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Deep Cross-Equatorial Flow in the Atlantic Measured With SOFAR Floats

PHILIP L. RICHARDSON AND WILLIAM J. SCHMITZ, JR.

Woods Hole Oceanographic Institution, Woods Hole, Massachusetts

Neutrally buoyant SOFAR floats at nominal depths of 800, 1800, and 3300 m were tracked for 21 months in the vicinity of tropical boundary currents in the Atlantic near 6°N and at several sites near 11°N as well as along the equator. Trajectories at 1800 m show a swift (>50 cm/s), narrow (100 km wide), southward flowing deep western boundary current (DWBC) extending from 7°N to the equator. The average transport per unit depth in the DWBC was estimated to be 13.8×10^3 m^2/s. Coupling this value with mean velocities measured in the DWBC by current meters gave a volume transport of 15×10^6 m^3/s between depths of 900 m and 2800 m. Approximately 6×10^6 m^3/s recirculated northward between the DWBC and the Mid-Atlantic Ridge, leaving 9×10^6 m^3/s as cross-equatorial transport. No obvious DWBC nor swift equatorial current was observed by the 3300-m floats; a low mean velocity at this depth lay between F-11 and higher velocity cores above and below. The 1800-m trajectories also suggest that at times (February–March 1989) the North Atlantic Deep Water in the DWBC turned eastward and flowed along the equator and at other times (August–September 1990) the DWBC crossed the equator and continued southward. The velocity near the equator, calculated by grouping floats in a box along the equator, was eastward at 4.1 cm/s from February 1989 to February 1990 and westward at 4.6 cm/s from March 1990 to November 1990. Thus the amount of cross-equatorial flow in the DWBC appeared to be linked to low-frequency variability of the structure of the equatorial current system. Floats in Antarctic Intermediate Water at 800 m revealed a northwestward western boundary current, although flow patterns were complicated. Three floats that significantly contributed to the northwestward flow looped in anticyclonic eddies that translated up the coast at 8 cm/s. Six 800-m floats drifted eastward along the equator between 5°S and 6°N at a mean velocity of 11 cm/s; one reached 5°W in the Gulf of Guinea, suggesting that the equatorial currents at this depth extended at least 35°–40° along the equator. Three of these floats reversed direction near the end of the tracking period.

1. INTRODUCTION

This paper describes SOFAR float trajectories in the equatorial Atlantic at depths of 800 m in Antarctic Intermediate Water and at 1800 m and 3300 m in North Atlantic Deep Water. The fundamental issue investigated is the exchange of water between the North and South Atlantic oceans; *Schmitz and Richardson* [1991] have identified 13×10^6 m^3/s of upper level water flowing northward as compensation for the formation and southward flow of North Atlantic Deep Water (see also *Schmitz and McCartney* [1993]). Water mass properties including chlorofluorocarbon F-11 [*Weiss et al.*, 1989] split near the equator, with an eastward tongue along the equator and another tongue extending southward along the western boundary. It is not known to what extent the tongue of F-11 lying along the equator near 1700 m could be due to advection or to enhanced mixing. Thus a secondary issue investigated is the nature of the connection between the deep western boundary current (DWBC) and the equatorial current system.

The results described here are the first subsurface float trajectories in this region. They reveal new information concerning the thermohaline circulation, including a swift, ~50 cm/s, southward-flowing DWBC at 1800 m that at times feeds into an eastward equatorial current and at other times crosses the equator directly. These data provide a first direct measurement of the cross-equatorial flow of deep water and its complex patterns. Some floats at 800 m and 1800 m drifted long distances along the equator, up to 38° of longitude, and give a first Lagrangian view of these equatorial currents and their connections to the currents along the western boundary.

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2. METHODS

During January and February 1989, 48 SOFAR floats were launched in the tropical Atlantic, 14 at 800 m in the intermediate water, 15 at 1800 m, and 15 at 3300 m in deep water, and 4, by J. Price (personal communication, 1992), as engineering tests of a bobber float, at depths near 300 and 650 dbar (Figure 1, Table 1). Details of the float logistics, data, and processing have been published in a technical report by *Richardson et al.* [1992]. Bobber floats bob every day between two preselected temperatures (or pressures), and then equilibrate and drift halfway between them. The floats were tracked acoustically from February 1989 to October 1990 by means of an array of six moored autonomous listening stations. Float tracking is continuing for an additional 2 years. Thirty-one of the floats were launched along a line spanning the Atlantic between 6°N and 11°N, with closest spacing between floats near the western boundary off French Guiana, where the velocity is swiftest. Seventeen floats were launched along the equator in the west, where meridional flow is thought to cross the equator and eastward flow along the equator originates. The whole width of the Atlantic between French Guiana and West Africa was instrumented with floats, although sparsely in the eastern region. Virtually all of the 800-m and 1800-m floats were tracked for the full 21 months and were heard out to ranges of 3000 km (Table 1). Six of the 3300-m floats were never heard, two owing to a reduced range of around 1000 km there, and four owing to unexplained failures.

