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Direct measurement of the deep circulation within the Brazil Basin

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Abstract

In support of the Deep Basin Experiment, part of the World Ocean Circulation Experiment, a large number of neutrally buoyant floats were released within the Brazil Basin during the 1990s in an attempt to measure directly the circulation in the deep ocean interior. Three levels corresponding to the three major subthermocline water masses were selected, and results from the deeper two (North Atlantic Deep Water, NADW, and Antarctic Bottom Water, AABW) are described. At this writing processing of acquired tracking data is incomplete. Hence, this paper reports on the progress of the observational program and gives our initial conclusions.

It appears that the flow in the deep Brazil Basin is unlike previous conjectures in which the circulation patterns can be characterized as being primarily meridional, both along the western boundary and in the interior. The existence of a deep western boundary current (DWBC) is quite clear in the float data at the NADW level, but less prominent in the AABW, and the interior flow is dominantly zonal with unexpectedly small meridional space scales. Integral time scales are long, of order 20–30 days, and eddy kinetic energy levels are low, of order 1 cm^2/s^2. In spite of the low energy levels a surprising number of our floats became caught up in vortices.

A line of seamounts extending offshore near 20°S, known as the Vitória–Trindade Seamounts, interrupts the DWBCs and is the location for eddy formation and apparent flow away from the boundary into the interior. Although it has been speculated that this could feed a narrow zonal current of NADW (the "Namib Col Current") our float trajectories suggest a return to the western boundary, rather than a continuation to the east. © 1999 Elsevier Science Ltd. All rights reserved.

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1. Introduction

Some 40 years ago Stommel (1957) proposed a revolutionary concept for the circulation of the abyss. His vision contained isolated and confined sources in the north and south polar regions of the Atlantic that fed their dense waters to Deep Western Boundary Currents (DWBCs). These transported the source waters equatorward and slowly bled water into the interior where it upwelled across the thermocline and returned poleward both to complete the overturning circulation and to satisfy angular momentum constraints. Although the DWBC part of this framework has been verified, beginning with the work of Swallow and Worthington (1957) off Cape Fear, early attempts to confirm the slow poleward interior circulation were defeated by the unexpected discovery of the mid-ocean mesoscale eddy phenomenon (Crease, 1962; Swallow, 1971). Our understanding of the mean circulation of the abyss has come mainly from indirect deductions based on property distributions (e.g., Reid, 1989), dynamic computations done on synoptic surveys, and the occasional moored array placed across a DWBC (Warren, 1981).

Several decades of research on the oceanic low-frequency eddy field, along with substantial technological advances, has brought us to the point, once again, of being able to consider the direct measurement of the "mean" circulation of the subthermocline region. With this in mind a World Ocean Circulation Experiment (WOCE) Core Project 3 program, known as the Deep Basin Experiment (DBE), was launched in 1990 to study the circulation, both horizontal and vertical, of the Brazil Basin (Fig. 1). This region was chosen for several reasons. Firstly, it was an area where WOCE Core Project 1 (the "Global Survey" component of WOCE) work was to be done by French, German and British researchers. Secondly, maps of eddy kinetic energy (EKE), as revealed by satellite altimeters (e.g., Cheney et al., 1983), showed this to be an area of especially low activity with variance levels of about $100\,cm^2/s^2$ at the surface away from the western boundary; if we were to measure the lower frequency, mean circulation, a weak mesoscale eddy field would improve the signal-to-noise ratio. A third attraction of the Brazil Basin was its relatively simple geometry. Stretching from the Rio Grande Rise at the south to the equator in the north and from the South American coast to the Mid-Atlantic Ridge, the bottom is relatively uncomplicated. Finally, there are three major water masses in the subthermocline region, Antarctic Intermediate Water (AAIW) near 800–900 m depth, North Atlantic Deep Water (NADW) centered at about 2500 m, and Antarctic Bottom Water (AABW) below about 3500 m. The last of these can only enter or exit the region through four passages: the Vema and Hunter channels in the Rio Grande Rise (Hogg et al., 1998), the Romanche-Chain Fracture Zones through the Mid-Atlantic Ridge at the equator (Mercier and Speer, 1998), and a zonal passage, also at the equator, that links the basin to the western North Atlantic (Hall et al., 1997).

An overview of the DBE was given by Hogg et al. (1996) in which the various elements and objectives of the program were described. Herein we concentrate on attempts to achieve the first objective, namely "to observe and quantify the deep circulation within an abyssal basin". The strategy developed is the modern equivalent of Swallow's attempt in the late 1950s: to seed the region with enough neutrally

