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Hemispheric asymmetry of deep water transport modes in the western Atlantic

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Abstract. Subtropical studies of the Atlantic meridional cold water flow show a hemispheric contrast in the dominant southward transport mode below 2000 m; in the North Atlantic, lower deep water (LDW) ($1.8° \leq \theta \leq 2.4°C$) dominates with small transport of middle deep water (MDW) ($2.4° \leq \theta \leq 3.2°C$), while in the South Atlantic, the opposite is observed. We use numerous observations in the western basins of the tropics to show that the transition occurs rapidly near the equator in the western Atlantic. A meridional section in the central Brazil Basin suggests zonal flows are responsible for the transition. LDW transport from the Guiana Basin (north of the equator) flows eastward in the northern Brazil Basin and is inferred to continue on through the Romanche Fracture Zone into the eastern Atlantic. An opposing flow of MDW from the eastern tropical Atlantic flows toward the western boundary, where it bifurcates to supply MDW to the Deep Western Boundary Current (DWBC) of the Brazil Basin, as well as to feed the northward flow of MDW in the Guiana Basin offshore of the DWBC. The magnitude of each of these oppositely directed flows is roughly 7 Sv. We furthermore speculate that they are connected predominantly by upwelling from LDW to MDW within the low-latitude eastern basin. The overall deep water transport system below 2000 m in the western basins of the mid- and low-latitude Atlantic is thus found to comprise the following three distinct components. (1) A strong DWBC transport of LDW with associated recirculation dominates the Guiana Basin north of the equator. (2) In the northern Brazil Basin (just south of the equator) a narrow eastward flow absorbs the LDW and carries it eastward, while a somewhat broader westward flow imports MDW into the western basin. (3) This MDW flow then bifurcates, with the southward branch causing the MDW dominance in the Brazil Basin, where the MDW dominated DWBC and associated recirculations are the third component of the deepwater transport system.

1. Introduction

The notion of a layered meridional flow system in the Atlantic Ocean is one of the very oldest interpretations of hydrographic measurements. With the realization that the system is associated with the conversion of warm water to cold water at high latitudes, there has been a surge of interest in better defining the system, as it is important for climate issues, as well as for its inherent interest as a manifestation of the thermohaline flow of the ocean. It now is commonplace to see the layered meridional flow conceptualized as a "conveyor belt," where warm water progresses northward through a complex series of linked upper ocean circulation gyres in the subtropical and tropical South and North Atlantic. North Atlantic Deep Water (NADW), the product of cooling at high northern latitudes, then provides a deep return flow.

The actual flow path of the warm water part of the system has always been difficult to trace owing to the dominance of the gyre recirculations over the transfer of warm water from one gyre to the next. Until recent years the cold water part of the system was thought to be inherently simpler and dominated by a monotonic north to south flowing Deep Western Boundary Current (DWBC) associated with very limited circulation intensity in the abyssal interior. Observations have long made clear that northern source influences, i.e., the NADW, are western intensified and project southward along the western boundary, across the equator into the South Atlantic [*Wüst*, 1935], and then to the rest of the world ocean [*Reid and Lynn*, 1971]. In his survey of the circa 1980 state of knowledge of the world

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ocean deep circulation, *Warren* [1981] commented that sections showing the geostrophic flow signature of the southward flowing DWBC were lacking for the boundary segment between the equator and 23°N. In the years since Warren's survey of the field this data deficiency has been rectified, with many hydrographic sections through that latitude range [*Fine and Molinari*, 1988; *Friedrichs and Hall*, 1993; *McCartney*, 1993; *Molinari et al.*, 1992; *Speer and McCartney*, 1991], arrays of current meters at several locations (26°N, [*Lee et al.*, 1990], 8°N [*Johns et al.*, 1990, 1993], 44°W [*Schott et al.*, 1993]), repeated Pegasus profiling programs at 26°N [*Leaman and Harris*, 1990] and at 44°W [*Schott et al.*, 1993; *Rhein et al.*, 1994], and a deep float program in the tropics [*Richardson and Schmitz*, 1993]. The major discovery of these measurements is an unexpectedly large DWBC transport between 26°N and the equator; estimates range from 20 Sv to as high as 40 Sv, which is two to three times the nominal size of the meridional overturning cell, about 12–15 Sv [*Worthington*, 1976; *Hall and Bryden*, 1982; *Friedrichs and Hall*, 1993]. Recently, authors [*Friedrichs and Hall*, 1993; *McCartney*, 1993] have demonstrated that a recirculation offshore of the DWBC and west of the Mid-Atlantic Ridge (MAR) may compensate for this large transport. Hence an image of simplicity of the Atlantic abyssal circulation is being displaced by one of a complexity approaching that of the warm water part of the system.

Our goal in this paper is to make a preliminary and limited description of the complex abyssal circulation field at mid- and low-latitudes of the western Atlantic. (Hydrographic sections used in this analysis are shown in Figure 1.) It is preliminary, in that all the circulation components may not yet have been discovered and in that the existing measurements are dominated by indirect geostrophic estimates of patterns and intensities, with very few direct measurements. It is limited because we will mostly address issues in the colder classes of the NADW, leaving the warmer classes, which interact directly with the overlying thermocline waters, to a future study. We are also limited in our examination of the eastern basins, where it is more difficult to be quantitative because the geostrophic shear is very weak.

This paper is organized as follows. In section 2 we contrast the vertical distribution of deep water in the North Atlantic and in the South Atlantic. We then develop horizontal circulation cartoons for the middle and lower deep water of the tropical Atlantic, which we introduce in section 3 to provide guidance for the reader as we systematically develop their basis. These cartoons draw on earlier equatorial observations and schematics [*Schmitz and McCartney*, 1993; *McCartney*, 1993; *Richardson and Schmitz*, 1993; *Friedrichs and Hall*, 1993], in an iterative process that will undoubtedly continue as the database grows. Section 4 summarizes our findings and offers some concluding remarks.

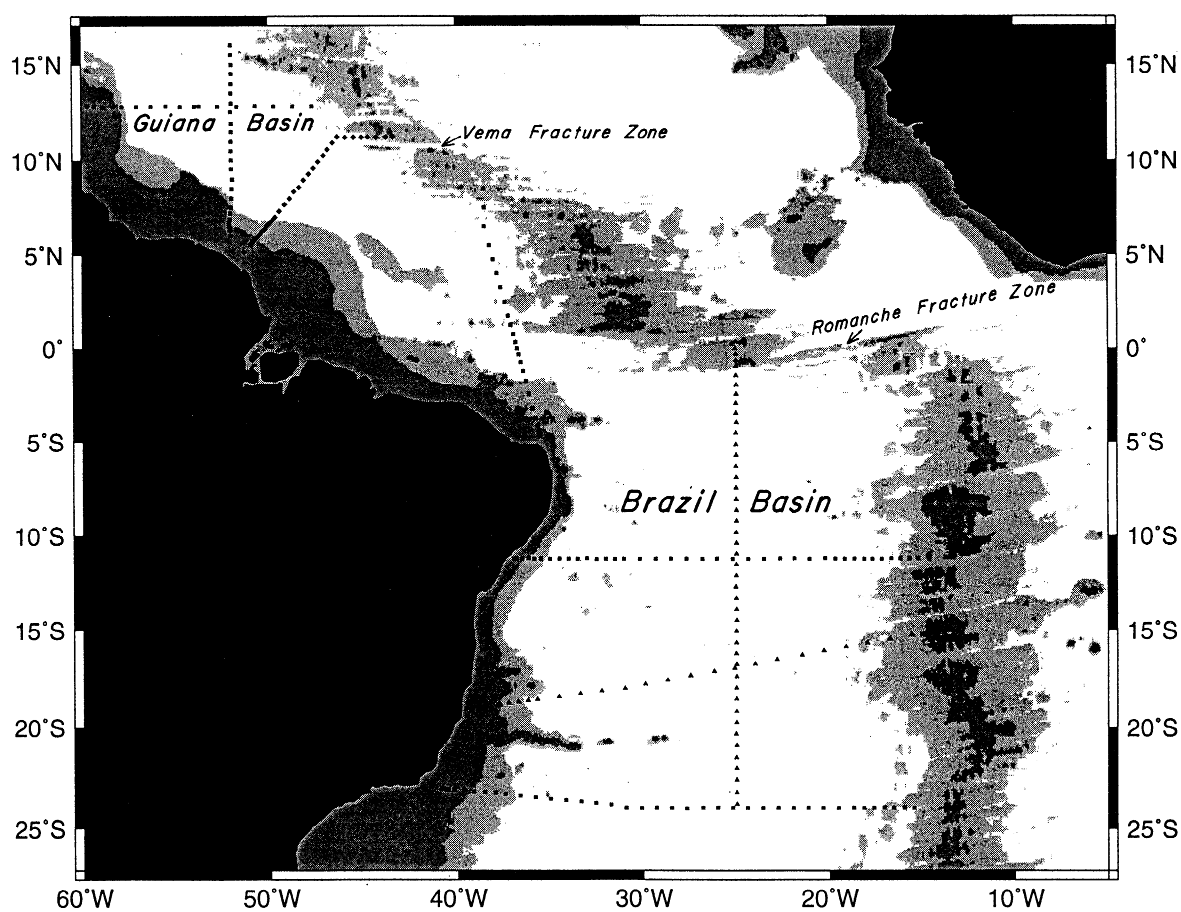

Figure 1. Chart of the Atlantic showing hydrographic sections, basin names, and fracture zones.

