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REVIEW

Deconstructing the Conveyor Belt

M. Susan Lozier

For the past several decades, oceanographers have embraced the dominant paradigm that the ocean's meridional overturning circulation operates like a conveyor belt, transporting cold waters equatorward at depth and warm waters poleward at the surface. Within this paradigm, the conveyor, driven by changes in deepwater production at high latitudes, moves deep waters and their attendant properties continuously along western boundary currents and returns surface waters unimpeded to deepwater formation sites. A number of studies conducted over the past few years have challenged this paradigm by revealing the vital role of the ocean's eddy and wind fields in establishing the structure and variability of the ocean's overturning. Here, we review those studies and discuss how they have collectively changed our view of the simple conveyor-belt model.

A single measurement of deep-ocean temperatures taken by the captain of a British slave-trade ship in 1751 was the catalyst for Count Rumford's supposition, nearly 50 years later, that ocean waters overturned, with high-latitude water "deprived of a great part of its heat by cold winds" descending to the ocean floor, spreading equatorward and necessitating a "current at the surface in an opposite direction" (1). In the following two centuries, as deep water masses were meticulously cataloged and surface currents were mapped across the globe, a long line of oceanographers worked to trace the route of the overturning waters from disparate observations (2). Despite these efforts, our modern conceptualization of the ocean's overturning and our understanding of its climatic importance coalesced only in the past few decades as a result of the work of two prominent oceanographers: one who provided a theoretical framework for the route of the deep waters that constitute the lower limb of the overturning, and another who provided a climatic context for the overturning itself.

Fifty years ago, Henry Stommel theorized that recently ventilated waters of high-latitude origin must be transported equatorward at depth along western-intensified boundary currents (3). Assuming that water masses formed via deep convection in isolated regions in the northern North Atlantic and near Antarctica essentially

fill the abyssal ocean, Stommel surmised that the deep ocean exports these waters via a distributed upwelling to the surface. Furthermore, he suggested that because such upwelling produces

structure: Deep waters are transported equatorward in a steady, continuous deep western-intensified boundary current from their formation sites at high latitudes (Fig. 1) (4). The interior flow, much weaker, moves poleward and upward. Another important element emerged from Stommel's study: The deep western boundary currents (DWBCs) of the global ocean are connected, linked across hemispheres and basins to form a continuous stream of deep waters spreading through the abyss. Later work (5) applied this theoretical construct to the actual ocean flow field, linking distant currents into a coherent overturning.

Almost 25 years after Stommel's conceptualization, work by Broecker and colleagues suggested that the ocean's overturning was responsible for the rapid climate fluctuations experienced during Earth's last glacial period (6). Using a moniker first introduced in the early 1980s (7) and popularized with an illustration appearing in *Natural History* (Fig. 2) (8), Broecker suggested that the "great ocean conveyor belt" flipped on and off during the last