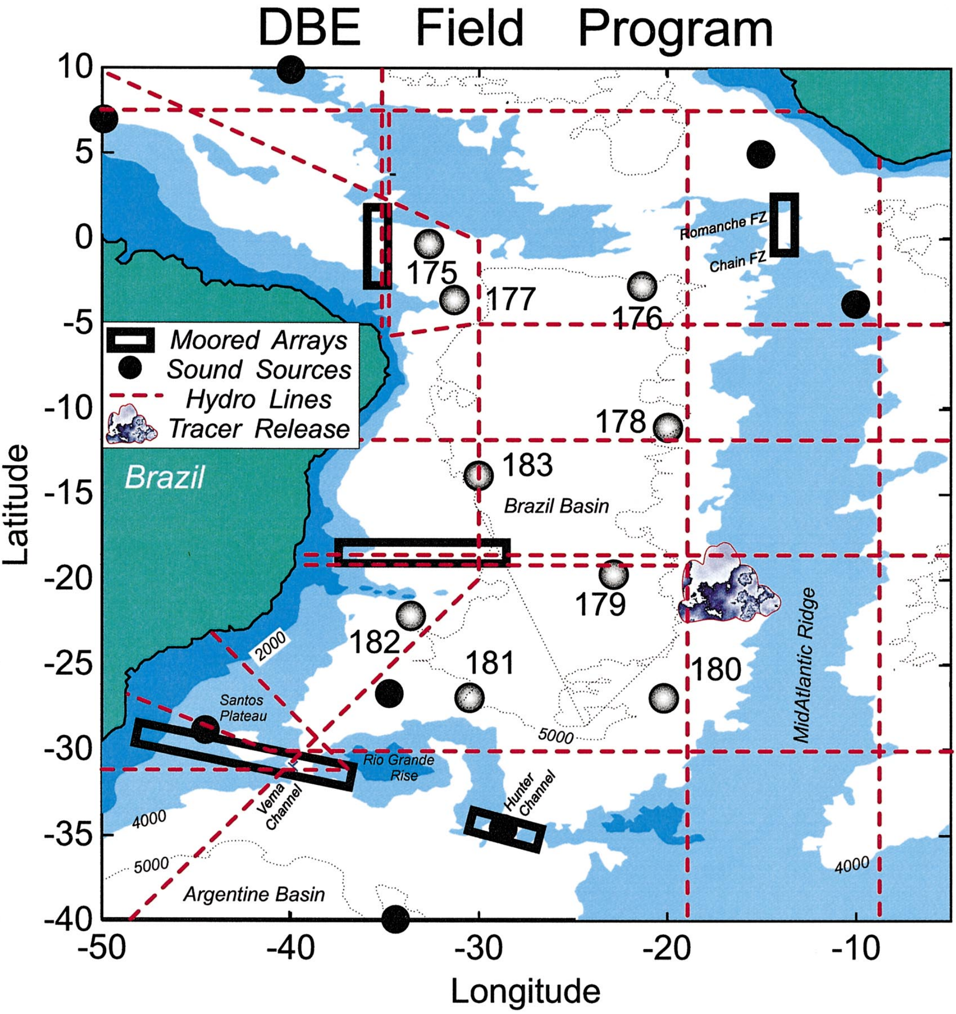


Fig. 1. The Deep Basin Experiment field program. Of particular relevance to this study are the sound source moorings (numbered lightly shaded circles are US sources, solid circles either French or German).

buoyant floats for a sufficient length of time that the general circulation would be revealed through averaging out the eddy motions. Moored current meters also were deployed to provide subsidiary observations and help quantify statistical measures of eddy activity.

2. Experimental design

The number of floats required to measure the deep circulation was estimated as follows (Table 1). The Brazil Basin has dimensions of roughly 3000 km in the

Table 1
Float program design parameters as proposed at three different times. For rows 1 and 2 we have used the information in columns 2–6 to determine the number of floats needed. For the last row we have used the information in columns 2–5 and 7 to determine the expected standard error for the mean velocity. We have assumed 800-day float missions

Activity	Spatial resolution (km)	Number of boxes	Eddy kinetic energy (cm^2/s^2)	Integral time scale (days)	Standard error of the mean (cm/s)	Number of floats needed
WOCE plan	300	70	10	10	0.2	4375
NSF proposal	500	24	1	10	0.05	240
Experience	500	24	1.5	20	0.16	70 Equivalent

North–South direction by 2000 km East–West. Given the usual tradeoffs between resolution and resource requirements, we aimed to resolve the circulation on 500 km scales, which implies 24 independent estimates. Estimates of the strength of the mean flow, based on Stommel's (1957) arguments, suggested that the signal could be as weak as 1 mm/s although Reid's (1989) schemes point to a stronger circulation with speeds as high as 1 cm/s. Using an EKE of 1 cm^2/s^2, as has been found typical of the interior regions of the North Atlantic (Schmitz, 1984; Owens, 1991), implies the need for more than 400 degrees of freedom in each box to reduce the standard error of the mean to 0.05 cm/s. Experience from the Northwest Atlantic suggested that the eddy integral time scale would be of order 10 days (McWilliams et al., 1983), thus yielding a total requirement of 192 000 float days for each level. With expected endurance of modern float technologies being of order several years we settled for deployments of 800 days: the total requirement, for each observation level, is then about 240 floats just to achieve a noise level about equal to the expected signal, and this was our request to the National Science Foundation. The initial WOCE plan (first row, Table 1) was considerably more ambitious, calling for better resolution and expecting much higher eddy kinetic energy levels. Experience, as we shall see, has diminished our expectations (bottom row, Table 1).

Floats were deployed at three levels corresponding to the three principal water masses, with German and French researchers setting instruments in the AAIW (see e.g., Boebel et al., 1997) and the US taking responsibility for the NADW and AABW levels. German and US programs used different variants of the RAFOS technology (Rossby et al., 1986) while the French program used a newer design known as a "MARVOR" (Ollitrault et al., 1994).

We used a commercialized version of the RAFOS float, developed jointly by the University of Rhode Island and Woods Hole Oceanographic Institution (WHOI), and now available from Seascan, Inc. of Falmouth, Massachusetts. These instruments listen for sound emitted by the array of sources that was set within the Brazil Basin

(Fig. 1) at depths ranging from 1000 to 2000 m. For DBE purposes 13 sources (9 US, 4 German) were deployed on an irregular grid of average spacing about 1000 km, so chosen that we expected to be able to track any float at any level within the Brazil Basin with at least two sources. This strategy has worked, in fact a little too well. The RAFOS float system is designed to record the strongest two signals within each of three 25 min listening windows. Often more than two sources were heard in each window, causing the float to not always record the arrival time of the best source for tracking purposes. This has complicated the tracking logic and slowed progress. The sources produce an 80 s signal every day. Our deep floats listen for this signal every other day while the shallow European ones record the daily signals.

Our first float was launched in October 1992, and the last one in early 1996 (Table 2). The early floats were programmed to surface after abbreviated missions lasting from 60 to 400 days as we gained confidence in the commercial version. These early floats performed quite well with all but one of the 24 short-mission floats coming to the surface and these returning about 90% of their expected messages through Argos. And, to our delight, the floats at the 4000 m level were able to hear the sources adequately, although this was by no means assured from computer-based sound propagation studies that we had done. This success encouraged us to continue with the full 800 day deployments, and floats were released from vessels of opportunity, in pairs at 2500 and 4000 m depths wherever this was possible, in four groups or settings. The schedule of these releases was determined by availability of funds, personnel and cruises of opportunity. Funding constraints ultimately limited the total number of floats to 168 with 99 at the NADW and 69 at the AABW levels, considerably short of the goal of 240 (Table 1). Factoring in the shorter duration of the early floats and those that did not surface, we estimate that there is an average of about 70 equivalent 800-day floats at each level (slightly more for the NADW and slightly less for the AABW).

