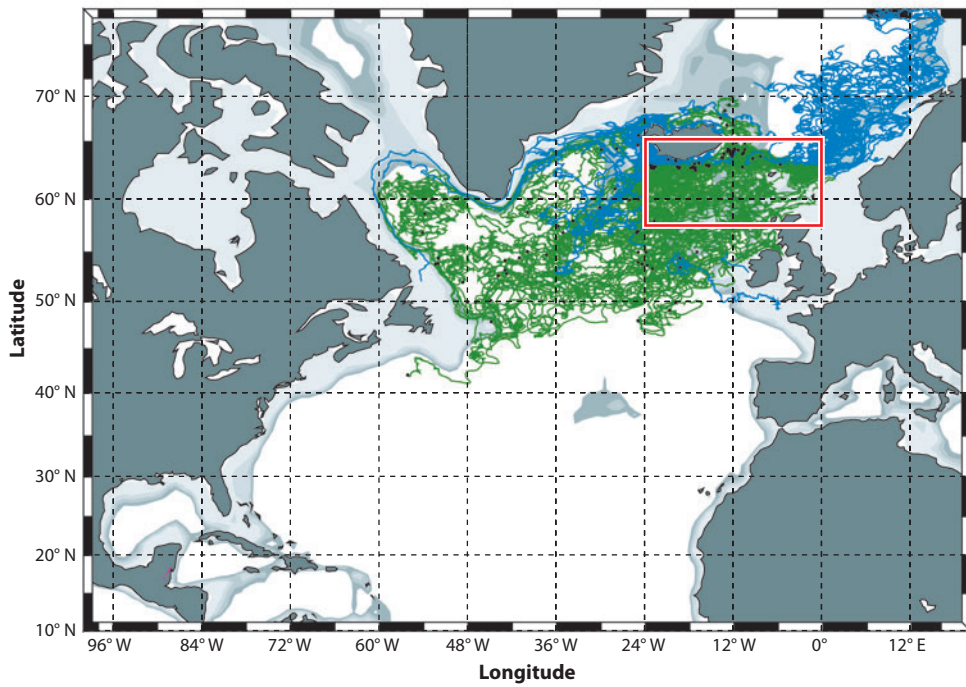
Figure 12

Trajectories of surface drifters deployed in the North Atlantic from 1990 to 2002, passing through (*a*) the Gulf Stream box and (*b*) the
Iceland Basin. Drifters entering and within the boxes are shown in green; drifters that have exited are shown in blue. (Figure adapted
from Brambilla & Talley 2006.)

a Gulf Stream
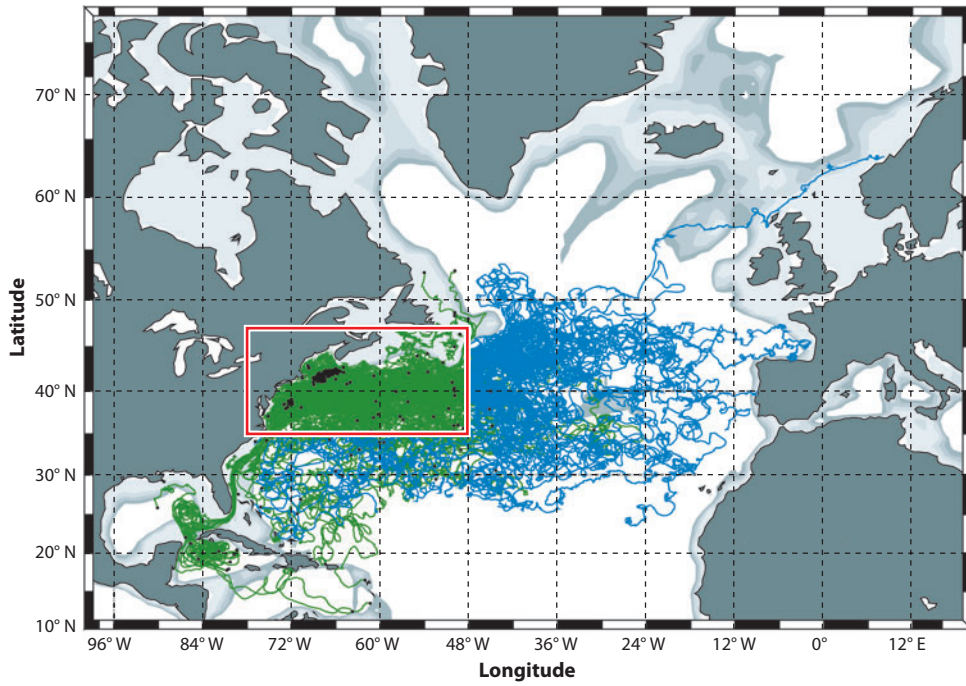
b Iceland Basin

the circulation of the deep ocean, as well as a broader view of the circulation itself, in part because subsurface floats have sampled the ocean interior—ending decades during which velocity measures of deep ocean currents were confined primarily to the boundary currents. However, studies reviewed herein suggest that further observations are needed to directly test the legitimacy of the decades-long supposition that variability in water mass production translates into meridional overturning variability. For an ocean within a warming world, such an assessment is sorely needed to understand how the ocean will both respond to and contribute to climate change.

DISCLOSURE STATEMENT

The author is not aware of any affiliations, memberships, funding, or financial holdings that might be perceived as affecting the objectivity of this review.

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Errata

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