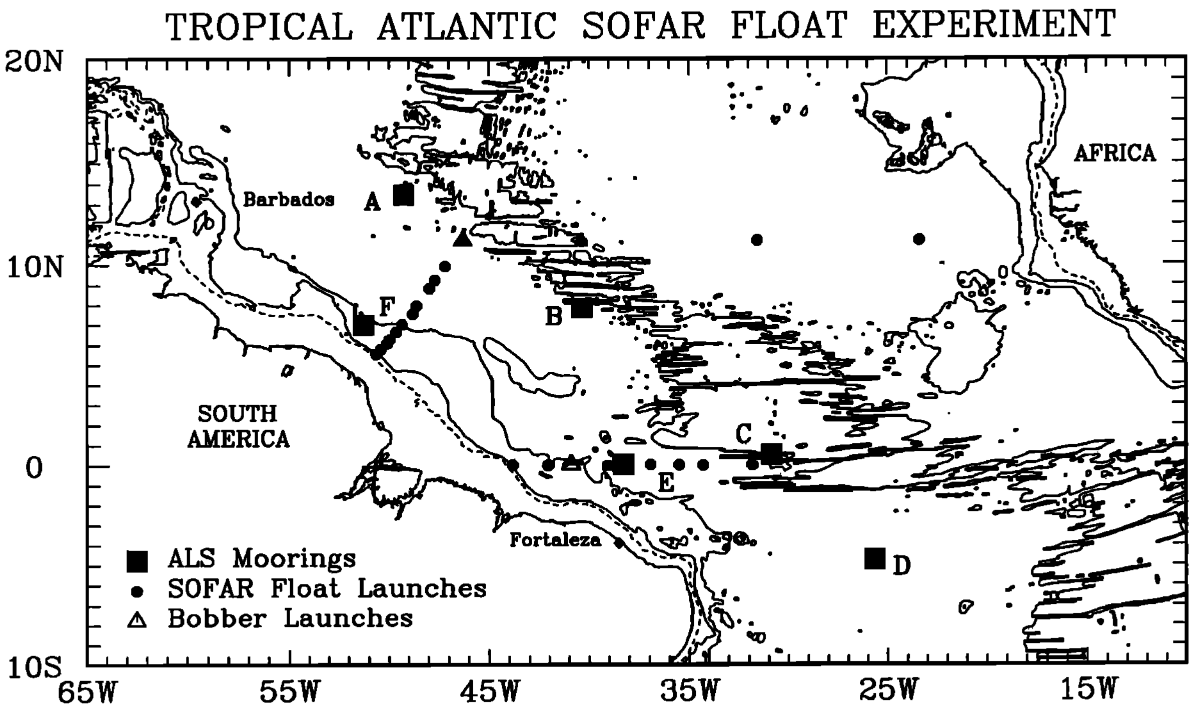

Fig. 1. Launch locations of SOFAR floats and autonomous listening stations (ALS) during January–February 1989. Depth contours are from *Uchupi* [1971]: 200 m is dashed, and 2000 m and 4000 m are solid lines.

2.1. *Temperature and Pressure*

All floats except the four bobbers failed to transmit correct temperature and pressure data after they had equilibrated, and they also failed to activate their buoyancy control which keeps them at constant pressure. In order to estimate equilibrium depths at sea, two floats at each level were followed acoustically from the ship as they sank. The floats at the 800-dbar level equilibrated at 795 dbar and 800 dbar, those at the 1800-dbar level equilibrated at 1825 dbar and 1770 dbar, and those at the 3300-dbar level equilibrated at 3255 dbar and 3250 dbar. In the following, the three equilibrium pressures will be referred to as 800 m, 1800 m, and 3300 m, but it is cautioned that individual floats could have differed from these nominal depths. In past experiments, most SOFAR floats equilibrated within around 50 m of the mean equilibrium depth.