Table 2
Performance data for the DBE RAFOS float program at the NADW and AABW levels, tabulated in the last four columns as NADW/AABW values. The last column gives the percentage of messages received through Argos of those possible and is a rough measure of the floats' average survival lifetime after surfacing. It is also a measure of the gappiness of the resulting float trajectories. n.d. ≡ not defined

Setting	Date	Intended duration (days)	Number set	Number to surface	Percent surfacing	Percent messages received
1	10/92	60	4/3	3/3	75/100	88/100
		200	7/3	7/3	100/100	99/59
		400	7/0	7/0	100/n.d.	92/n.d.
		800	18/0	13/0	72/n.d.	74/n.d.
2	9/93–5/94	800	26/26	25/25	96/96	66/60
3	2/95	800	24/24	23/21	96/88	71/64
4	1/96	800	13/13	13/12	100/92	23/51
Total			99/69	91/64	91/93	64/60

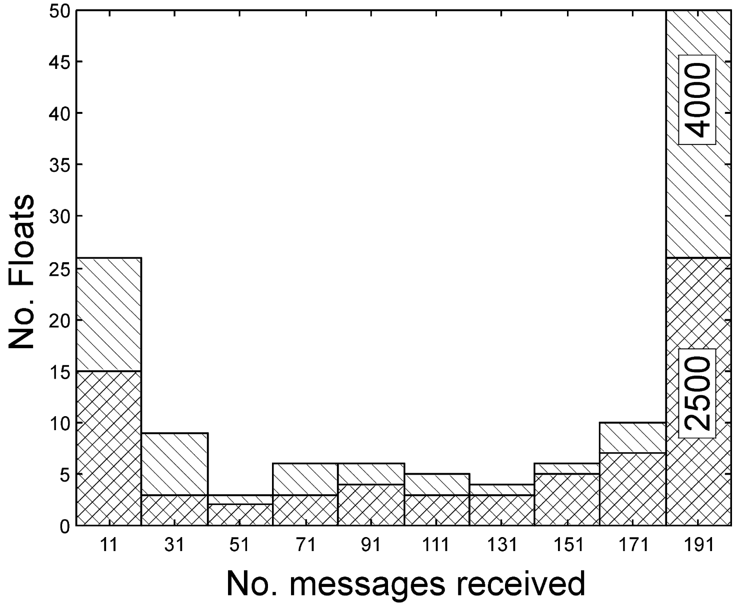


Fig. 2. Histogram of the number of messages received from those floats that were expected to send more than 180 messages. A float records sound delays from the sources every other day and sends these in groups of two. This yields a maximum of 201 messages for an 800 day float. Hatching is used to distinguish the two depth levels that were seeded with floats, as indicated.

The excellent performance realized by the abbreviated missions of setting 1 have not been maintained by the later 800 day floats. The principal cause of failure, although exhibiting consistent symptoms, remains a mystery: floats come to the surface on schedule and begin to transmit their information but then fail after just a few days on the surface. A variant of the DBE float design used in the Brazil Basin Tracer Release Experiment (Polzin et al., 1997) has had similar difficulties, but floats running identical missions have functioned properly in the lab. Identical floats used in the North Atlantic also have functioned normally. About a third of the floats have transmitted their full quota of 201 messages (each message contains information from two separate sound source cycles, or 4 days with our 2-day listening schedule) and one-sixth fail shortly after surfacing (Fig. 2). Otherwise the distribution is rather even and independent of target depth. About 30 days on the surface are needed to transmit a full 800 day record.

An additional element of this float program was the inclusion of a current meter at 2500 m (the NADW level) on each of the nine US sound source moorings (lightly shaded circles in Fig. 1). These were recovered after about $2\frac{1}{2}$ yr, when the sound sources were refurbished, and returned over 95% of expected data. Just one record was short because of excessive battery drain. The current meters were used to obtain direct measures of the crucial eddy statistics such as variance and time scale.

3. Eulerian measurements

The NADW layer is the one with the most complete information, as more than half the floats were ballasted for this depth and the sound source moorings had current meters only at this level. Before discussing the float trajectories it is worth summarizing the basic statistical information obtained from the moored instruments. We will supplement this with additional data collected from an array located across most of the southern boundary of the basin (see Hogg et al., 1998, for more detail).

The eddy kinetic energy per unit mass is of order 1 cm^2/s^2 over much of the basin that is away from the equator and the western boundary (Fig. 3a). Although these values are in line with our expectations and a factor of 100 lower than the surface values (Cheney et al., 1983; Stammer, 1997), the integral time scale (Fig. 3b) which we have inferred from these records is about double the 10 days on which we based our float program design (and increasing toward the equator). The net result is that our a priori error estimates of experimental error in the mean flow should be increased by a factor of $\sqrt{2}$ or, equivalently, that we would need to double the number of floats to achieve the same accuracy (order 1 mm/s).

Although the current meters provide rather sparse coverage of the Brazil Basin they do reveal a characteristic of the mean flow that will be reinforced by the float trajectories: namely that it is dominated by zonal motions (Fig. 3c and d). This zonality is especially striking in the three moorings closest to the equator but is also characteristic of those in the basin interior north of the southern boundary region. A puzzling aspect of the mean flow vectors (Fig. 3c) is that all four instruments in the western half of the basin (again, away from the equator and southern boundary) have statistically significant mean flows toward the boundary while those in the eastern half are more variable. The float trajectories described in the next section will help clarify this pattern. The progressive vector diagrams (Fig. 3d) give a better visual indication of the steadiness of the low-frequency flow: instruments close to the equator are most dominated by a steady zonal streaming while the one near 22°S, 34°W (#182) has the strongest eddy component.

These features of the flow also can be seen in the vector time series or "stick" plots (Fig. 4): the four instruments in the western half of the basin (Fig. 4a and b) show a better defined mean toward the west and longer time scales for the zonal component. The increase in variance at mooring 182 is dramatic: it is just downstream, in the NADW sense, from the line of seamounts that extend eastward from Cabo Frio near 20°S (the Vitória-Trindade Seamounts). Of all the instruments within the NADW layer this is the one with the largest variance.

One other feature is noteworthy: early in the record from mooring 179 there is a strong event in which the east component (Fig. 4d) rapidly switches from an abnormally strong eastward current to an equally strong one to the west while the north component (Fig. 4c) turns from north to south. If this were to result from the passage of a small, intense eddy it would imply either a cyclone (i.e., clockwise) traveling to the northwest or an anticyclone going to the southeast. Neither sign of meridional movement is consistent with dynamical arguments for monopoles on a β-plane (McWilliams and Flierl, 1979). There is no obvious temperature signal