A few remarks follow on terminology. Names of the various strata of the cold water system always seem to create controversy through their inevitable association with specific distant sources (with the controversy increasing as distance from and dilution of a given source increase). Our focus will be on the tropics, where the Atlantic abyss is most distant from the various source regions for cold water; hence we adopt the simple name "deep water" (DW) for the bulk of the layer associated with the names North Atlantic Deep Water, Circumpolar Deep Water, and Circumpolar Water, the latter two being of southern origin. We borrow the *Wüst* [1935] classification system, adapted to modern property measurements and notions of source regions, and divide the DW into lower, middle, and upper strata, LDW, MDW, and UDW. We discuss only LDW and MDW, since the UDW is complicated by its interactions with overlying Antarctic Intermediate Water (AAIW). We define the base of the LDW layer as 1.8°C, based on the transition from an apparent northern source dominance (relatively high oxygen and low silicate) to a southern source dominance (relatively low oxygen and high silicate) in the tropical zone of the western basin; this definition is consistent with a number of previous studies, such as *Molinari et al.* [1992] and *Friedrichs and Hall* [1993], who base their definitions primarily on tracer and chlorofluorocarbon (CFC) data. (All temperatures in this paper are potential temperatures referenced to zero pressure, and will be referred to simply as temperatures.) Also following *Molinari et al.* [1992] and *Friedrichs and Hall* [1993], the MDW is defined in the North Atlantic as $\theta = 2.4° - 3.2°C$. These correspond closely to limits of $\sigma_2 = 36.96$ and 37.055 for the warmer isotherms and to $\sigma_4 = 45.9$ for 1.8°C. Also, we note that an overlying temperature inversion in the uppermost MDW of the South Atlantic requires the use of an alternate definition for the Brazil Basin sections, $36.95 < \sigma_2 < 37.045$; this corresponds to the potential temperature limits, $\theta = 2.4° - 3.2°C$. We have preferred to use temperature rather than density bins because most readers are more familiar with the vertical structure of the former; however, in order to insure that the transport modes are not an artifact of some peculiar $\theta(z)$ profile, we have verified that transport in density classes displays the same character. We retain the traditional name Antarctic Bottom Water (AABW) for water colder than 1.8°C.

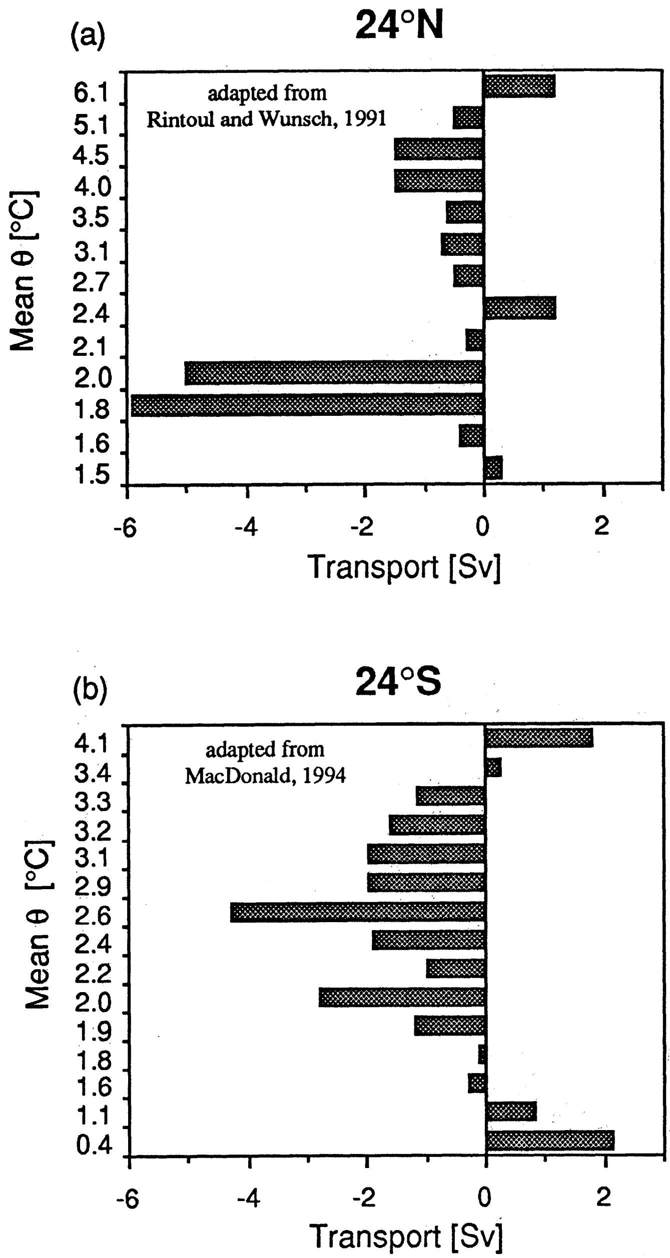

Figure 2. Net transport histograms at (a) 24°N (adapted from *Rintoul and Wunsch* [1991]). (b) 24°S (preliminary results for 24°S, A. MacDonald, 1994, personal communication).

2. Vertical Distribution of DW Transport

Histograms of net meridional transport across zonal transects at 24°N and 24°S are shown in Figure 2, for layers defined by density surfaces and plotted versus the mean temperature associated with each layer [after *Rintoul and Wunsch*, 1991; preliminary results for 24°S, A. MacDonald, 1994, personal communication]. There are two striking features concerning the distribution of transport among the cold water temperature classes. The first is perhaps the more familiar; in the North Atlantic transect the transport of AABW is much smaller than it is in the South Atlantic, reflecting the impact of persistent upwelling across isotherms (warming) of the AABW [*McCartney and Curry*, 1993]. The second, which to our knowledge has not been discussed before, is an antisymmetry between the South Atlantic and the North Atlantic in the vertical distribution of the DW transport.

In the transect from the northern hemisphere (Figure 2a) the DW transport is sharply peaked in a temperature range traditionally associated with the LDW, near 2°C; we will call such a peak a transport "mode." A second, weaker mode occurs at a much warmer temperature near 4°C, the traditional UDW, which is believed to originate in the Labrador Sea [*Pickart*, 1992] and is associated with a strong CFC signal [*Weiss et al.*, 1985]. The structure and transport of this layer have been described in detail by *Fine and Molinari* [1988] and *Molinari et al.* [1992] between about 3°N and 26°N; we will not address it in this paper. The upper and lower transport modes are separated by the southward transport minimum of the MDW, which displays a weak reversal near 2.5°C. Although this transport minimum has been recently observed and discussed by *Molinari et al.* [1992] and *Friedrichs and Hall* [1993], unfortunately, in many earlier studies, such as *Roemmich* [1983], coarse vertical resolution has caused the MDW and LDW layers to be indistinguishable; however, a similar vertical structure within the North Atlantic is apparent in the results of *Roemmich and Wunsch* [1985, Table 1], which clearly delineate a strong LDW mode with weak flow in the layers above.

In the southern hemisphere transect (Figure 2b) the distribution is quite different: a single transport mode with a comparatively broad temperature range is centered near 2.7°C, almost a degree warmer than the strong LDW mode of the North Atlantic, where this temperature is associated with a weak MDW flow. Similar results are also found in other studies of the South Atlantic; for instance, *Rintoul* [1991] finds a very similar profile at 32°S.