Without active ballasting, SOFAR floats gradually sink as a result of the slow deformation of their pressure housing, which is aluminum for 800-m and 1800-m floats and glass for 3300-m floats. In order to estimate this sink rate, all available historical float data were examined. The mean sink rate and standard error of aluminum floats was 0.37 ± 0.05 dbar/d [*Richardson et al.*, 1992]. No obvious relationship was seen between their sink rate and the pressure level, which suggests that the mean sink rate is appropriate for all depths. The mean rate implies that the 800-m and 1800-m floats would have sunk around 230 m over the 21 months discussed here. The mean sink rate of the glass floats was 0.62 ± 0.11 dbar/d, which implies that the 3300-m floats would have sunk around 220 m over their mean lifetime of 12 months. The gradually decreasing acoustic range observed with the 3300-m floats is inferred to be due to their gradual sinking toward the lower limit of the sound channel.

A few 1800-m floats on the inshore edge of the DWBC drifted into water shallower than their equilibrium depth and probably dragged along the seafloor. One of these (float 10) clearly went aground after 51 days and remained stuck for the rest of the 21 months.

2.2. *Float Tracking and Data Processing*

The floats transmitted an 80-s, 250-Hz acoustic signal once per day. Float clock corrections and positions were calculated from the arrival times of signals received at the moored listening stations. Spurious positions were edited manually, gaps less than 10 days long were linearly interpolated, and the resulting time series were smoothed by means of a Gaussian-shaped filter ($\sigma = 1$ day) to reduce position errors and tidal and inertial fluctuations. In general, the data were of high quality with few gaps. Velocity along trajectories was calculated at each final position by means of a cubic spline function. Accuracy of a fix was estimated to be 10 km based on a comparison of float launch locations and first tracked positions.

Boxcar averages of velocity were used to characterize certain regions. The standard error of this average velocity was estimated using $(2s/\nu)^{1/2}$, where s is the variance of velocity about the mean velocity and ν is the degrees of freedom. Here, ν is roughly equal to N/τ, where N is the number of daily velocity observations and τ is the integral time scale of the lagrangian autocorrelation function, which was assumed to be 10 days. In practice, ν was estimated from the number of 10-day intervals for which each float was within a box [see *Owens*, 1991].

3. THE 1800-M TRAJECTORIES

A summary plot (Figure 2) of 1800-m trajectories shows strikingly different kinds of trajectories in different regions.