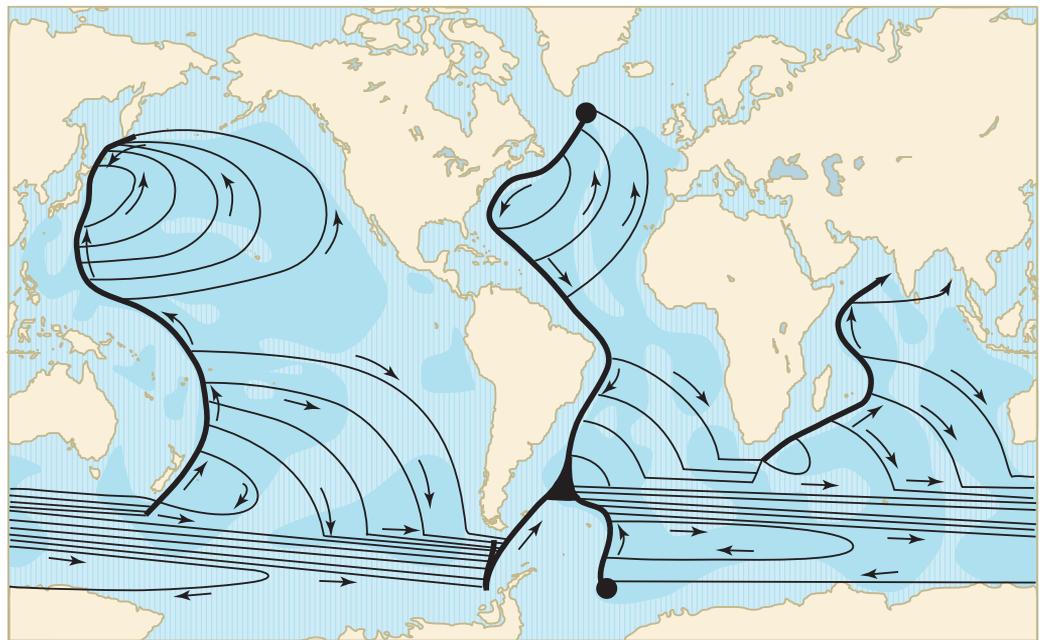


Fig. 1. The abyssal flow field, as theorized by Stommel in 1958 (4). Water mass source regions in the northern North Atlantic and Antarctica are denoted by black dots. These water masses are spread equatorward by interconnecting western intensified boundary currents (thick lines) that feed the poleward interior circulation (thin lines). Arrows indicate direction of flow. [Reprinted from (4), with permission from Elsevier]

a stretching of the water column that induces a loss of angular momentum, the deep interior waters must compensate by flowing poleward toward regions of higher angular momentum. Thus, the equatorward transport of deep water masses was confined to the western boundaries of the basins. Stommel's theory gave the ocean's overturning, previously amorphous in its third dimension, a

glacial period in response to strong freshwater forcing, presumed to result from melting of the continental ice sheets. Though the importance of the ocean's overturning to Earth's climate had previously been understood, Broecker's work essentially cemented the role of the conveyor belt as an agent of climate change. Thus, just as Stommel's work gave spatial structure

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to the overturning, Broecker's provided a temporal context.

Since these efforts, oceanographers have collectively supported the paradigm that the ocean "conveyor belt" transports recently ventilated waters from the subpolar North Atlantic along the "lower limb" of the conveyor belt to the rest of the global ocean, where the waters are upwelled and then transported along the "upper limb" back to deepwater formation sites. This conveyor belt is assumed to operate continuously along western boundary currents in the deep ocean, be vulnerable to changes in deepwater production at high latitudes due to variable buoyancy forcing, and provide a continuous supply of relatively warm surface waters to deepwater formation sites. Since its inception, oceanographers have understood that the conveyor model grossly oversimplifies the mechanics and pathways of the overturning: No one expects a water parcel tagged at the surface in the northern North Atlantic to be swept along the conveyor belt unimpeded in its equatorward, surfaceward, and ultimately poleward progress. However, this conceptual model has still fostered expectations for the response of the ocean's circulation to a warming climate: If high-latitude surface waters warm or freshen, deepwater production would diminish or cease. Because the conveyor belt is assumed to be driven by deepwater production, it would share this same fate. Northern Europe, robbed of the heat that prevailing westerlies gain at the expense of surface waters returning northward, would cool.

After decades as a dominant paradigm, some major features of the conveyor belt have recently been called into question. One study finds that most of the subpolar-to-subtropical exchange in the North Atlantic occurs along interior pathways (9), another that the DWBC breaks up into eddies at 11°S (10), another that there is little meridional coherence in the overturning transport from one gyre to the next (11), and another that wind forcing, rather than buoyancy forcing, can play a dominant role in changing the transport of the overturning (12). All told, the sum of these studies calls for a revamping of our conceptual model of the ocean's overturning. Added impetus for revamping comes from a recent study (13) revealing a considerable reservoir of anthropogenic CO₂ in the deep North Atlantic, surmised to result from the production of high-latitude water masses and their subsequent

equatorward spread. Clearly, an improved understanding of the pathways of the upper and lower limbs of the ocean's overturning will aid assessments of the ocean's role in the uptake, transport, and storage of heat and CO₂, crucial components of Earth's climate system. This review, with a focus on the Atlantic because of

in the northern North Atlantic. These suppositions are revisited below.