We thus find that the LDW classes that dominate southward transport in the North Atlantic show little net flow in the South Atlantic, while the MDW classes that dominate the southward transport in the South Atlantic show little net flow in the North Atlantic; there is clearly a hemispheric asymmetry in the transport distribution. This switch from LDW dominance in the northern hemisphere to MDW dominance in the southern hemisphere is apparent in the inversion results of *Wunsch* [1984, Figure 7b]; however, the usefulness of this figure is limited owing to its zonal integration. The remainder of this paper focuses on the horizontal circulation of the MDW and LDW, in an effort to understand the resolution of the hemispheric contrast and to define the circulation patterns that account for it.

One of the first interpretations that comes to mind to explain the hemispheric asymmetry of Figure 2 is that it reflects warming and upwelling following the flow, where downgradient heating from above balances upwelling across isotherms. As described by *McCartney and Curry* [1993] (see especially their Figure 6), this is indeed the case for the topographically confined AABW; however, the role of upwelling is a more complex issue in the much thicker and less confined DW, where water can upwell into the layer from below, as well as leave out of the top. To guide us through our discussion of the circulation elements of the Atlantic cold water system, we now pose a series of questions suggested by Figure 2. We begin with the DWBC part of the abyssal circulation and work our way eastward.

Is the hemispheric asymmetry in Figure 2 apparent not only in these zonal averages, but also in the DWBC? In this study we examine six sections which cross the western basin between 13°N and 24°S. (See Figure 1 for section locations.) These particular sections were selected because of their high resolution at the western boundary and because they all completely cross the recirculations noted above. The geostrophic method has been applied to each of these sections, and meridional transports have been computed in temperature bins. Reference levels have been chosen as follows: for the Guiana Basin sections we have used isopycnal reference levels which closely correspond to the isobaric ones used by *Friedrichs and Hall* [1993], whereas in the Brazil Basin a reference level between the LDW and AABW appears to be most appropriate [*McCartney*, 1993]. Uncertainties in estimated transports are difficult to quantify rigorously for this type of calculation, especially since it is well known that time variability plays an important role in the DWBC flows [*Johns et al.*, 1993]. The variability in the northern hemisphere transports, all located fairly close together, suggest that the expected uncertainty of the transport estimates for the two layers is of the order of 1 Sv in the DWBC and about 2 Sv in the offshore northward flows. These are similar to the error estimates presented by *Friedrichs and Hall* [1993] for the section at 11°N.

If there is a smooth transition from the northern to southern distributions, it should be apparent in the DWBC, since that is the predominant southward advection agent. Figure 3 shows DWBC transport histograms for the three sections north of the equator (Figure 3a) and the three south of the equator (Figure 3b), where the DWBC has been defined as the maximum southward transport integrated seaward from the western boundary. The apparent width of the current (not all sections cross it perpendicularly) ranges from 400 to 1000 km and is partially dictated by the shape of the continental margin.

The three examples of tropical DWBC observations from the Guiana Basin (Figure 3a) are dominated by nearly the same LDW classes as were the net flows at 24°N (Figure 2a); there is a clear persistence of the LDW dominance throughout the mid- and low-latitude DWBC in the North Atlantic. We have examined the DWBC transport distributions at a number of additional North Atlantic locations using Subtropical Atlantic Climate Studies (STACS) data [*Fine and Molinari*, 1988; *Molinari et al.*, 1992; R. L. Molinari, R. A. Fine, and E. Johns, 1993, personal communication] and find that all of these sections located from 3°N to 26°N, as well as the current meter data at 8°N [*Johns et al.*, 1993], show a pronounced LDW mode concentrated in the 1.8°to 2.2°C range, augmented by southward flowing AABW colder than 1.8°C. It is not present in the moored array [*Lee et al.*, 1990] or Pegasus profiler [*Leaman and Harris*, 1990] current fields east of Abaco (26°N) because of their narrow spatial scope; however, hydrographic sections extending farther offshore at these locations do reveal the shear of this mode.

Moving to the South Atlantic, the three examples of DWBC observations in the Brazil Basin (Figure 3b) are dominated by the same MDW classes as is the 24°S transect net (Figure 2b), suggesting a persistence of this MDW dominance throughout the low- and midlatitude

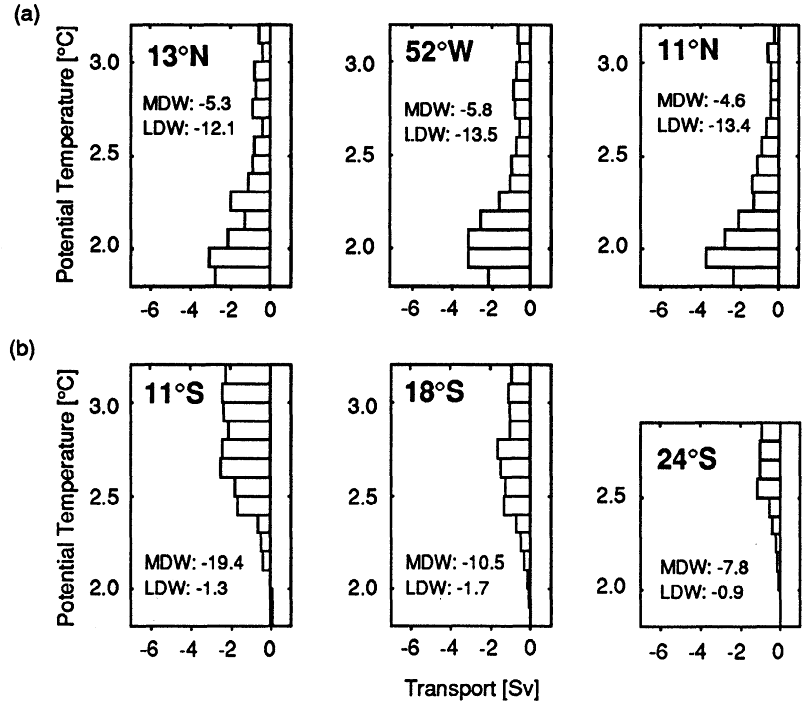

Figure 3. Histograms of Deep Western Boundary Current (DWBC) transport in temperature classes in the lower and middle deep waters (a) in the north, 13°N, 52°W, and 11°N, and (b) in the South, 11°S, 18°S, and 24°S; totals for each are inset. In the southern hemisphere, although the distribution is shown as a function of θ, the transport is integrated over $36.95 < \sigma_2 < 37.045$ (see Introduction in text). MDW is middle deep water; LDW, lower deep water.

DWBC in the South Atlantic. We have examined three additional locations, the South Atlantic Ventilation Experiment (SAVE) sections near 10°S and 25°S [*Scripps Institution of Oceanography*, 1992] and a section near 37°W [*McCartney*, 1993], where the DWBC lies from 1–3°S. At all three the DWBC transport carries a pronounced MDW mode between 2.4–3.2°C, with the latter section demonstrating its existence at very low latitudes of the Brazil Basin.

Thus, in answer to the above question, essentially the same contrast and antisymmetry between the North and South Atlantic that is found in the subtropical transects of Figure 2 is also found in the DWBC. Moreover, the transport mode does not steadily or smoothly evolve along the western boundary from LDW dominance in the north to MDW dominance in the south; instead, the DWBC data suggest a relatively rapid transition within the equatorial region. We anticipate that recirculation gyres and other interior circulation elements must accomplish this hemispheric transport redistribution. We noted above that deep recirculations in the Guiana and Brazil Basins can significantly reduce the net southward transport of cold water, but we did not address their vertical structure, so we now ask the following.

What is the vertical distribution of DW transport in the offshore recirculation at each latitude? Is the hemispheric asymmetry reduced if we include this part of the circulation? The transport modes in the DWBC itself do not evolve smoothly from north to south (Figures 3a and 3b). Since the large DWBC transports are known to be partially canceled by opposing flows offshore, it is possible that these recirculations carry a different distribution of transport than the DWBC and that the combined flow of both might exhibit a smooth progression from the LDW dominance of northern midlatitudes to the MDW dominance in southern midlatitudes. In order to examine this possibility, Figure 4 shows transport histograms for the interior transports (from the eastern edge of the DWBC to the western flank of the MAR), while Figure 5 shows the complete western basin crossings (the sum of the histograms in Figures 3 and 4.)

