Aspects of the Observed Deep Circulation of the Atlantic Ocean

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Two of the three goals of the ACCP involve the variability of the thermohaline circulation (monitoring, describing, modeling). I have argued in the past that in order to address such issues we must first have a proper zeroth order understanding of the "mean" circulation, a quantitative circulation diagram, if you will. I have also argued that the "conveyor belt" is not a proper zeroth order description. My own evolving concept of what the proper diagram more resembles is the baggage claim system in a large airport: somehow the bag gets from the airplane to a person's hand, hopefully without going to Toledo along the way. The actual route, however, is rather circuitous, involving one or more localized recirculations with an overall transit time much larger than the distance from the plane and the mean speed of the bag would suggest, and sometimes with its final destination different from what you expected. I describe below several of the components of my "baggage carousel" vision of the deep water circulation. The general topic has evolved rapidly the last several years, perhaps over the next year or two it will be possible to assemble the needed quantitative circulation diagram with a degree of completeness, including perhaps key locations for monitoring changes.

The lower limb of the conveyor belt scheme recognizes that there is a deep western boundary current (DWBC) in the western basin, and that northern source characteristics are more intense near the western boundary. This is cartooned as a monotonic current filament flowing southward along the continental slope. The magnitude of the filament is set at the estimated intensity of the warm to cold water mass conversion, order 15×10^6 $m^3 s^{-1}$. That the conveyor belt is a rather gross simplification of reality seems generally recognized, but often only lip service is paid to that fact. It seems that, at best, a rather haphazard collection of patches and fixes has been applied to force given measurements to make sense within its framework, rather than dealing directly with the flaws in its structure. These flaws are not in any sense small perturbations to the conveyor belt: deep circulation components are missing from the conveyor belt whose transport amplitudes can be several times the above net conversion amplitude. The action of these components certainly must dominate the physics of the circulation, and their presence also presents problems for the interpretation of tracer distributions.

The theme of my remarks is recirculation: that there are circulation components in the deep water that flow in opposition to the southward flow of North Atlantic Deep Water (NADW) in the DWBC. I use the term recirculation in a generalized sense for the northward flowing deep and bottom water between hemispheres or within basins. The northward flow of Antarctic Bottom

Water (AABW) in the North Atlantic, strictly speaking, is flow away from the source, not a recirculation towards the source; it is included in this generalized recirculation definition for simplicity because it flows in many locales in opposition to the net export of cold water from the North Atlantic to the South Atlantic. Recirculation implies a gyre flow, with therefore no particular starting point for a discussion. I will begin with the magnitude of the southward flow of the DWBC in the North Atlantic, specifically the observations of large DWBC transport.

One of the most important observations made in the North Atlantic in the past decade is reported by Dickson, et al. (1990): the direct measurement (by well resolved current meter array) of a DWBC transport of $10.9 \times 10^6\ m^3\ s^{-1}$ off the east coast of Greenland (i.e., EGA for East Greenland Array), close to but downstream of the dense overflows. The data are remarkable as to their steadiness, with it being easy to conclude that what little variability there is in the records represents spatial sampling uncertainty not time change. Dickson (personal communication, 1991) indicates that the final average transport estimate, incorporating the second setting of the EGA, will be order 10% higher than this. One might be tempted to write this estimate onto the conveyor belt, south of where the descent from the warm level of the belt occurs, as a step towards a quantitative circulation schematic. There are several problems with this (a detailed discussion is given in McCartney, 1992a).

The sum total of the dense overflows is, according to the Dickson, et al review of the literature, only $5.6 \times 10^6\ m^3\ s^{-1}$, roughly equi-equipartitioned between the Denmark Strait and those overflows east of Iceland. The actual fraction of this outflow that represents the "northern source" water—deep and/or intermediate waters from the "Nordic Seas" (the basins north of the silled passages)—rather than entrained thermocline waters is not really known. The fraction is a model dependent number, depending on the details of the source water's entrainment of neighboring water masses, principally Subpolar Mode Water (SPMW), as it flows out through the silled passages.