Are Western Boundary Currents Continuous Conduits of Recently Ventilated Deep Waters?

Early and strong evidence for the existence of DWBCs followed on the heels of Stommel's

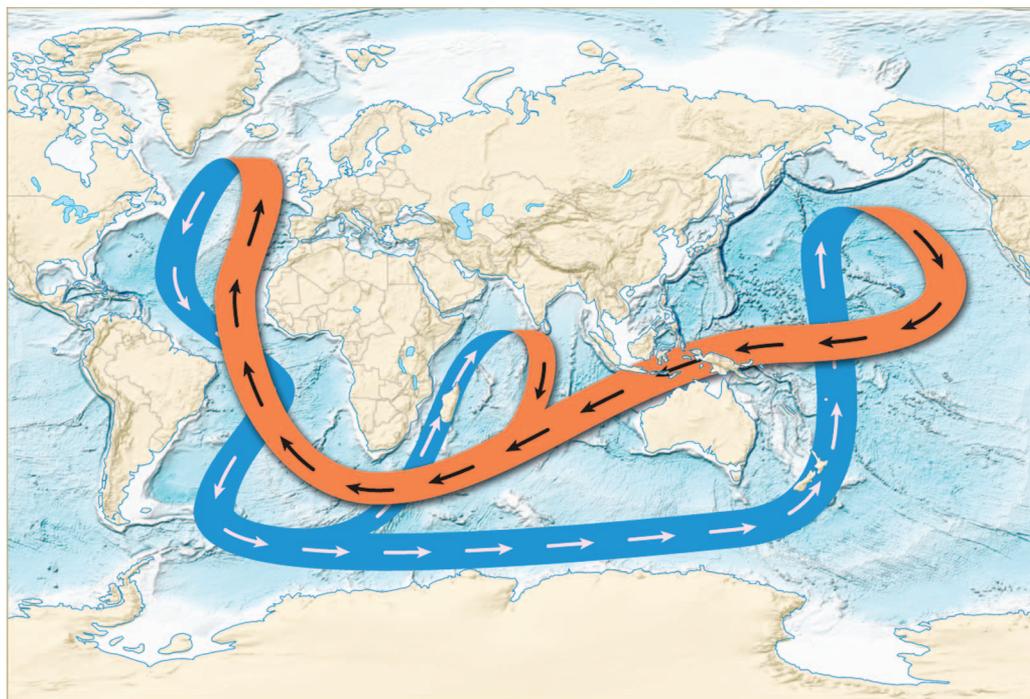


Fig. 2. Schematic of the ocean conveyor belt. Arrows indicate direction of flow. Orange, the warm, shallow waters of the upper limb of the conveyor belt; blue, the cold, deep waters of the deep limb. [Adapted from (8)] [Credit: Joe LeMonnier]

the preponderance of observations in that basin, examines whether the ocean conveyor-belt model is an appropriate framework for that assessment.

What Is the Conveyor Belt?

A critical examination of the conveyor-belt model has actually been under way for a number of years. As pointed out in 2002 (14), the conveyor belt is only loosely defined as flow that carries heat and salt from high to low latitudes and vice versa: It has never had an operational definition with mathematical rigor. Today, oceanographers refer to the meridional overturning circulation (MOC) as the two-dimensional (2D) flow field with a transport defined as the zonally integrated meridional flux of mass. However, despite the precise definition, many of the suppositions held for the conveyor belt have carried over to the meridional overturning; namely that overturning waters are principally carried in boundary currents and that overturning transport is continuous in space and time, yet susceptible in the main to changes in deepwater production