Although we have seen that the net MDW flow is generally weak at 24°N (Figure 2a), the DWBC in the Guiana Basin sections does carry a significant southward transport of MDW (Figure 3a); however, a closer examination of these sections reveals that this transport is almost entirely canceled by the northward interior flow of MDW (Figure 4a), yielding net western basin histograms (Figure 5a) with weak MDW transport, roughly matching the 24°N level, but here achieved by flow cancellation. There is substantial recirculation of LDW as well, but when added to the DWBC flow, the combined transports in the Guiana Basin (Figure 5a) remain dominated by the LDW mode, with no additional evidence of systematic southward evolution toward MDW dominance.

In the South Atlantic the interior histograms of Figure 4b are essentially mirror images of the corresponding DWBC histograms (Figure 3b), and thus the net

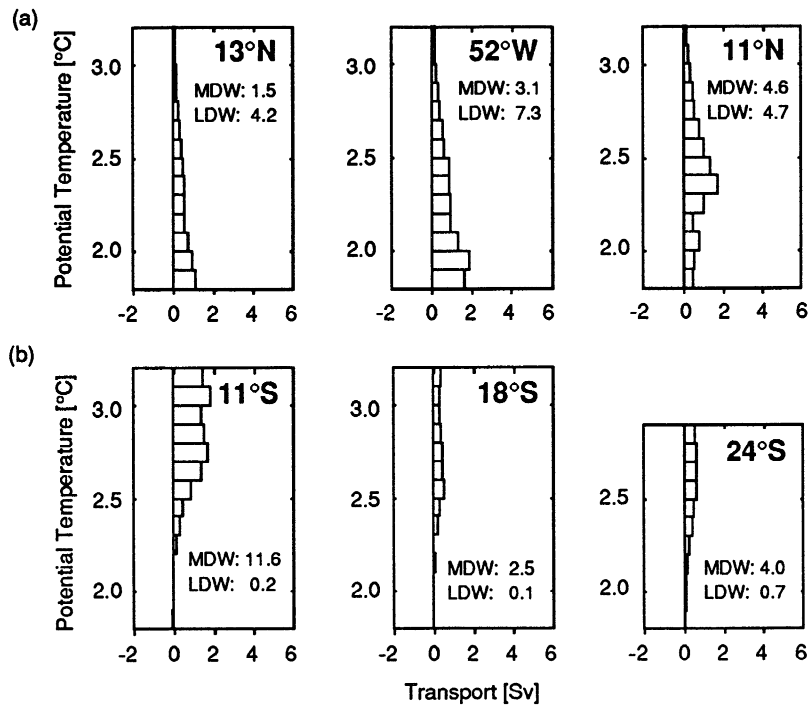

Figure 4. Same as in Figure 3, but for the recirculation.

western basin transports are still dominated by the MDW transport mode (Figure 5b). This mode shows no significant vertical redistribution of transport throughout the Brazil Basin. Furthermore, since there are only small LDW transports in the interiors of these South Atlantic sections, the net flow of the Brazil Basin has essentially the same vertical structure as that found in the full South Atlantic transect at 24°S (Figure 2b).

As in the northern sections, the addition of the recirculation to the DWBC in the Brazil Basin does not redistribute the transport in a fashion helping to smooth the transition from the LDW dominance of the North Atlantic to the MDW dominance of the South Atlantic. Thus the options seem limited to two, either (1) the southward flow upwells in the restricted area of the western basin between 11°N and 11°S or (2) within this

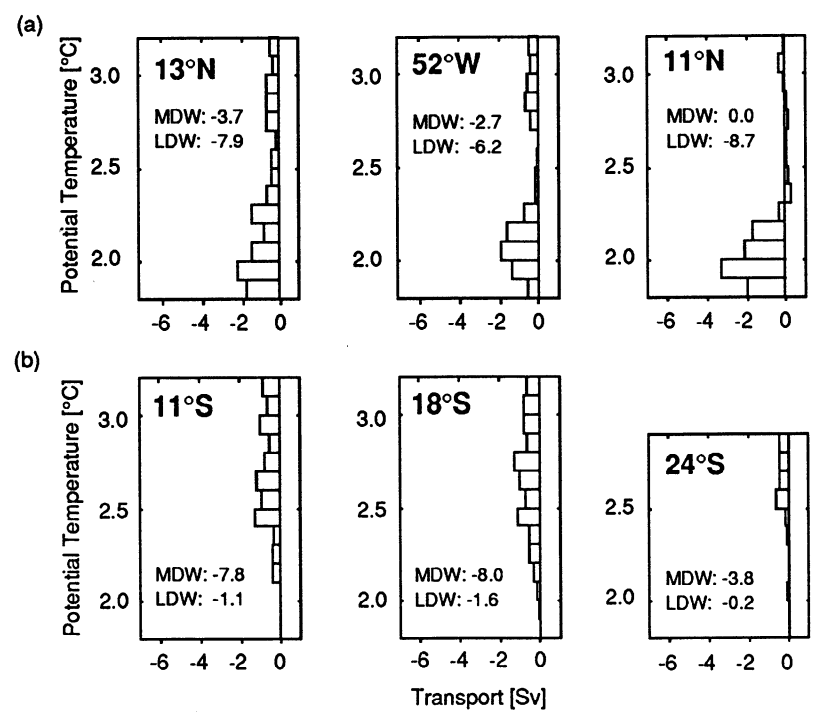

Figure 5. Same as in Figure 4, but for the entire western basin (sum of Figures 3 and 4).

limited area there is a substantial export of LDW from the western basin to the eastern basin associated with an import of MDW from the eastern basin to the western basin. In the following section we provide extensive evidence indicating that the latter is occurring.

3. The Role of Horizontal Circulation

A significant product of this study is a pair of circulation cartoons for the LDW and MDW. These we present here as Figure 6, with the hope that they will aid the reader in obtaining a more complete understanding of the following analysis. Since the resolution of the circulation issues is rather different at the LDW and MDW levels, we will complete the discussion of each layer separately, beginning with the LDW.

In the previous section, Figures 3a and 4a established the existence of a large LDW DWBC and offshore northward flow within the Guiana Basin. An examination of property values, primarily oxygen and salinity, has indicated that this interior LDW flow is, in fact, a recirculation of the DWBC and not a separate northward current [*Friedrichs and Hall*, 1993]. These flows are illustrated in Figure 6a, where they are labeled with transports of 13 Sv for the DWBC and 5 Sv for the recirculation. These values were obtained by averaging the three estimates of Guiana Basin LDW transports listed in Figures 3a (DWBC) and 4a (recirculation). Although few previous studies have quantified the magnitude of the LDW recirculation, a number of authors have estimated the magnitude of the LDW DWBC. For instance, using the same definition of LDW, *Molinari et al.* [1992] have computed the average LDW component of the DWBC from 12 sections between 3°and 14°N to be 13.0 ± 2.7 Sv. Since *Schott et al.* [1993] have found a significant component of the LDW DWBC south of the Ceara Rise at 44°W, while *Whitehead and Worthington*'s [1982] data to the north of this topographic feature also show a large LDW transport, we indicate on Figure 6a that the LDW DWBC may flow around both sides of the Ceara Rise. Unfortunately, the LDW crossing the 37°W section (see Figure 1) lies directly over the equator, and thus a geostrophic transport calculation is not possible from these data. Within the Brazil Basin, only 1–2 Sv is found within the LDW DWBC, and as shown in Figure 6a, there appears to be no significant net transport of LDW across the 24°S section (see also Figure 5b). This strong hemispheric contrast leads us to ask the following.