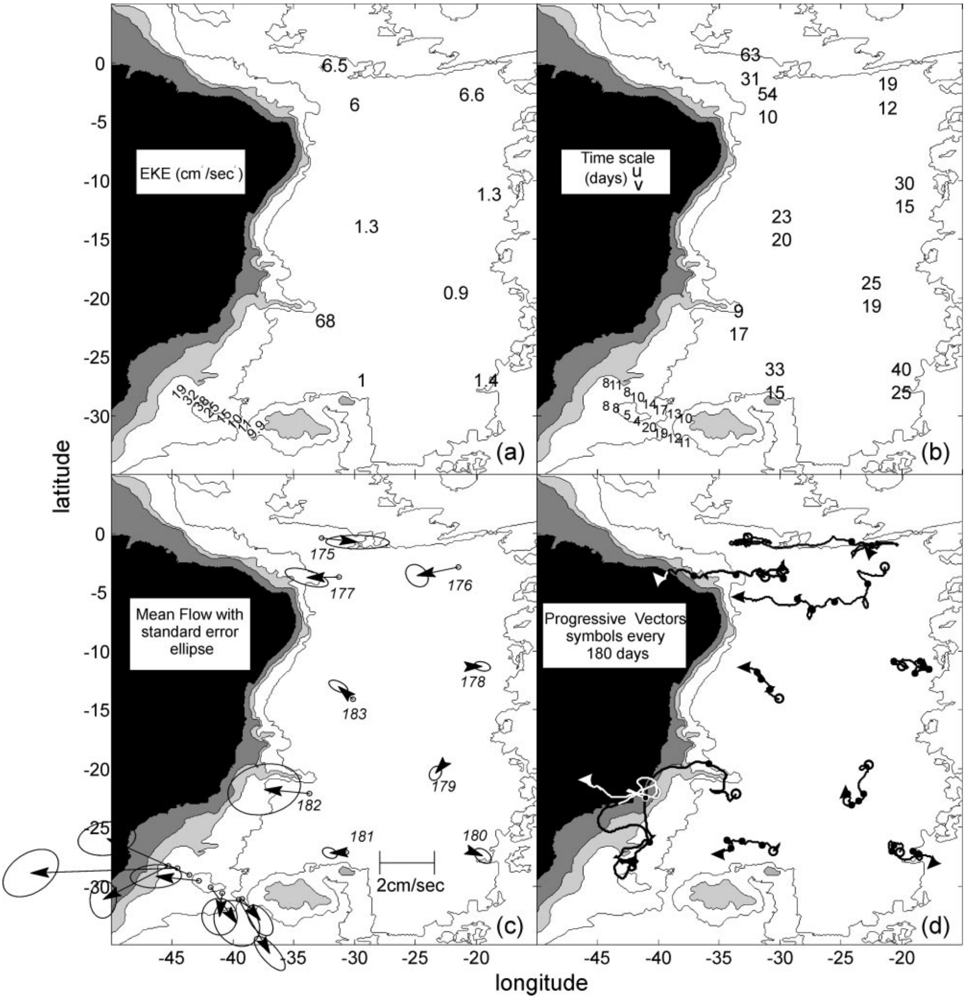
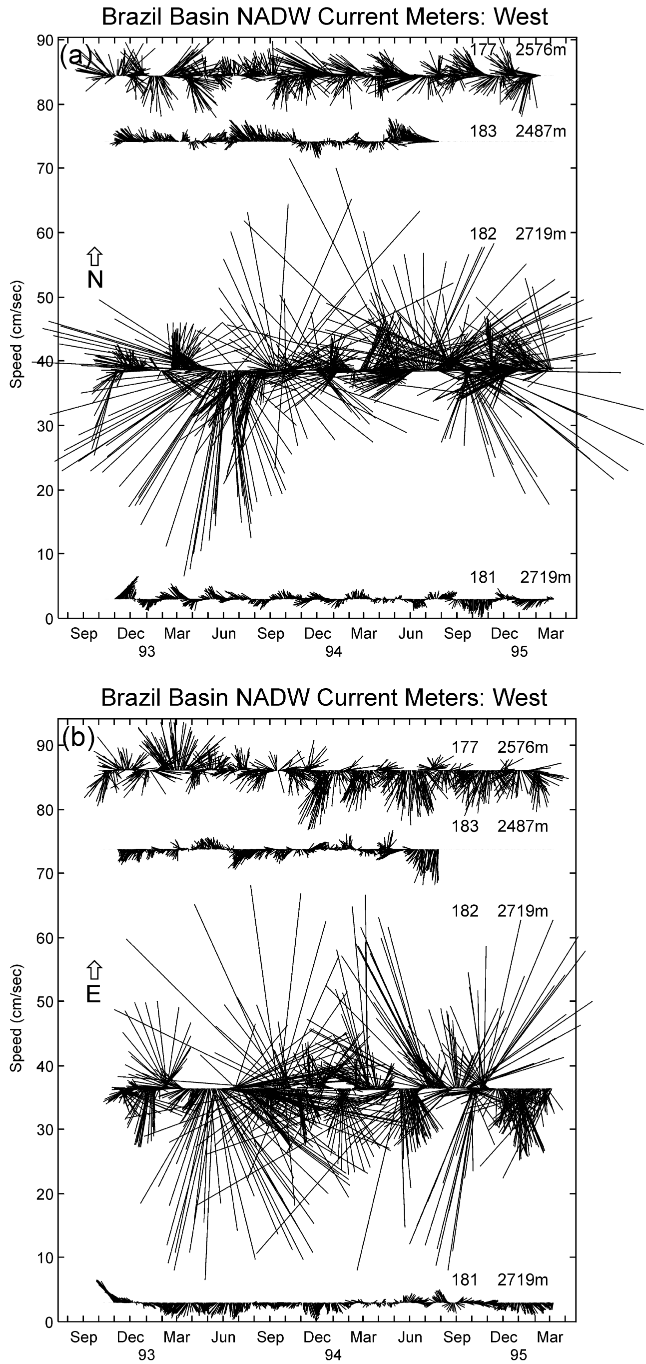


Fig. 3. Various statistics and computations from the nine current meters that were placed on the US deployed sound sources (lightly shaded circles in Fig. 1) supplemented by those installed along the southern boundary of the Brazil Basin. All instruments were between 2300 and 2500 m depth. (a) Eddy kinetic energy per unit mass. (b) Eddy time scale defined as the integral of the time-lagged autocorrelation function from zero lag to the first crossing through zero. (c) Mean horizontal flow with standard error ellipse. (d) Progressive vectors with position indicated by solid dots every 120 days.

Fig. 4. Stick plots for eight of the nine current meters (excludes the equatorial one on the western line) grouped into western and eastern lines and displayed from south (bottom) to north (top). Numbers to the right of each time series give mooring number, as indicated on Fig. 1, and nominal depth. (a) The western instruments, north being up. (b) The western instruments, east being up. (c) The eastern instruments, north being up. (d) The eastern instruments, east being up.