TABLE 1. Summary of SOFAR Float Data

Float ID	Pressure,* dbar	Launch			End			Number of Days Tracked	Mean Velocity, cm/s	
		Date	Latitude, °N	Longitude, °W	Date	Latitude, °N	Longitude, °W		$\bar{u}$	$\bar{v}$
				800-m Floats: Equatorial						
16	(800)	890125†	00.01	43.83	901107	−06.10	28.96	650	2.95	−1.16
31	800	890125	00.01	42.01	901102	00.94	36.32	646	1.13	0.17
B63	650	890124	00.05	40.94	901030	09.97	49.93	643	−1.83	1.98
B62	350	890124	00.04	40.86	890827	01.42	42.58	214	−1.11	0.72
28	795	890123	00.00	39.00	900422	12.19	61.19	453	−6.24	3.42
34	(800)	890122	00.00	35.50	890725	−03.67	19.41	182	11.45	−2.45
24	1125‡	890121	00.00	31.81	901030	−01.93	09.92	644	4.31	−0.39
				800-m Floats: IWBC/Line						
25	(800)	890205	05.52	50.62	901102	03.74	45.34	634	1.10	−0.48
21	(800)	890205	05.78	50.40	900928	05.74	48.96	598	0.32	0.00
23	(800)	890206	06.04	50.09	901102	11.55	56.60	634	−1.30	1.13
22	(800)	890206	06.62	49.61	901102	15.37	58.72	633	−1.84	1.79
20	(800)	890207	07.54	48.78	901030	07.54	44.09	630	0.95	0.00
26	(800)	890207	09.23	47.67	901107	03.32	14.46	637	6.74	−1.20
B12	300	890208	11.20	46.29	890714	07.30	44.82	156	1.21	−3.09
B81	625	890208	11.21	46.29	891230	09.94	59.60	325	−5.23	−0.46
19	(800)	890209	11.15	40.36	901024	05.43	25.83	621	3.03	−1.18
18	(800)	890213	11.17	31.57	901111	11.37	34.73	634	−0.62	0.07
17	(800)	890215	11.18	23.40	901107	11.40	18.79	629	0.90	−0.01
				1800-m Floats: Equatorial						
9	(1800)	890125	00.01	43.82	901108	−00.35	31.32	651	2.48	0.07
6	1775	890125	00.01	42.08	901012	−02.77	38.79	624	0.61	−0.57
1	1825	890123	00.00	39.03	901103	00.70	17.73	646	4.18	0.25
3§	(1800)	890122	00.01	35.51	···	···	···	···	···	···
15	(1800)	890121	00.01	31.84	901101	00.14	39.60	648	−1.55	0.03
				1800-m Floats: DWBC/Line						
10¶	(1800)	890205	05.52	50.62	890329	04.41	48.60	51	4.79	−2.92
5	(1800)	890205	05.77	50.39	901102	00.71	40.19	634	2.04	−1.01
14	(1800)	890206	06.04	50.09	901102	05.98	45.70	634	0.91	−0.13
2	(1800)	890206	06.63	49.61	901112	−03.26	36.43	642	2.60	−1.99
8	(1800)	890207	07.54	48.78	901106	−03.95	36.37	637	2.53	−2.34
13	(1800)	890207	09.23	47.67	901030	03.71	45.63	629	0.43	−1.16
11	(1800)	890208	11.20	46.30	901106	09.43	46.31	635	−0.03	−0.35
4	(1800)	890209	11.15	40.36	901103	06.93	47.51	631	−1.44	−0.76
12	(1800)	890213	11.17	31.57	901112	10.65	30.82	636	0.17	−0.09
7	(1800)	890215	11.18	23.40	901112	11.95	25.08	635	−0.38	0.14
				3300-m Floats: Equatorial						
41¶	(3300)	890125	00.02	42.01	···	···	···	···	···	···
30	(3300)	890123	00.00	39.02	900925	−04.59	34.66	605	0.91	−1.00
45	(3300)	890123	00.03	36.95	891017	−01.13	36.71	267	0.11	−0.62
35	3250	890122	00.00	34.29	901028	00.32	32.95	623	0.35	−0.17
38	(3300)	890121	−00.01	31.79	900521	−01.46	34.18	483	−0.64	−0.39
				3300-m Floats:DWBC/Line						
42	3255	890206	06.25	49.96	891021	07.82	50.93	257	−0.57	0.83
39	(3300)	890206	06.63	49.62	891205	05.52	46.19	301	1.44	−0.38
40	(3300)	890206	07.02	49.31	900213	08.81	45.82	371	1.17	0.60
36	(3300)	890207	07.95	48.59	890930	09.24	51.04	235	−1.27	0.64
29¶	(3300)	890207	08.82	47.95	···	···	···	···	···	···
37¶	(3300)	890207	09.92	47.17	···	···	···	···	···	···
43¶	(3300)	890208	11.20	46.29	···	···	···	···	···	···
44	(3300)	890209	11.15	40.37	890522	11.15	41.15	99	−0.90	0.39
33¶	(3300)	890213	11.17	31.57	···	···	···	···	···	···
32¶	(3300)	890215	11.18	23.40	···	···	···	···	···	···

Floats are sorted by pressure, general location, then by longitude.
*Initial float pressure was observed for two floats at each level and the average pressure for the four bobber floats. Target pressures of other floats are shown in parentheses.
†Read 890125 as January 25, 1989.
‡Ballasted deep to lie in the eastward current jet.
§Not tracked because the acoustic signal was overwhelmed by a simultaneous test signal in each listening station.
‖Grounded on continental slope.
¶Never heard by listening stations.