Where does the LDW transport mode of the Guiana Basin go, since it does not appear to completely recirculate in the Guiana Basin or to continue southward across the equator and into the Brazil Basin? We now examine the possibility of eastward flow of LDW near the equator, motivated by a possible analogy to observations of eastward flow of

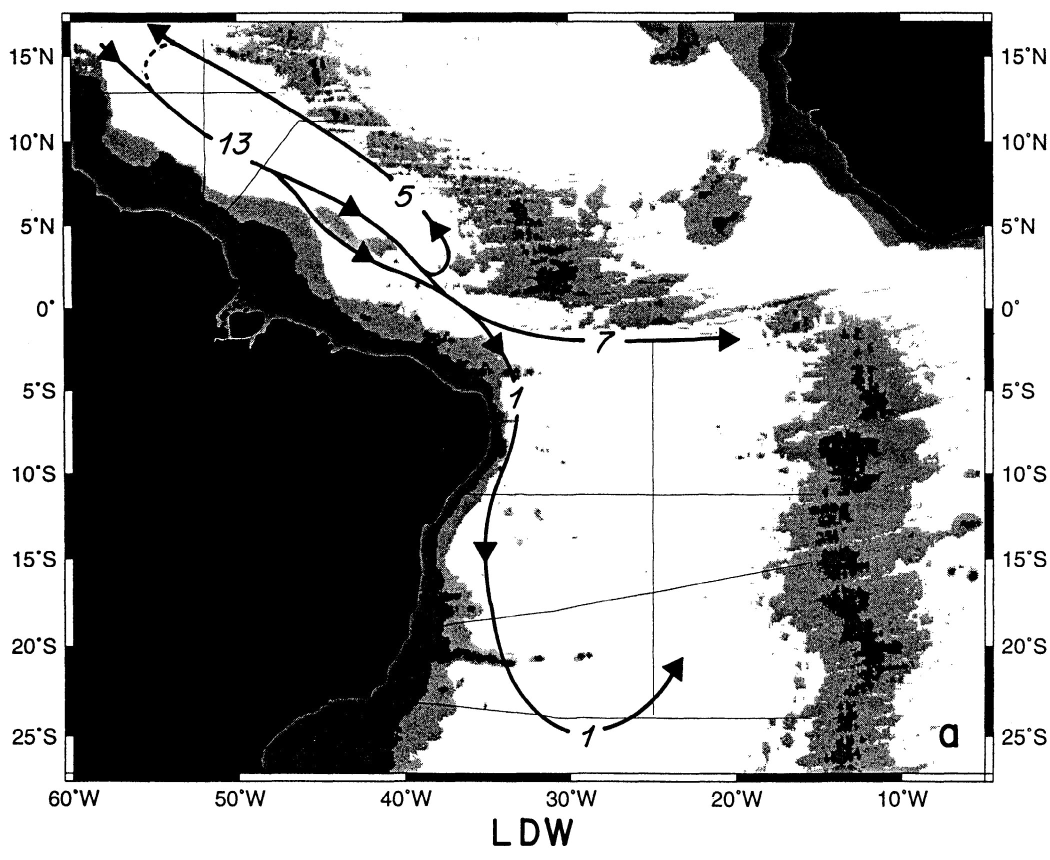

Figure 6. Circulation cartoons for (a) lower deep water and (b) middle deep water. See text for further explanation.

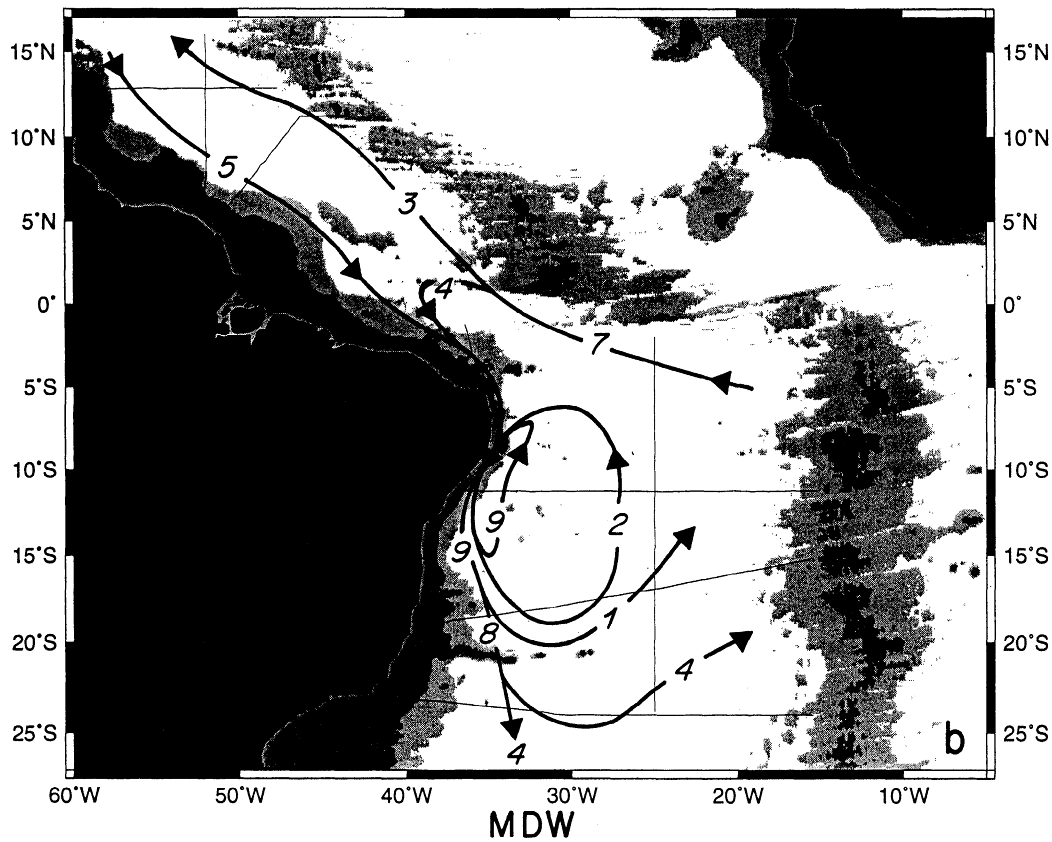

Figure 6. (continued)

UDW along the equator [e.g., *Richardson and Schmitz*, 1993; *Weiss et al.*, 1985, 1989]. Although LDW is more constrained topographically, it could potentially be diverted through the MAR to the eastern basin at two locations where deep passages exist; LDW could be drawn from the northward flowing Guiana Basin recirculation through the Vema Fracture Zone near 11°N (located just south of our 11°N section), or if LDW flows eastward near the equator, it could flow through the Romanche Fracture Zone. (See Figure 1 for fracture zone locations.) The Vema Fracture Zone can be ruled out as a pathway for diversion of LDW to the eastern basin by the data described by *McCartney et al.* [1991]. As shown in Figure 7, although cold water does flow eastward through the Vema, it is dominated by AABW, not LDW; the small LDW transport dispersed over a broad range of temperature classes cannot account for the missing LDW mode within the southern hemisphere. The question of whether LDW flows eastward through the Romanche is a little more difficult to resolve, owing to the limitations of geostrophic calculations for near-equatorial sections and to the lack of direct velocity measurements in this area. (A moored array is currently located at the Romanche Fracture Zone (K. Speer and H. Mercier, personal communication, 1994) which should yield a direct quantification of this flow.) Thus, to investigate this second possibility, we begin with examining indirect evidence from property fields.

Although several charts of LDW properties, particularly oxygen, have been shown to be suggestive of an eastward spreading axis for the northern source influence in the northern Brazil Basin [*Reid*, 1989; *Speer and McCartney*, 1991], data from several recent cruises

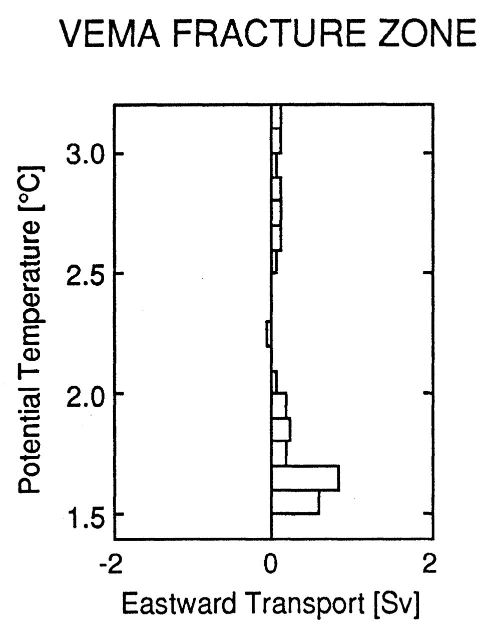

Figure 7. Transport histogram of the flow through the Vema Fracture Zone.

with improved data resolution have allowed us to prepare a new and striking visualization of this field. Figure 8a shows the low-latitude distribution of oxygen in the LDW on the $\theta = 2.0°C$ surface and illustrates the high oxygen influence from the Guiana Basin DWBC separating from the western boundary, projecting eastward near the equator and extending across the Brazil Basin. (The data are surprisingly compatible, given the 0.05 ml/L contour interval, which is only slightly greater than the current accuracy of water sample processing.) The tongue is topographically limited to the north by the MAR, while to the south the full Brazil Basin has no limiting topography east of 33°W; yet the tongue still appears to be confined to latitudes equatorward of 5°S. A cross-sectional view along the 25°W hydrographic section (Figure 8b) shows that it is also confined vertically to the LDW layer; below is lower-oxygen AABW, while above is primarily lower-oxygen MDW.