Brazil Basin NADW Current Meters: West
(a)
177 2576m
183 2487m
182 2719m
181 2719m
N
Speed (cm/sec)
Sep Dec Mar Jun Sep Dec Mar Jun Sep Dec Mar
93 94 95
Brazil Basin NADW Current Meters: West
(b)
177 2576m
183 2487m
182 2719m
181 2719m
E
Speed (cm/sec)
Sep Dec Mar Jun Sep Dec Mar Jun Sep Dec Mar
93 94 95

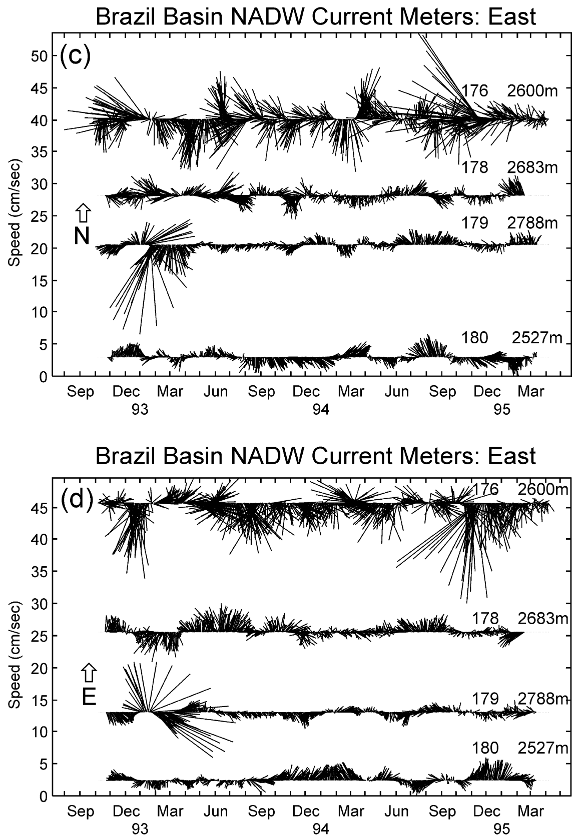


Fig. 4. Continued.

associated with the feature (not shown). Although this is the only vortex-like event clearly obvious in the current meter records, we will report below on one revealed by the float trajectories.

The different time scales for zonal and meridional motions are best illustrated by variance preserving spectra (Fig. 5). With two exceptions the meridional component peaks at periods of 50–100 days, as has been found typical of the mid-ocean eddy field (e.g., Richman et al., 1977). On the other hand, the zonal spectra are almost all red, suggesting that the record means of Fig. 3c are not yet resolved in spite of the formal error bounds so indicating. The most prominent exception is also the most energetic one (# 182).

4. Lagrangian measurements

We have only about one-half of the returning floats tracked at this time. However, we do have all the launching and surfacing positions and, when connected by arrows,

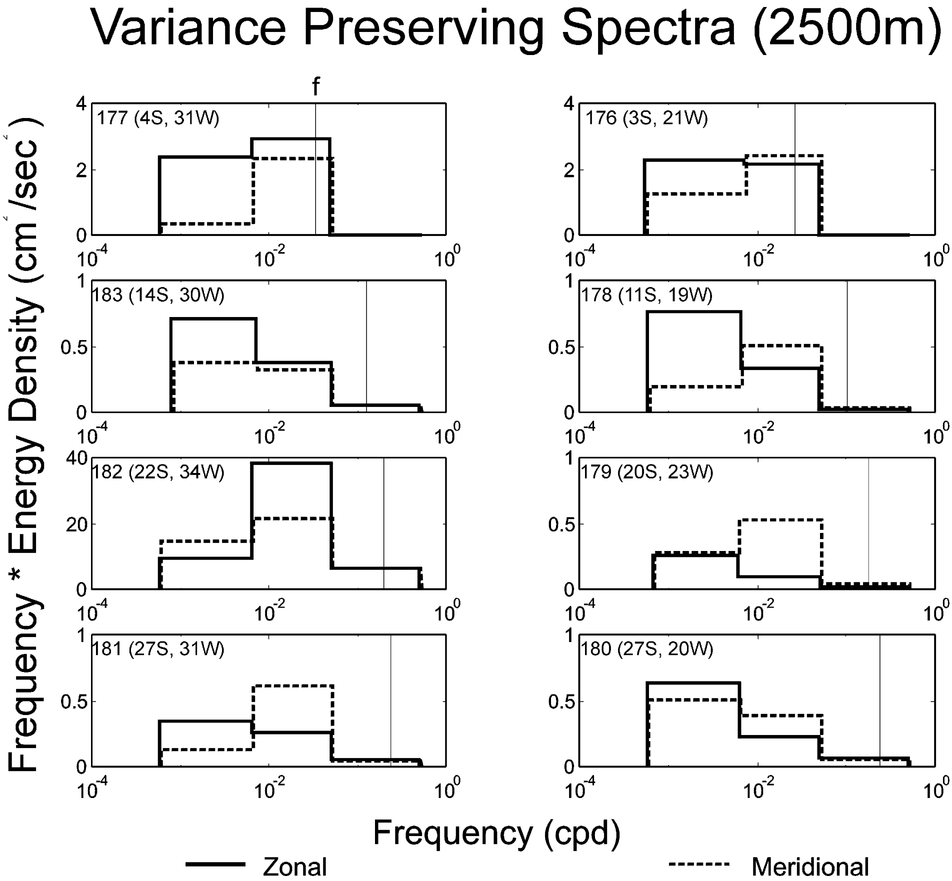


Fig. 5. Variance preserving spectra of horizontal velocity components at the NADW level for the eight time series displayed in Fig. 4. The thin vertical line is at the inertial frequency above which energy has been removed by low-pass filtering. The ordinate scale is variable. Mooring number and latitude, longitude pairs are given.

these give the net displacements shown in Fig. 6a and c (800 day floats, only). Available trajectories are shown in Fig. 6b and d. Several features are clearly evident. First, the DWBC of the NADW is evident by the long displacements along the Rise at 2500 m depth (Fig. 6a). The three floats that were set near the equator behave similarly to those set in the tropics at 1800 m in 1989 (Richardson and Fratantoni, 1999): the one complete trajectory we have at present shows a long excursion to the east along the equator with a loop back to the west near the end of its life (Fig. 6b). Another (Fig. 6a) appears to take the shorter route along the western boundary, although we cannot be sure as the tracking information is not yet available.