Whatever the northern source proportion in the overflows, there clearly is a confluence of additional transport into the DWBC between the overflow's sills and the EGA, effectively a transport doubling. The traditional scenario would achieve this confluence by entrainment of warm water from the thermocline. This would mean that the warm to cold water (nominal boundary = 4.0°C) source in the northern North Atlantic is very dispersed, with only a small fraction of the EGA transport attributable to source waters in the overflows, the rest due to entrainment at and south of the sills. Farther south, the northern source fraction becomes even smaller, with Labrador Sea Water (LSW) joining the DWBC east of Labrador.

The other scenario (McCartney, 1992a) draws attention to three elements of recirculation that contribute to boosting the DWBC transport. The first is that the LSW, itself part of the NADW complex, has a cyclonic gyre aspect to its circulation in the subpolar basin. Some of the entrainment into the overflows occurs from the LSW rather than the warmer SPMW, and some of the LSW completes the gyre recirculation "intact," so that LSW flowing in the interior in opposition to the DWBC returns in the DWBC. At the EGA, well north of the central Labrador Sea where warmer water is converted to LSW, this system means that in the ocean interior east of the EGA there is some net northward flow of LSW, some of which is entrained downward to return southward as part of the evolving overflow water mass, the rest returning with little alteration as a LSW component of the DWBC. The EGA transport is inflated above the basinwide net flow by the southward return of this interior northward LSW flow (to the extent that Dickson et al.'s use of σ_Θ = 27.8 as the top bounding surface for their estimate includes part of the recirculating unaltered LSW).

The second and third recirculation elements involve the lower deep water (LDW, loosely classified as 2°C to 2.5°C). In the eastern basin a net northward flow of LDW onto the northern boundary initiates the westward flow of the deep northern boundary current, rather that the traditional image of its initiation by the Faroe Bank Channel outflow. This southern source LDW is lower in oxygen and higher in silicate than, and easily distinguished from, the overflow waters. It appears that the water passing from the eastern to the western basin in the neighborhood of the Charlie-Gibbs Fracture Zone (CGFZ) is about equi-partitioned between the eastern overflows and the LDW from the south, and that a recirculation gyre in the West European Basin acts to mix the two waters. In the western basin a northward flow of LDW is also seen offshore of the DWBC, joining the waters emerging from the CGFC to continue into the Irminger Basin. This combined flow ultimately must turn back south to pass through the EGA. Thus, a recirculation completely within the LDW level is observed, with the southward transport of the LDW supplied by the overflows and entrained warmer waters augmented by the southward return of LDW that has flowed north over the rest of the width of the basin, both east and west of the Mid-Atlantic Ridge.

These recirculation elements are not small. In the eastern basin perhaps equi-partition of northern and southern sources is indicated, with the West European Basin cyclonic recirculation acting to mix the two. In the western basin the quantitative situation is less clear: the transport of southern source water is difficult to ascertain because of a strong deep cyclonic recirculation in the Newfoundland Basin, one sufficiently strong that the southern source transport is a small residue compared to the gyre flow.

In both the eastern and western basins the southern source LDW is directly derived from AABW. AABW enters from the South Atlantic only in the western basin, at a rate of about 4 or 5 x 10^6 m^3 s^{-1} (McCartney, 1992b, McCartney and Curry, 1992). About 2 x 10^6 m^3 s^{-1} passes to the eastern basin through the Vema Fracture Zone at 11°N (McCartney et al., 1991), continuing northward (and evolving) with western intensification (within the eastern basin) to about 35° N, then with eastern intensification (Saunders, 1987) to reach the Western European Basin as discussed above. The remainder, 2 or 3 x 10^6 m^3 s^{-1}, continues northward in the western basin, with eastern concentration at all but the lowest latitudes, 5°N (Speer and McCartney, 1992, and McCartney and Speer, 1992). Ultimately some part of this reaches the Irminger basin as discussed above, but with many carousel diversions along the way. While this net transport is not large, its importance is out of proportion to the transport, because the tracer characteristics of the AABW are so different from the NADW.