The oxygen distribution is interpreted as showing the flow of high-oxygen LDW arriving at the equator with an eastward orientation, primarily owing to the shape of the continental slope of South America at the equator. This flow passes eastward through the southern end of the 37°W section (Figure 8c), but instead of making a sharp (nearly 90°) turn south to continue as a DWBC, it continues eastward in the northern Brazil Basin. In the process it thus crosses from the western boundary to a "northern" boundary; that is, it flows along the zonally oriented offset of the equatorial MAR which forms the northern limit of the Brazil Basin. Since the 25°W section (Figure 8b) lies only a couple of hundred kilometers from the western entrance of the Romanche Fracture Zone and since there is no indication from Figure 8a that the tongue turns southward, we infer that the eastward flow enters this fracture zone. Recent property data within the Romanche showing the high O_2 tongue continuing right along the fracture (K. Speer and H. Mercier, personal communication, 1994) further supports this hypothesis.

We note, however, that property tongues must be interpreted with care, since they do not necessarily imply a strong advection pathway. In the UDW of this region, for example, an eastward projecting tongue of high tracer concentration can reflect a dilution of the strong DWBC by the waters of a recirculation rather than a weakness of the southward flow of the DWBC. In the present case we feel safe in inferring a dominance of the eastward flow for two reasons. First, our preceding discussion revealed the LDW farther south in the Brazil Basin as a layer of negligible flow. Second, at 25°W, geostrophic flow calculations provide evidence of an eastward transport of LDW just south of the equator. Estimates are given in Figure 9 for three station

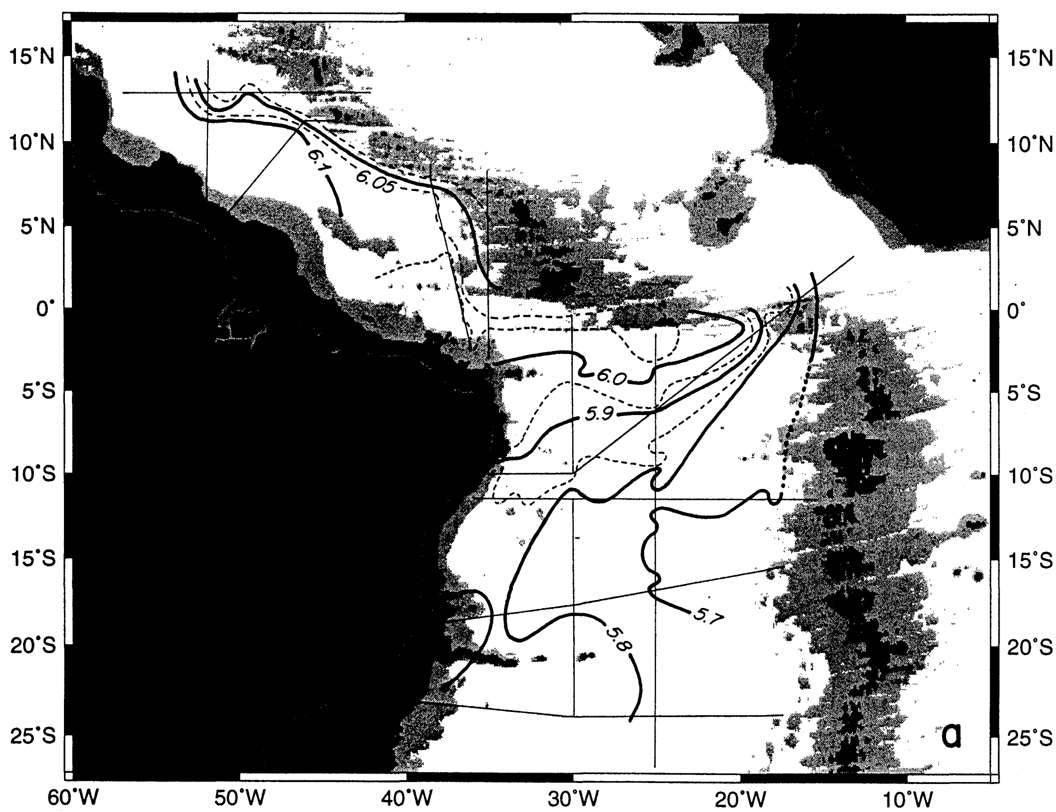

Figure 8 . (a) Low-latitude distribution of oxygen on the LDW $\theta = 2.0°C$ surface, based primarily on values measured by conductivity-temperature-depth (CTD)-mounted oxygen profilers calibrated with bottle samples. (b) Oxygen section at 25°W, plotted as a function of θ and along-track distance. (c) Same as in Figure 8b, except for 37°W. (d) Same as in Figure 8b, except for 11°N.

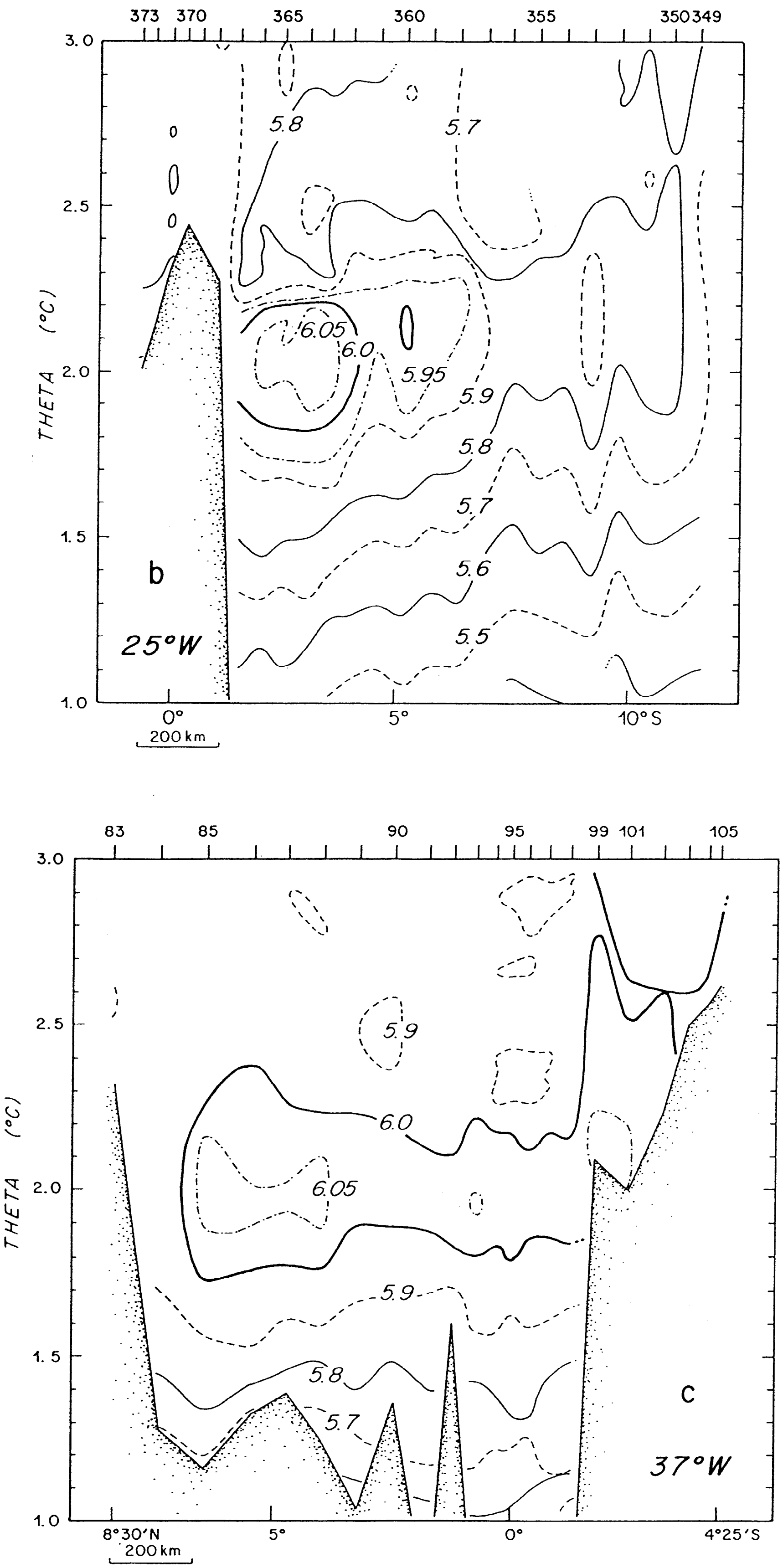

Figure 8. (continued)