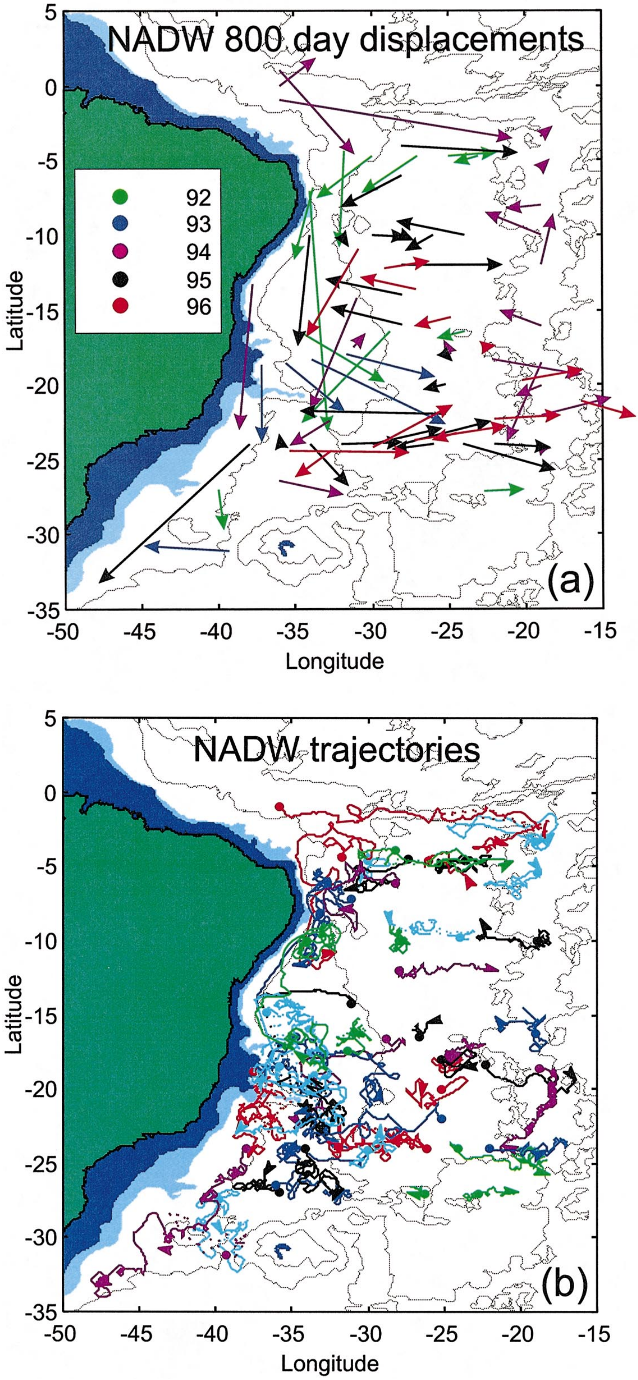
NADW property distributions suggest flow offshore from the DWBC. A tongue of high oxygen centered near 20°S extends eastward from the boundary, and this prompted Wüst (1935) to conclude a down-gradient flow into the interior. Warren and Speer (1991) and Speer et al. (1995) have suggested that this tongue is the western source of a current that they believe extends across the whole South Atlantic near 22°S (named, by Warren and Speer, the Namib Col Current after a depression in the Walvis Ridge over which they first noticed the anomaly). The detailed float trajectories (Fig. 7a) that we have available from this region suggest a different interpretation. The southward flow of the DWBC is interrupted by the Vitória–Trindade Seamount Chain at about 20°S and the southward moving floats (#s 38, 64, 153, 155, 195, 197 and 233) are all deflected to the east but those that last long enough then return to the west. Two, #s 155 and 197, detour completely around the feature, and one float, # 250, makes its way steadily westward just to the south of the seamount chain at the presumed latitude of the Namib Col Current, consistent with the mean flow measured here (Fig. 3c). This points to a primarily advective balance for the tongue as has been recently argued by Zangenberg and Siedler (1998) on potential vorticity and mass conservation grounds rather than Wüst's down gradient, advective–diffusive one. At this point, however, we cannot exclude the western boundary region as a source for the Namib Col current: four floats deployed in the longitude range 30°W to 35°W to the north of the seamounts are displaced well to the east (Fig. 6a). Two of these have not yet been tracked.

The DWBC is not nearly so obvious in the AABW at 4000 m (Fig. 6c). Two floats deployed in the Vema Channel travel a considerable distance to the north along the boundary, as expected. However, a float released near 10°S at similar water depths is displaced well to the south and there is a broad band of southeasterly displacement near 19°S just north of the Vitória-Trindade Seamount Chain (but, note the single float in the middle of this group which is displaced northward). This offshore flow also appears at the NADW level (Fig. 6a).

Within the AABW floats released to the south of the seamount chain have some difficulty in moving northward (Fig. 7b). Of the seven that are presently available from the region only one is able to make it north of 20°S and two have net displacements toward the south. Two of the three set north of the seamount chain head to the east-southeast away from the western boundary. In conjunction with the net displacement data (Fig. 6c) there is surprisingly little support for a northward moving DWBC of AABW north of about 20°S.

Away from the boundary flows are much more difficult to characterize. It is visually clear that zonal motions dominate over meridional, contrary to the mean circulation schemes put forward in recent years (e.g., Reid, 1989; Durrieu De Madron and Weatherly, 1994). In principle, it is possible that the complete trajectory information will reveal a simpler pattern to what appears rather confused from the net displacement data, but it seems more likely that the interior deep circulation has short space

Fig. 6. Float displacements and trajectories. Topography is shaded for depths above the nominal float level. (a) 2500 m or NADW displacements for floats lasting 800 days. (b) Available 2500 m or NADW trajectories for floats lasting at least 1 yr. (c) 4000 m or AABW displacements for floats lasting 800 days. (d) Available 4000 m or AABW trajectories for floats lasting at least 1 yr.


NADW 800 day displacements
92
93
94
95
96
(a)
Latitude
Longitude
5
0
-5
-10
-15
-20
-25
-30
-35
-50
-45
-40
-35
-30
-25
-20
-15
NADW trajectories
(b)
Latitude
Longitude