theory (1). Measures of water-mass properties and geochemical tracers have consistently revealed that North Atlantic Deep Water (NADW), the conglomeration of recently ventilated waters from the Nordic and Labrador Seas, is carried along a narrow corridor of the continental slope from the North Atlantic subpolar basin to the subtropics and equatorward (15, 16). Although the geochemical tracers in this DWBC confirmed the presence of recently ventilated waters, they also raised a conundrum. The age of boundary-current waters is greater than that calculated from a simple model of advection along the boundary current (17, 18). To explain this mismatch, it was conjectured that boundary-current waters mix with older interior waters as they transit downstream. Indeed, confirmation of such mixing came from a study of deep floats purposely seeded in the DWBC downstream of the Tail of the Grand Banks (19). These floats revealed a pattern of detrainment and reentrainment as they flowed equatorward, providing a visualization of along-stream aging. Thus, the notion of continuous flow along the ocean's deep limb of the conveyor

belt was modified to include the role of eddies in essentially diluting the boundary-current waters.

Eddies were elevated from a supporting role in the transport of waters along the lower limb of the overturning circulation to a starring role with the publication of an observational and modeling study of the DWBC in the South Atlantic (10). In this study, the southward transport of deep waters at 8°S, off the Brazilian coast, was shown to be carried entirely by migrating coherent eddies: Direct velocity measurements showed no evidence for a continuous, mean flow at the depth of the NADW. An accompanying modeling analysis attributed the generation of eddies to the instability of the DWBC. This study provided the first evidence that not only do eddies disrupt the transport of deep waters along the western boundaries, but, at least at this one locale, they constitute the transport. The ubiquity of this phenomenon remains unknown.

Is the DWBC a Unique Path for the Transport of Recently Ventilated Deep Waters?

Stommel's theorized structure for the western intensified DWBC was based on steady-state, large-scale dynamics. At the time, there was little to no appreciation for the ubiquity and strength of the eddy field, which is hardly surprising because the flow field was vastly undersampled. In

Stommel's theory, the DWBC was needed to satisfy a steady, poleward interior flow. Though the expectation of this poleward flow has largely been abandoned, repeated confirmation of a DWBC continues to fuel our expectation that it is the primary conduit for the transport of recently ventilated waters. However, profiling floats released in the Labrador Sea during the 1990s (20), including those placed directly in the southward-flowing boundary current (21), exited the basin by either recirculating back into the Labrador Sea or heading eastward along the North Atlantic Current. Surprisingly, no floats were exported from the subpolar basin to the subtropics along the DWBC.

A follow-up study using dozens of acoustically tracked RAFOS floats (to avoid possible biases in deep pathways due to intermittent surfacing) placed in the DWBC at the depth of the Labrador Sea Water over a period of 3 years successfully revealed the export of subpolar waters to the subtropics (9). However, the primary route for this export was via interior pathways, not along the DWBC. In fact, only 8% of the floats launched in the DWBC stayed within the current as it transited the subtropics; all others were detrained along its length, particularly so at topographic "choke points" (9). The detrained floats subsequently drifted generally southward within the basin interior. An accompanying analysis using an ocean

general-circulation model (22) quantitatively partitioned the export of Labrador Sea Waters into those that made the transit along the DWBC and those that transited the interior. The latter transport far outweighed the former, revealing the interior as the primary route for the equatorward transport of deep waters. Though the observational program with RAFOS floats and the companion modeling study were focused on waters of Labrador Sea origin, an analysis of the pathways of the Nordic Sea overflow waters within the same ocean-circulation model reveals similar results: Floats launched within the DWBC at 53°N do not follow a continuous boundary current, but instead take multiple paths to the subtropics, including interior pathways far removed from the DWBC (Fig. 3).