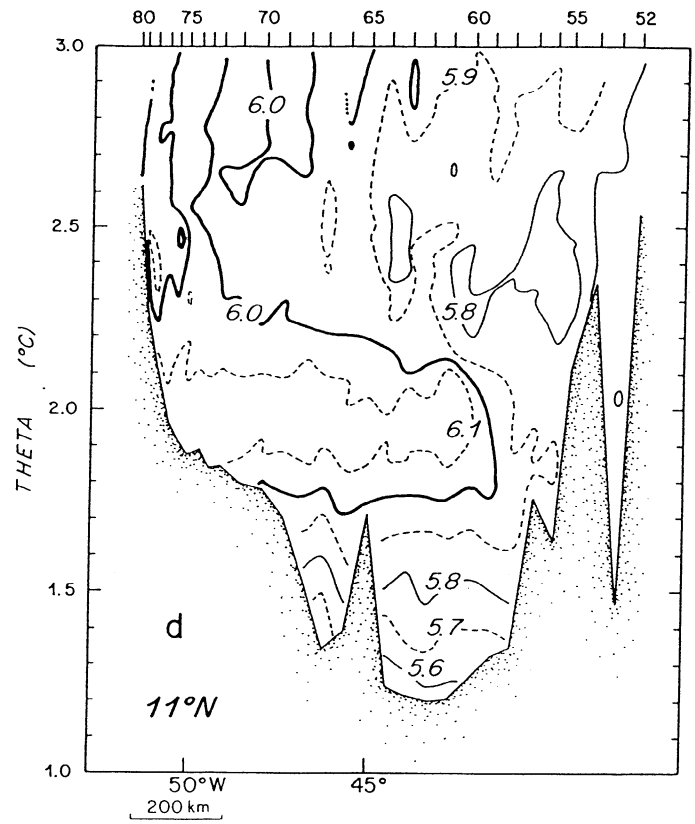

Figure 8. (continued)

groups, a group between 2° and 4°S, where the high oxygen values are located; a group between 4° and 15°S; and a group between 15° and 24°S. Figure 9a illustrates the large eastward LDW transport mode located only a few degrees south of the equator, with a magnitude of 6 Sv. (As we see from Figures 9b and 9c, integrating this LDW transport all the way to 24°S does not significantly change this net LDW transport.) Although a comprehensive budgeting of transport is beyond this paper's scope, we can see that this eastward flow of LDW accounts for nearly all of the difference between the LDW transport in the Guiana Basin (−8 Sv) and that in the Brazil Basin (−1 Sv). Since our estimate of the magnitude of this eastward LDW jet may be a lower bound (we have not been able to obtain the geostrophic transport north of 2°S owing to the proximity of the equator), we have adopted a rough estimate of 7 Sv for inclusion on Figure 6a; this maintains a necessary degree of internal consistency.

This completes the discussion of the observations and transport estimates that lead to the western basin part of the LDW circulation cartoon (Figure 6a); before we speculate on the possible fate of the LDW after it enters the Romanche Fracture Zone, we consider the remaining issues for the western basin MDW layer. The Guiana Basin histograms of Figure 3a yield an average MDW DWBC transport of 5 Sv, in good agreement with the *Molinari et al.* [1992] estimate, again between 3° and 14°N, of 6.3 ± 2.1 Sv. Using property data along 11°N, *Friedrichs and Hall* [1993] have concluded that this MDW current along the western flank of the MAR is probably not a recirculation of the DWBC, but rather represents a separate northward current perhaps derived from the South Atlantic; this flow is illustrated in Figure 6b and labeled with a transport value of 3 Sv, obtained as an average from Figure 4a. Although the Guiana Basin MDW DWBC is only 5 Sv, the corresponding MDW transport in the northern Brazil Basin DWBC is nearly 20 Sv. In order to understand this hemispheric asymmetry, we now ask the following.

Where does the MDW transport mode of the Brazil Basin sections come from, since it appears to be considerably stronger than the MDW transport in the Guiana Basin? The answer to this question follows from the same property distributions and geostrophic calculations just discussed in the LDW context. The 25°W transport histogram in Figure 9a indicates a flow reversal near 2.4°C, where the oxygen distribution (Figure 8b) also shows a simultaneous transition from high- to relatively low (< 5.8 ml/L) oxygen concentrations. From this evidence it appears that the MDW at 25°W does not originate from the DWBC at the 37°W section where high oxygen (> 6.0 ml/L) MDW is carried (Figure 8c); instead, it must have a significant South Atlantic component. Geostrophic calculations support and quantify this flow; Figure 9a shows a westward MDW transport of nearly 3 Sv in the northernmost Brazil Basin, while Figure 9b indicates that additional westward flowing MDW occurs between 4° and

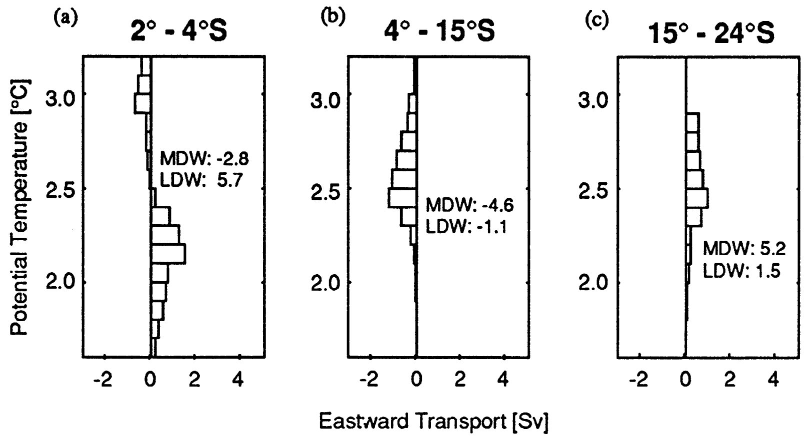

Figure 9. Transport histograms for 25°W section, (a) 2°to 4°S, (b) 4°to 15°S, and (c) 15°to 24°S.

15°S. As illustrated in Figure 6b, a net westward flow of roughly 7 Sv crosses 25°W within the tropical South Atlantic.

From Figure 4a we see that roughly 3 Sv of MDW is found flowing northward in the Guiana Basin along the western flank of the MAR. In order to aid in understanding the fate of the remaining 4 Sv from the east, we compute the MDW transport across the 37°W section just south of the equator to be 9 Sv. (*McCartney's* [1993] larger value of 11–12 Sv results from a slightly different definition of MDW boundaries. Note also that as he pointed out, this 37°W section could not be used to compute LDW geostrophic transports, since the LDW lies equatorward of 2°S.) Figure 3a shows roughly 5 Sv of MDW flowing southward within the DWBC of the Guiana Basin, suggesting that (for a consistent mass balance) the remaining 4 Sv of westward flowing MDW from the eastern basin must retroflect in the low latitudes of the Atlantic and join up with the southward flowing DWBC, as illustrated in Figure 6b. This yields a net 9 Sv of MDW flow across 37°W. In support of this interpretation we note the pool of generally low-oxygen MDW (< 5.9 ml/L; Figure 8c) located north of the DWBC (i.e., north of station 98) at 37°W. At 11°N (Figure 8d), MDW in the DWBC is high in oxygen (> 6.0 ml/L), but much lower-oxygen MDW hugs the Mid-Atlantic Ridge (< 5.8 ml/L), suggesting that the low-oxygen isopleths at 25°W sweep west and northwest into the Guiana Basin.

As shown in Figure 3b, the 9 Sv of MDW in the DWBC near the equator must increase to nearly 20 Sv by 11°S. From our sections alone we cannot resolve how rapidly this increase occurs. One possible scenario, supported by Figures 3b and 4b and illustrated in Figure 6b, is that this additional growth is achieved through a compact recirculation in the western Brazil Basin, only a portion of which extends southward across the 18°S section. Farther south in the Brazil Basin, the DWBC transport of MDW diminishes (Figure 3b); this is accomplished via recirculation into the interior (Figure 4b) and penetration eastward through the 25°W section (Figure 9c).