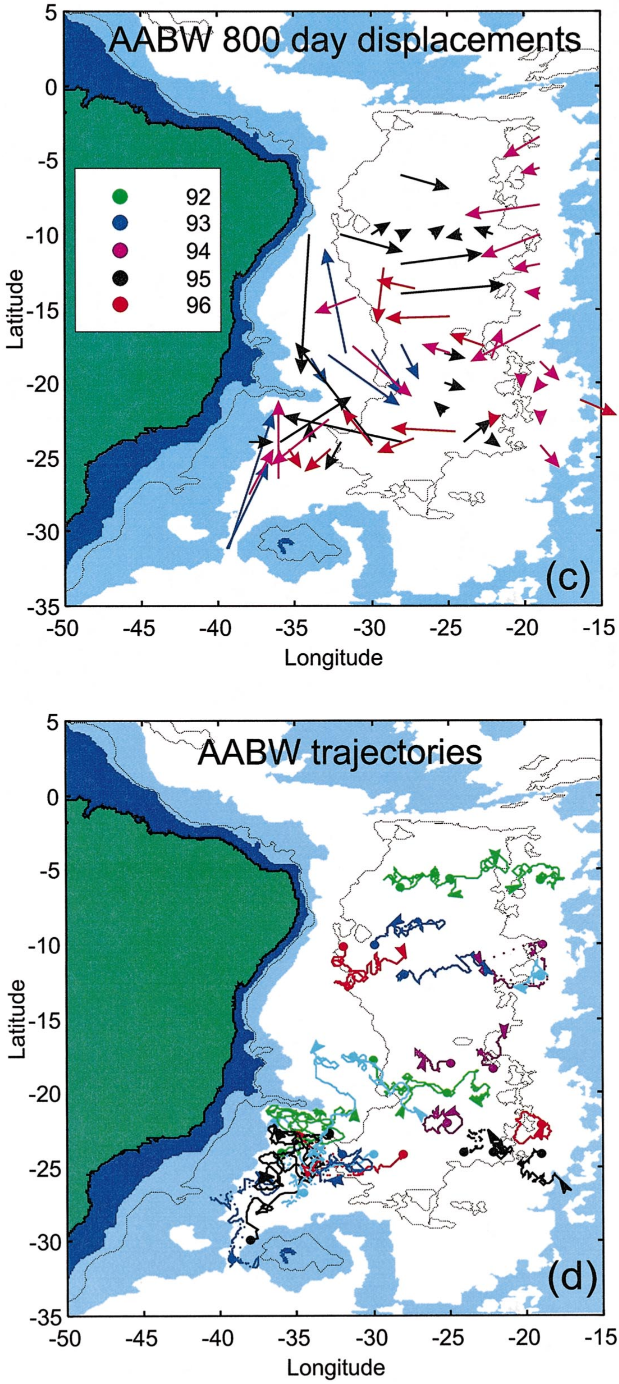


Fig. 6. Continued.

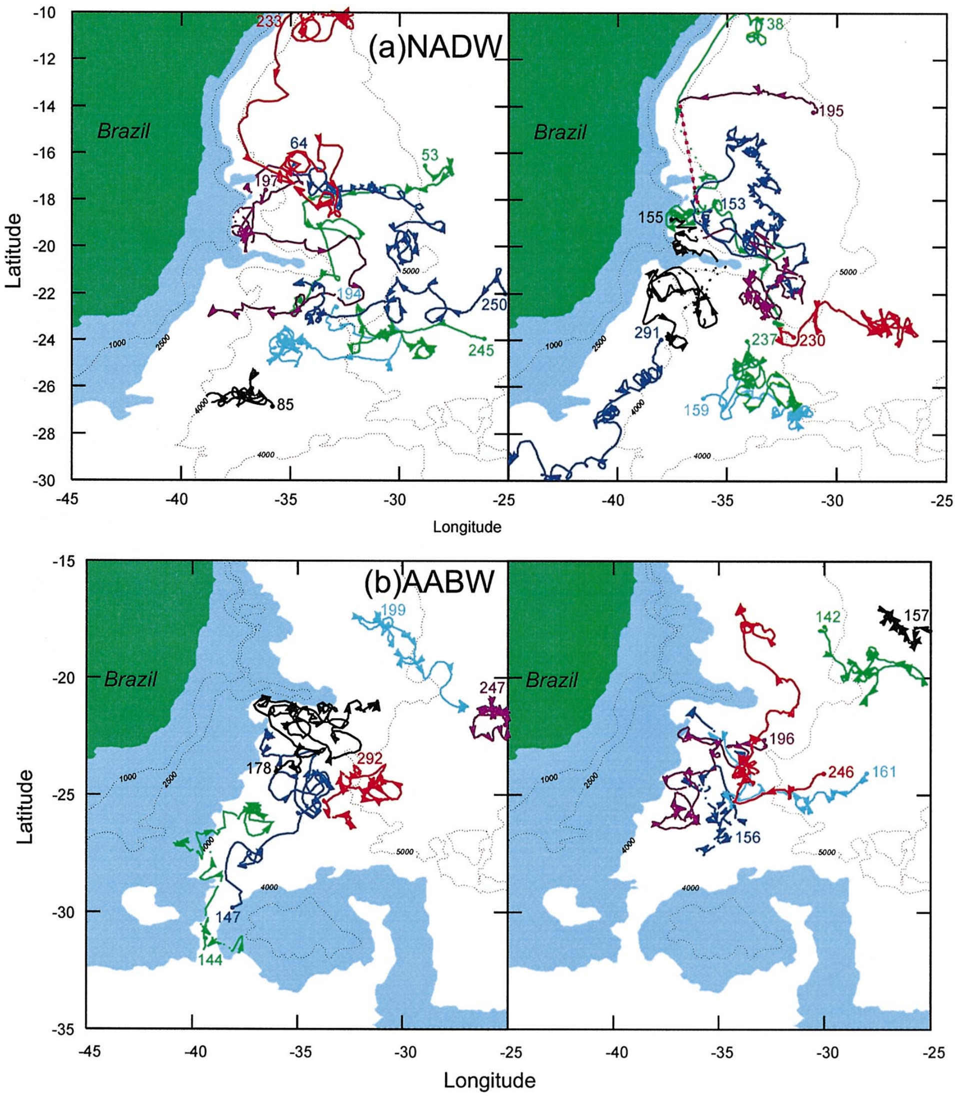


Fig. 7. Float trajectories from the southwest corner of the Brazil Basin in the vicinity of the Vitória-Trinidade Seamounts and the Rio Grande Rise. Arrowheads give positions at 120-day intervals. Topography is shaded above the nominal float level. (a) NADW and (b) AABW.

and long time scales. The variance-preserving spectra from the current meters (Fig. 5) show energy that is concentrated at periods shorter than 100 days in the meridional component but continues to increase with time scale for the zonal component.

The AABW floats present another puzzle. Focusing on the line of floats along the eastern edge of the basin near 19°W (Fig. 6c), we find that all those in the northern half of the basin travel westward, as though coming out of the ridge just a hundred kilometers or so to the east (at the 4000 m depth). Adding to the puzzle is the additional curiosity that two of these appear to be on a collision course with floats deployed at midbasin (e.g., Fig. 8a). It has been suggested to us by a reviewer that the westward drift could be a result of a "diffusion bias": in the absence of any mean flow, eddy stirring could cause such a drift as the floats cannot diffuse into the ridge. We think that this is an unlikely explanation as the floats' motion is dominated by more-or-less steady translation (Figs. 6d and 8a) and a quasi-biennial oscillation. It seems more likely that this is related to the enhanced mixing that has been observed