The fact that these recent float observations and modeling results directly contradict the predicted dominance of the DWBC theorized by Stommel is reconciled by considering the effect of eddies on the deep flow. Early modeling work in the 1970s (23), when the ocean eddy field was receiving deserved attention, demonstrated how eddies, generated from instabilities of mean currents, could drive deep mean flow in the form of strong recirculations adjacent to energetic boundary currents. Subsequent theoretical work linked eddy-driven flow with a signature of homogenized potential vorticity (24). This link-

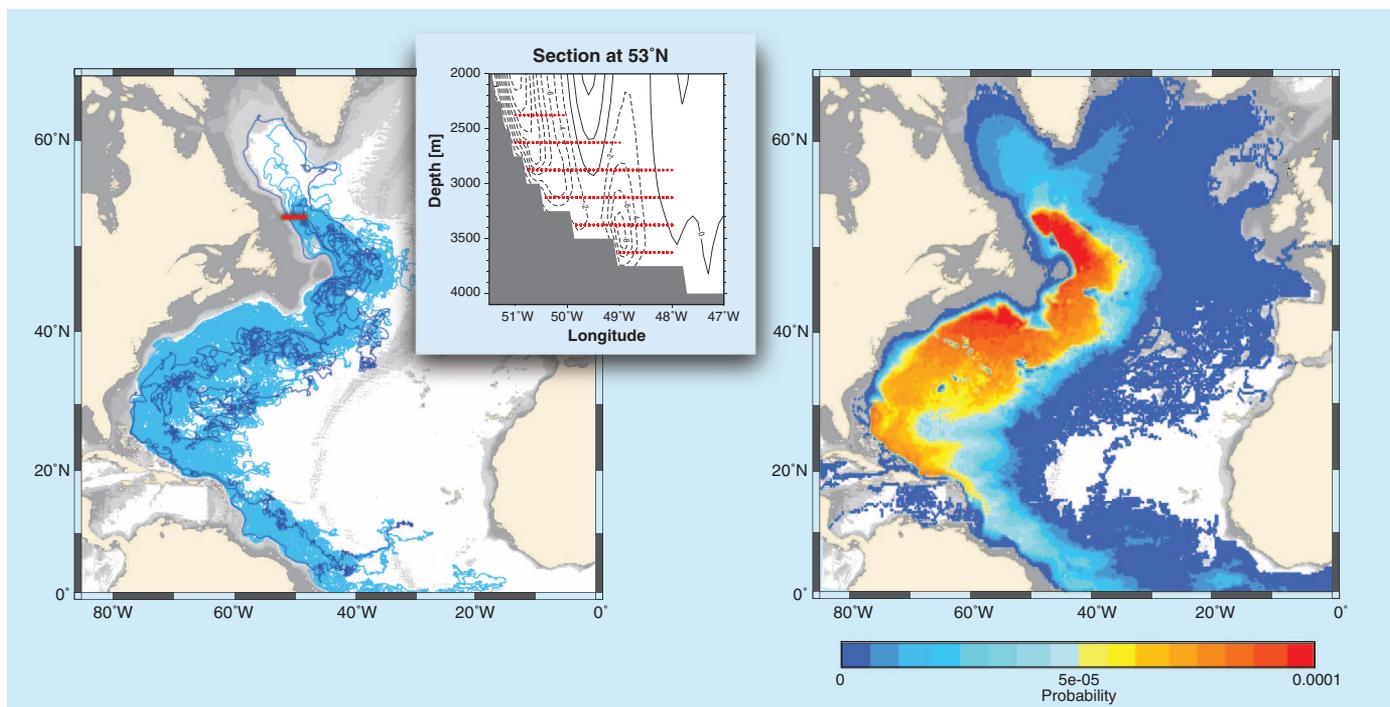


Fig. 3. (Left) Fifty-year trajectories of 50 e-floats randomly selected from a total of ~18,000 deployed within an eddy-resolving ocean general-circulation model (9, 22) at the depth of the Nordic Seas overflow waters. Floats were launched at 53°N in the southward-flowing DWBC (inset) with mean launch locations marked with red bars. The meridional velocity is contoured at 2-cm/s increments, with solid and dashed lines indicating

northward and southward flow, respectively. The model's DWBC structure compares favorably with the observed flow at 53°N (40). Launches were made only if the temperature was $\leq 2.3^\circ\text{C}$ at the time of the launch. Three selected trajectories (dark blue) highlight the interior pathway. (Right) A 2D probability map of float locations from the entire set of e-floats over 50 years.