What is the fate of the eastward equatorial LDW jet, and what is the source of the westward MDW transport crossing 25°W? We can only speculate on the fate of the eastward transport of LDW through the 25°W section in the Brazil Basin. As we have seen, there is no evidence in either the oxygen distributions or geostrophic calculations to suggest that the LDW heading eastward across 25°W turns southward before reaching the Romanche Fracture Zone, and thus we infer that the 7 Sv of LDW passes from the Brazil Basin through the Romanche into the eastern basin. Since *Friedrichs and Hall* [1993] have estimated a northward net LDW flow of nearly 2 Sv across the eastern basin at 11°N, there is a residue of > 5 Sv which needs to be accounted for. Using *Warren and Speer's* [1991] reference levels for the eastern basin of 11°S, we compute the net LDW flow to be < 1 Sv southward there. One possible scenario which might accomplish this is an upwelling from the LDW to the MDW layers between 11°N and 11°S of about 4 Sv. Any AABW transport flowing eastward through the Romanche Fracture Zone must also upwell, as there is no eastern basin AABW at 11°S and its northward flow is blocked by the Kane Gap sill at 8°N, 20°W [*McCartney et al.*, 1991]. Since we estimate a net eastward AABW flow of 2 Sv through the 25°W section, our total upwelling estimate is roughly 6 Sv moving into the MDW layer between 11°N and 11°S. Distributed over an area roughly 2200 km by 2500 km, this implies upwelling (cross isopycnal) velocities of 1.1×10^{-6} m/s, which is similar to those recently estimated by *Wijffels* [1993] for the eastern equatorial Pacific.

How does this estimate compare with what we find in the MDW? That is, where does the westward transport of MDW toward the western boundary through the 25°W section in the Brazil Basin come from? Although there is only a small net zonal flow of MDW between 2°and 24°S (Figure 9), its transport distribution at 11°S does not allow a simple closure scheme of MDW transport in the western basin (Figure 6b). Instead, most of the westward flowing 7 Sv in the northern Brazil Basin must come from the eastern basin, where it is fed by a strong upwelling of LDW and AABW. The documented MDW transports at 11°N and 11°S for the eastern basin, however, seem to imply an additional divergence of MDW transport, which also must be fed by the upwelling. At 11°N *Friedrichs and Hall* [1993] observe a northward eastern basin MDW flow of 1.5 Sv, while, once again, using *Warren and Speer*'s [1991] reference levels combined with our MDW definition yields a net southward eastern basin transport also of 1.5 Sv. Such a combination of circulation patterns would seem to require a net upwelling of roughly 9 Sv (1.6×10^{-6} m/s), somewhat larger than the estimate of 6 Sv (1.1×10^{-6} m/s) derived from our corresponding LDW analysis. However, we note that (1) the weak, deep geostrophic shears make the eastern basin horizontal flows more difficult to resolve than those in the western basins and (2) the near-equatorial transports are subject to large errors. Nevertheless, we speculate that upwelling of deep and bottom water in the tropical eastern Atlantic may be an important mechanism.

4. Discussion and Summary

The cold water part of the layered meridional flow system in the Atlantic exhibits a net southward transport that is dominated by distinctly warmer water in the subtropical South Atlantic than in the subtropical North Atlantic. The distributions are antisymmetric, with a strong LDW (1.8°C to 2.4°C) transport and weak MDW (2.4°C to 3.2°C) transport in the north, contrasting with a strong MDW transport and negligible LDW transport in the south. A smooth evolution from one dominance to the other might be expected in the intervening tropical Atlantic and would be manifested by a steady warming of the dominant mode following the current, reflecting a balance between upwelling and downward diffusion of heat; however, this is not observed. Instead, DWBC measurements exhibit the same antisymmetry at tropical locations as well, including observations to within a few degrees latitude of the equator. Thus a sharp transition near the equator is implied.

In the subtropics and tropics of both hemispheres the basin net transports are achieved as the difference between large southward transports in the deep western boundary current and smaller, opposing interior flows. These flows substantially reduce the total southward cold water transport, but because they are dominated by the same temperature classes as the adjacent DWBC, they only slightly reduce the hemispheric asymmetry of the net cold water transport. Many of these flows are recirculations of DWBC water, as indicated by property distributions. Such deep recirculation gyres appear to be a common feature of deepwater circulation; several have been identified farther north by *Pickart and Hogg* [1989] and *McCartney* [1992], and farther south by *Zemba* [1991].

Between the Guiana Basin and the Brazil Basin there is a net loss of nearly 7 Sv of southward LDW transport, accompanied by an even larger gain in MDW transport. Although the hemispheric difference in the western basin net meridional flows could be achieved by concentrated upwelling in the near-equatorial latitude band, a zonal exchange of lower and middle DW between the western and eastern basins could also achieve this shift. Observations suggest that the latter mechanism dominates. Most of the net southward flow of LDW through the Guiana Basin flows eastward in the northern Brazil Basin and is inferred to pass into the eastern basin through the Romanche Fracture Zone. In contrast, westward flow of MDW through the northern Brazil Basin is also observed; this flow bifurcates, with one branch supplying the northward flow in the Guiana Basin, offshore of and in opposition to the DWBC, and the other branch feeding the downstream growth in DWBC transport from the Guiana Basin to the Brazil Basin. Additional MDW DWBC transport in the northern Brazil Basin is obtained via a relatively tight recirculation cell. Thus the cartoons of Figure 6 suggest that of *McCartney*'s [1993, Figures 2a and 2b] two extreme models of deep circulation at and south of the equator, the first is more appropriate, i.e., "an interpretation as two disconnected gyres, with a small transport DWBC bridging them" [McCartney, 1993, p. 1,955]. However, McCartney's schematics did not distinguish between the MDW and LDW contributions. We now see that the "disconnected gyres" actually reflect the fact that the dominant contributions to the recirculating deep waters are in different layers in the two hemispheres; primarily LDW recirculates in the north, whereas MDW recirculates in the south. Thus it is important to view the system as a layered one, in order to understand the crossing of the equator by the DWBC more completely.

Since our near-equatorial geostrophic transports are subject to large errors, and furthermore, since the eastern basins are dominated by extremely weak deep shears, it is difficult to determine the fate of the equatorial LDW jet or the source of the equatorial westward MDW transport. However, after examining transports across the eastern basins of 11°N, as well as 11°S, we infer that upwelling of deep and bottom water in the tropical eastern Atlantic is an important mechanism. The picture that emerges from this study has several implications.

1. The dominance of the LDW transport mode over large areas of the North Atlantic and the dominance of the MDW transport mode over large areas of the South Atlantic mean that there is little signature of upwelling and warming following the flow in these large areas. Instead, the circulation fields and transport estimates imply a concentration of upwelling in the eastern tropical Atlantic. Thus the upwelling is inferred to be spatially highly nonuniform, and the strong amplitude recirculations are observed in places where the signatures of warming and cross-isotherm flow are nearly imperceptible.

2. The deepwater flow field often is represented as dominated by the north to south flow of the DWBC, particularly in the conveyor belt conceptualization. We find three distinct components to the deep water flow.

In the North Atlantic the DWBC carries LDW to the equator, which, together with the UDW (which we have not addressed here), dominates the export of deep water from the North Atlantic. In the northern Brazil Basin, LDW flows eastward toward the Romanche Fracture Zone and presumably continues on into the eastern basin. From a rough mass balance we infer that within the eastern basin the LDW upwells to become MDW, which then returns to the western boundary region. Most of this MDW retroflects and joins the DWBC flow of UDW crossing the equator from the Guiana Basin, and together, these constitute the DWBC waters of the South Atlantic. A consequence of this circulation pattern is that the North Atlantic deepwater characteristics will appear only in weak form in the South Atlantic DWBC. In other words, the zonal flows within the tropics interrupt the flow of information carried by the DWBC from the northern to the southern hemisphere.

3. In each hemisphere the net western basin flow consists of the difference between the opposing branches of deep recirculation gyres. Hence a water mass characteristic fed into the northern end of the DWBC is diluted by the confluence of water into the current from the northern side of the gyre. The deep gyre in the Guiana Basin acts as one such dilution agent, although for the MDW it is not clear that the two branches of opposing flow are connected to form a gyre, since the property contrast between them is strong enough to suggest negligible interaction between them. In the Brazil Basin the deep recirculation gyre in the LDW is weak, but in the MDW the gyre acts as a strong dilution agent. Farther south (27°S), the recirculation gyre associated with the deepening of the Brazil Current also dilutes DWBC waters [*Zemba*, 1991].

These elements yield a rather different expectation for the propagation of information through the cold water layer of the Atlantic than that implicit in the monotonic flow of the cold water limb of the conveyor belt conceptualization.

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