There are two forms of gyre flow that this AABW is involved in at low- and mid-latitudes. First, is a direct gyre type flow in which AABW flowing northward in the interior is seen returning south in the DWBC. Two examples from older literature are the Amos, et al. (1971) observation of AABW flowing southward along the Blake-Bahama Outer Ridge, and the Weatherly and Kelly (1985) observation of a westward flowing filament of AABW in the DWBC north of the Gulf Stream. A third is the McCartney (1992a) description of a deep cyclonic gyre flow in the Newfoundland Basin--the same shear signature as the deep part of Worthington's (1976) Northern Gyre, but rotating in the opposite sense due to a mid-depth reference level rather than Worthington's bottom reference level. The most dramatic, however, is the centered over the Demerara Abyssal Plain (McCartney, 1992c), where the net northern flow of about 2 or 3 x 10^6 m^3 s^{-1} is achieved as a difference between a northward interior transport of order 8 x 10^6 m^3 s^{-1}, and a partially compensating southward DWBC flow with AABW as cold as 1.3°C.

The second form of gyre flow is sort of an upside version of the LSW one, in that it involves entrainment from one layer to another within the deep water, in this case upward rather than downward. AABW moving northward in the interior moves "up" into LDW and returns southward in the DWBC as part of a mixture. There is a pronounced transport mode in the DWBC at mid- and low-latitudes, centered on Θ = 1.9°C, manifested by a very low potential vorticity (low vertical density gradient) in the high-speed part of the DWBC (McCartney, 1992c). This transport mode is the largest contributor to the unexpectedly large southward transport of NADW by the DWBC, a large transport that seems to cross the equator (McCartney, 1992e). It appears that this layer is formed east of the Bermuda Rise in the deep level of the Gulf Stream anticyclonic recirculation, and represents a mixture of the AABW flowing northwards with the intense westward flow of NADW in the recirculation, with the product (low potential vorticity, oxygen and silicate in between the northern and southern source waters) carried westward to the western boundary, but turning south with the DWBC rather than staying in the deep Gulf Stream system. This thick layer lies above the cold AABW in the DWBC, but below the parts of the DWBC that have crossed under the Stream from farther north. At the Blake-Bahama Outer Ridge (Fine abstract, this meeting) the low potential vorticity water is east of the classical core of the DWBC. At Abaco (Lee abstract, this meeting) the merger had not yet occurred—transport is actually a minimum at 1.9°C in the current meter array. From 24°N to the equator the mode is a distinct component of the DWBC (Molinari abstract, this meeting).

The low potential vorticity mode is the densest variety of true NADW: the high volume ridge of deep water on the Worthington and Wright (1970) volumetric census of the North Atlantic, with this water representing the point of contact between the invading tongues of northern and southern source waters (Luyten, et al, 1992). Why it has such a weak vertical density gradient is not clear, but may be related to the AABW wedging itself under the deep flow of the Gulf Stream recirculation with its 100 times larger eddy kinetic energy (Thompson and Schmitz, 1989). In a sense it thus appears that the "origin" of the LDW flowing south in the DWBC at mid and low-latitudes is the blending action of the deep Gulf Stream system acting on northern and southern source waters.

The final component to note is that the Demerara Abyssal Gyre (McCartney, 1992a), mentioned above as having a intense flow in the AABW, also is found in the LDW. The large southward flow of LDW in the DWBC at mid- and low-latitudes extends across the equator to low latitudes of the Brazil Basin (McCartney 1992e). The northward flow of AABW from the Brazil Basin to the North Atlantic is accompanied by LDW from the Brazil Basin. This recirculation acts to reduce the net southward flow of NADW from the large transport observed in the DWBC to the smaller net value of order 15 x 10^6 m^3 s^{-1}. The circulation within the Brazil Basin is turning out to be equally complex. At 11°S, for example, the western basin has a net southward flow of NADW amounting to about 13 x 10^6 m^3 s^{-1}, but achieved as the difference between a southward 39 x 10^6 m^3 s^{-1} in the DWBC, and a compact northward recirculation of 22 x 10^6 m^3 s^{-1}, and an additional northward 4 x 10^6 m^3 s^{-1} over the rest of the basin. This particular carousel is very strong, and its mixing action hard to ignore.

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