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age, coupled with an analysis of hydrographic data that revealed extensive homogenization of potential vorticity in the deep waters adjacent to the Gulf Stream/North Atlantic Current, prompted the conjecture that eddy-driven recirculations provide an alternate pathway for the export of deep waters from the subpolar to the subtropical basin (25). Attribution of this pathway to eddy-driven recirculations was recently made explicit by model simulations (9) that reveal equatorward flow in the ocean interior, opposite that theorized 50 years ago when ocean flow at depth was presumed steady. Thus, there is now an observational, modeling, and theoretical basis for discarding the notion that DWBCs provide a continuous and unique pathway for the deep limb of the MOC. Though most observational and modeling studies to date have focused on the North Atlantic, there is little reason to suspect that other DWBCs are not similarly affected by the presence of eddies and, consequently, that alternate pathways exist for the spreading of the deep waters. The North Atlantic does not hold a monopoly on energetic eddy fields at depth (10).

In sum, the impact of eddies on our concept of a continuous lower limb for the ocean's overturning has evolved from an understanding that eddies can detrain and entrain fluid along the DWBC to the recognition that the DWBC can, at certain locales and perhaps certain times, be a series of migrating eddies, to the realization that eddy-driven flow provides an alternate pathway for deep waters to spread globally.

This impact of the eddy field on pathways for recently ventilated waters has clear implications for the interpretation of the age, transport, and variability of the waters that compose the DWBC. With large-scale recirculations whose extent and strength vary in depth (25), the age of boundary-current waters will be a strong function of local physics, potentially overriding the imprint of upstream source characteristics (26). The diversion of floats from the DWBC into the interior at multiple locations implies that the DWBC will not have a continuous throughput of recently ventilated water and that coherence in transport along the DWBC will be weak. Finally, if eddies are the product of the instabilities of the swift boundary currents, themselves driven principally by the wind field, a simple deduction leads to the suggestion that recirculations, and the alternate pathways they create, must also be dependent on wind forcing and its temporal variability. Thus, a varying transport of a water mass in a boundary current cannot simply be interpreted as varying upstream export. The disconnect goes even further: Studies of convection in the Labrador basin (27, 28) have demonstrated that variable export is largely divorced from variable deepwater production in that basin, breaking another long-standing expectation of the conveyor belt.

Is the Upper Limb of the Overturning Continuous?

Concurrent with surprising turns of the deep limb, two recent studies have found unexpected path-

ways in the upper ocean. An analysis of hundreds of surface drifters that transited the Gulf Stream from 1990 to 2002 (Fig. 4) (29) revealed that only one followed a pathway to the subpolar gyre. This result was identified as a conundrum because a sizable portion (~20 to 25%) of Gulf Stream waters are expected to flow northwestward into the subpolar basin as the MOC upper limb. Possible explanations for the missing throughput include insufficient drifter lifetimes, insufficient sampling, and the influence of a strong southward Ekman transport that inhibits exchange across the subtropical/subpolar boundary. A follow-up study (30), however, suggests another possible mechanism for the missing throughput. Using an expanded drifter data set that is subdivided by temporal periods, this study suggests that throughput to the subpolar ocean is temporally variable, controlled by large-scale winds. Though it remains to be seen whether undersampling can indeed be discounted as a factor and/or whether the expected exchange is found beneath the near-surface layer, the suggestion of variable exchange finds support from a study of property fields in the eastern subpolar gyre (31), where the relative proportion of salty subtropical water entering the subpolar latitudes was found to be highly variable, a function of winds that control the shape, extent, and strength of the ocean gyres.