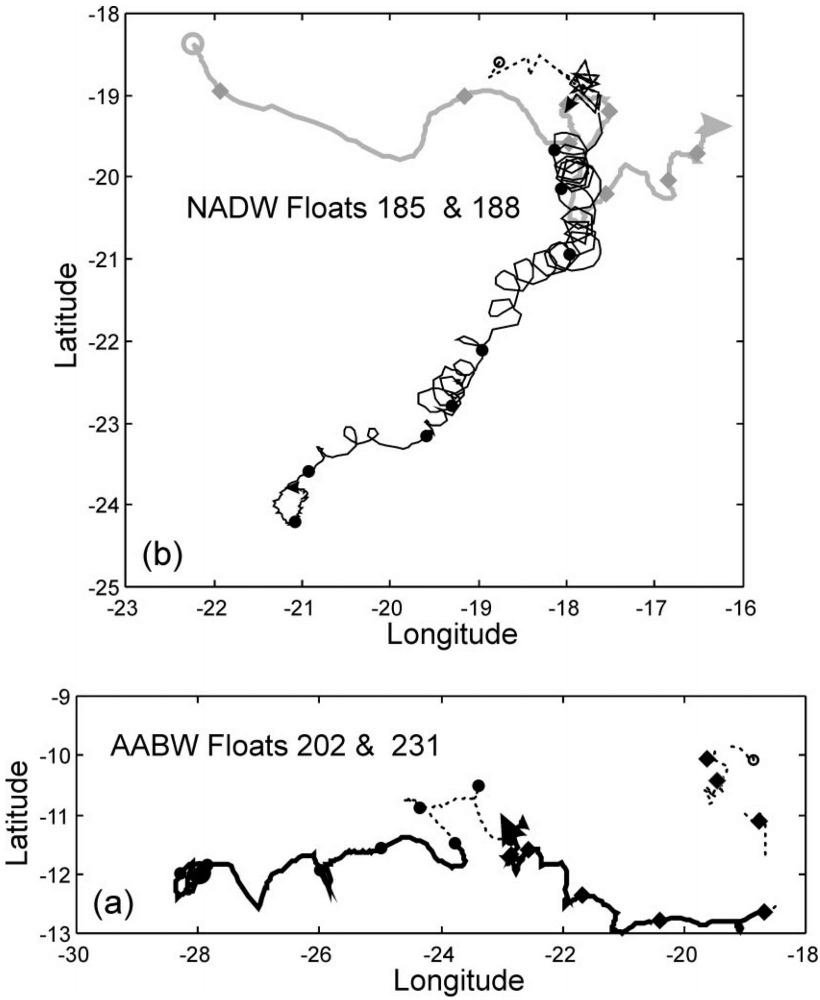


Fig. 8. Examples of floats which appear to be on (a) collision courses or (b) cross one another. Solid portions of the tracks are coincident in time and symbols are plotted every 3 months.

over the Ridge (Polzin et al., 1997) and the hypothesized, diffusively driven secondary circulation that accompanies it (Ledwell et al., 1999).

Some of the mysteries no doubt, will be solved when we have the complete trajectories and take temporal variability into account. For example, there are two floats at 2500 m near 20°S, 20°W that cross one another at right angles. The detailed trajectory data for this pair (Fig. 8b) show that both headed eastward, initially, but soon the more eastern one was caught up in a small vortex that carried it to the southwest, presumably under its own dynamics (a cyclone should propagate to the southwest on the β-plane). Preliminary inspection of the data suggests that such vortices are quite common in the deep Brazil Basin: we already have made note of one from the current meter time series that, coincidentally, was from the instrument closest to this float (but about 2 yr earlier), and symptoms of several can be seen in Fig. 7a (e.g., #s 64, 153 and 291).

5. Summary

We have been surprised by the complexity of the flow in the two deeper water masses of this region. We had based our program on a desire to sample the general circulation of the region on spatial scales of 500 km with an accuracy of about 1 mm/s

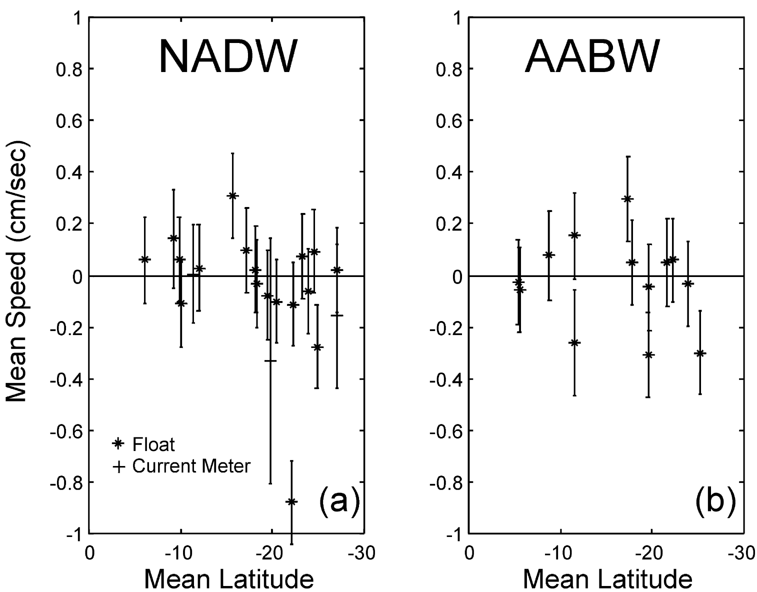


Fig. 9. Mean meridional flow in the interior of the Brazil Basin at (a) NADW and (b) AABW levels. Estimates from current meter measurements are the record means of the meridional components at the four easternmost moorings. Estimates for the floats come from the least square trend of the meridional displacement and are plotted at their midpoints, in latitude. Only floats whose average position was east of 30°W were used.

as estimates from Reid's (1989) scheme suggested flow speeds up to an order of magnitude greater than this. In doing so, we had to guess at the time scales and eddy energy levels (Table 1). Funding realities and the technical problems outlined above have limited the number of effective floats to about 50% of what we requested. The added spatial complexity that is appearing will have a further impact on our goal of quantifying the deep circulation. However, it seems clear that our existing ideas of how the subthermocline regions works will have to be rethought. For example, the expectation that the deep flow might conform to simple Stommel–Arons (1960a, b) dynamics with associated poleward interior flow seems unrealistic (Fig. 9). Instead flows are more zonal than meridional and no consistent poleward component emerges from the combined data sets, at either the NADW or AABW levels. This zonality could well be related to the intensification of cross-isopycnal mixing over the Mid-Atlantic Ridge that has been observed (Polzin et al., 1997; Ledwell et al., 1999) for weak mixing would imply the near conservation of potential vorticity whose isopleths are nearly zonal at these low latitudes (O'Dwyer and Williams, 1997). Of course, the unexpectedly long time scales found in these quiet areas of the ocean imply the need for even more measurements than we have been able to assemble, at this point, and it is possible that the weak meridional flow will yet emerge. It is our hope that combining the velocities from the three float levels with geostrophc vertical shear estimated from hydrographic data collected as part of the DBE will yield reliable estimates of the meridional flow as well as the vertical circulation.

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