Collectively, these studies raise questions similar to those asked of the lower limb: Is the upper-limb transport continuous in time? If not, what mechanism principally controls its variability and what are the dominant time scales for this variability? Though answers to these questions have not yet been ascertained, there are indications that wind-driven gyre dynamics plays a strong role in the determination of the exchange of mass and heat across gyre/gyre boundaries. These indications include a discontinuity in the meridional coherence of transport anomalies at gyre/gyre boundaries in the surface waters of the North Atlantic (11) and MOC changes in that basin with a gyre-specific pattern (12).

What Forces the Overturning?

The question of whether and how wind forcing affects the pathways of the upper and lower limbs of the overturning is inextricably linked to the question of what drives the overturning itself. Although many past studies have invoked buoyancy forcing at high latitudes as the driving mechanism for the overturning, other studies over the past decade have pointed to the possibility that wind forcing—by creating surface mass

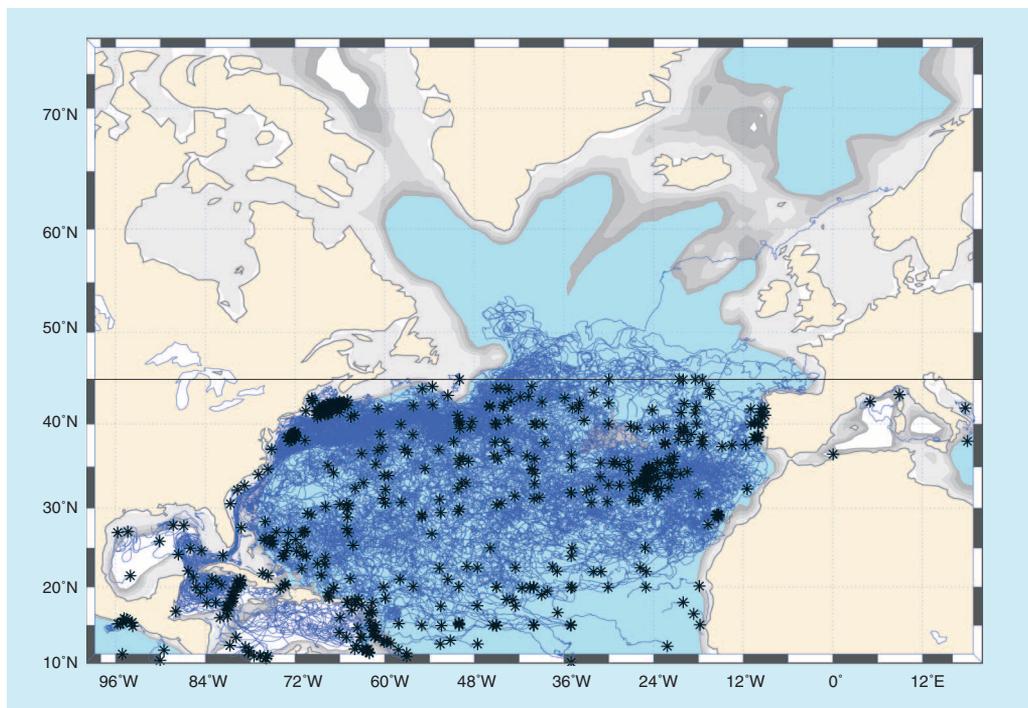


Fig. 4. Trajectories of surface drifters deployed in the North Atlantic from 1990 to 2002. Only drifters deployed south of 45°S (black line) are shown, with asterisks marking the deployment locations. [Reprinted from (29), with permission from the American Geophysical Union]

fluxes and/or by providing the mixing needed to return deep waters to the surface—is instead the dominant mechanism (14). These opposing hypotheses for the forcing of the overturning have been neatly summarized as “push” or “pull” views of this circulation feature (32). The question of which forcing controls the variability of the overturning may depend crucially on time scale: A recent study that isolated the impact of buoyancy and wind forcing on MOC transport in the North Atlantic found the latter dominated on interannual to decadal scales, whereas the former dominated on longer, centennial time scales (12). Of course, this neat categorization may not hold if climate variability brings changes to the strength and position of the large-scale wind fields, as suggested by recent modeling studies (33, 34). Furthermore, historical assumptions about the conveyor belt and its operation are being overturned on other fronts: A recent study shows that MOC transport in the subtropical North Atlantic is susceptible to variability in the “leakage” of warm and salty Agulhas Current water into the South Atlantic (35). Because this variability is remotely forced and because it depends on wave propagation and eddy processes, it elegantly illuminates the progression of our understanding of the overturning’s complexity.

What Are the Open Questions About the Overturning?

Recent evidence that the ocean’s overturning limbs are not spatially and temporally continuous should not cast a shadow on the certainty of the overturning itself: There is clear and abundant evidence that ocean waters overturn. Deep water masses, primarily from the North Atlantic, spread to other ocean basins, with a concomitant surface mass flux of ~20 sverdrups. Considerably less certain is the 3D structure of the overturning. Global pathways for the waters in the lower and upper limbs and the mechanisms governing their spatial and temporal variability remain unknown. Equally uncertain are the dominant mechanisms governing the overturning transport and its accompanying property transports. Such uncertainty surrounding the mean forcing of the overturning presents a cornucopia of possibilities for the forcing that creates overturning changes: High-latitude warming and/or freshening, as well as local and/or remote wind variability, all remain plausible.

Of all questions surrounding the MOC, one looms largest: What is the importance of MOC variability to the meridional transport of heat compared with other forcing? Clear and convincing evidence that sea-surface temperature changes in the North Atlantic impact the climate of northern Europe is coupled with an unproven supposition that overturning changes will create such temperature changes. Though ocean models have repeatedly demonstrated that high-latitude

freshening will lead to a diminution of the overturning (36)—and, thus, a substantial change in North Atlantic sea-surface temperatures—no observational study to date has been able to successfully link sea-surface temperature changes with overturning changes. Presumably, this link is difficult to establish because of the strength of the ocean’s eddy and/or wind field, but that too has yet to be made evident.

How Are These Questions Being Addressed?

Since 2004, a monitoring array for MOC volumetric and heat transport has been in place at 26°N in the North Atlantic. Results from this array are providing an unprecedented view of the temporal variability of the overturning (37) and the challenges accompanying such variability (38). Interestingly, the overturning transport showed more range over the course of one year than had previously been expected for decades of change. In the context of an ocean conveyor belt, such a result would have been surprising, but with the emerging understanding of the contributions from the ocean’s wind and eddy field to the transport of mass and heat in the ocean, such a result is decidedly unsurprising. Though the array at 26°N was initially envisioned to monitor the overturning circulation of the entire Atlantic, studies showing little to no coherence across gyre boundaries have prompted interest in monitoring the overturning circulation in the South Atlantic and the subpolar North Atlantic. Clearly, the connectivity of the overturning and, more importantly, of the meridional heat transport from one basin to the next can no longer be assumed on inter-annual time scales. To complement current and planned direct observations of the overturning, new methods to estimate the transport with profiling floats and satellite products are yielding promising results (39).

Summary

Though appealing in its simplicity, the ocean conveyor-belt paradigm has lost luster over the years, precisely because it has overdistilled the complexity of the ocean’s overturning. This complexity has slowly been revealed as the ocean has increasingly been observed at finer scales in space and time and in places previously only sparsely sampled. As discussed, the ocean’s eddy field, unaccounted for just decades ago and now uncovered by measures at appropriate scales, figures prominently in the dismantling of the conveyor-belt paradigm. Another player in this dismantling is the ocean’s wind field. The traditional assignation of surface ocean gyres to wind-forcing and overturning to buoyancy forcing has ignored the vital impact of winds on overturning pathways and mechanics. As the study of the modern ocean’s role in climate continues apace, the conveyor-belt model no longer serves the community well—not because it is a gross oversimplification but because it ignores

crucial structure and mechanics of the ocean’s intricate global overturning.

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