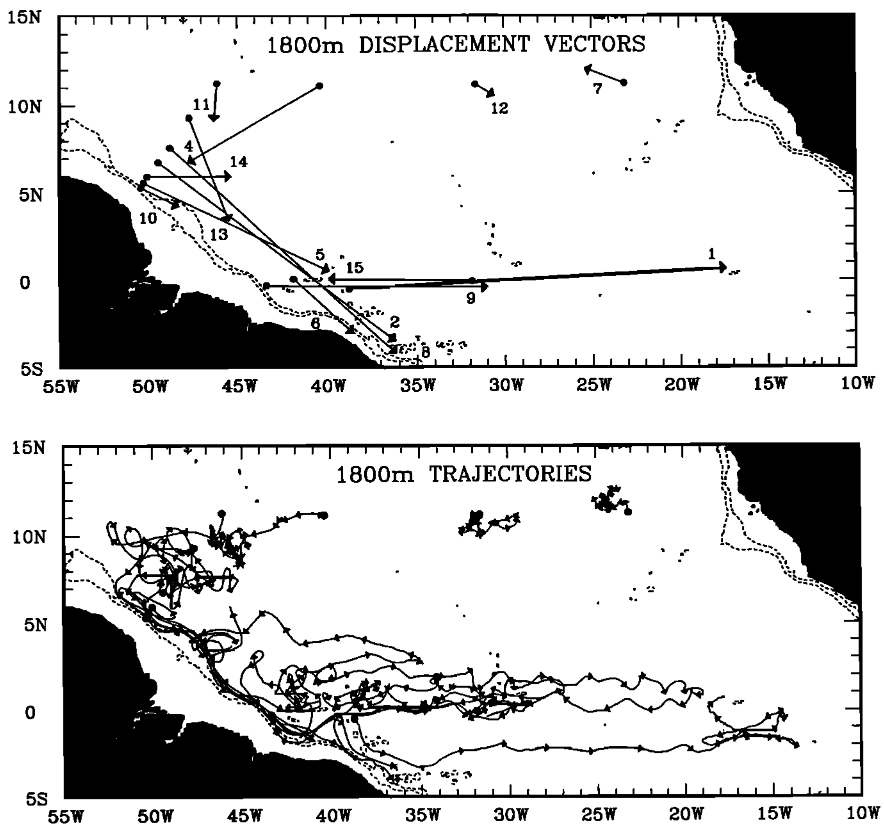

Fig. 2. Summary of 1800-m SOFAR float trajectories and overall displacement vectors from January 1989 to October 1990. Arrowheads are spaced at intervals of 30 days along trajectories. Dashed contours are 200-m and 2000-m depths.

Eight of the fifteen floats drifted southeastward for various lengths of time in a fast (50–60 cm/s), narrow (~100 km), deep western boundary current. Five floats drifted long eastward distances, up to 25° of longitude, within a few degrees of the equator. Compared with these, the two floats in the eastern Atlantic near 11°N barely moved.

3.1. *DWBC Trajectories*

The best evidence for a narrow, swift DWBC comes from the first 2 months, February and March 1989, when three floats (5, 10, and 14) drifted south (Figures 3 and 4). Float 10 grounded on the continental slope after 51 days; the two others reached the equator. Float 14 returned northward and ended up near the DWBC near 6°N in November 1990. Float 5 drifted eastward along the equator to 29°W (July 1989), and then westward, ending near 1°N, 40°W.

The next three floats (2, 8, and 13) drifted westward from offshore launch positions and were entrained into the DWBC near 7°N. Floats 2 and 8 drifted southward in the DWBC during January–April 1990. Float 8 reached the equator in April, recirculated to the north, was reentrained into the DWBC in July, crossed the equator in August, and reached 4°S by October, the farthest south of any 1800-m float. Float 2 crossed the equator in April 1990, recirculated inshore during May–July, and then continued southward to 3°S at the end. Float 13, launched farthest east, entered the DWBC in February 1990, where it made numerous loops and reached as far south as 4°N by November 1990. This float and float 14 looped in a 200-km-diameter cyclonic eddy centered near 4.5°N, 46.5°W, next to the western boundary (July–October 1990).

Three other floats, shown and discussed later, were briefly in the DWBC south of the equator. Float 9, launched in the DWBC near the equator, drifted eastward along the equator. Float 6 drifted near the equator for most of the 21 months, entered the DWBC in October 1990, and drifted south to 2.5°S. Float 1, launched on the equator near 39°W, briefly drifted southeastward in the DWBC, then eastward to 14°W, then north across the equator near 18°W. This path showed that a float crossing the equator in the DWBC may return northward again, although the float ended up near the equator. Out of the six floats in the DWBC, two (2 and 8) crossed the equator within 21 months.

3.2. *DWBC Velocity*

Most 1800-m floats near the western boundary drifted southeastward paralleling the 1800-m depth contour in the DWBC (Figure 5). In order to calculate the cross-stream and along-stream characteristics of this current, float positions were converted to distances seaward of the 1800-m contour and velocity components were rotated normal and parallel to the contour. The mean velocity and transport per unit depth of the DWBC as measured by 1800-m floats in this coordinate system are shown in Figure 6. Only floats west of 43°W were included in this composite in order to screen out floats in swift equatorial currents. Figure 6 is noteworthy because it represents a space (0°–7°N) and time (12 months) average that shows the horizontal structure of this portion of the DWBC. Individual along-boundary velocity values peaked at around 55 cm/s, and 10-km-bin averages reached 26 cm/s. The DWBC was bounded by a weak flanking counterflow or

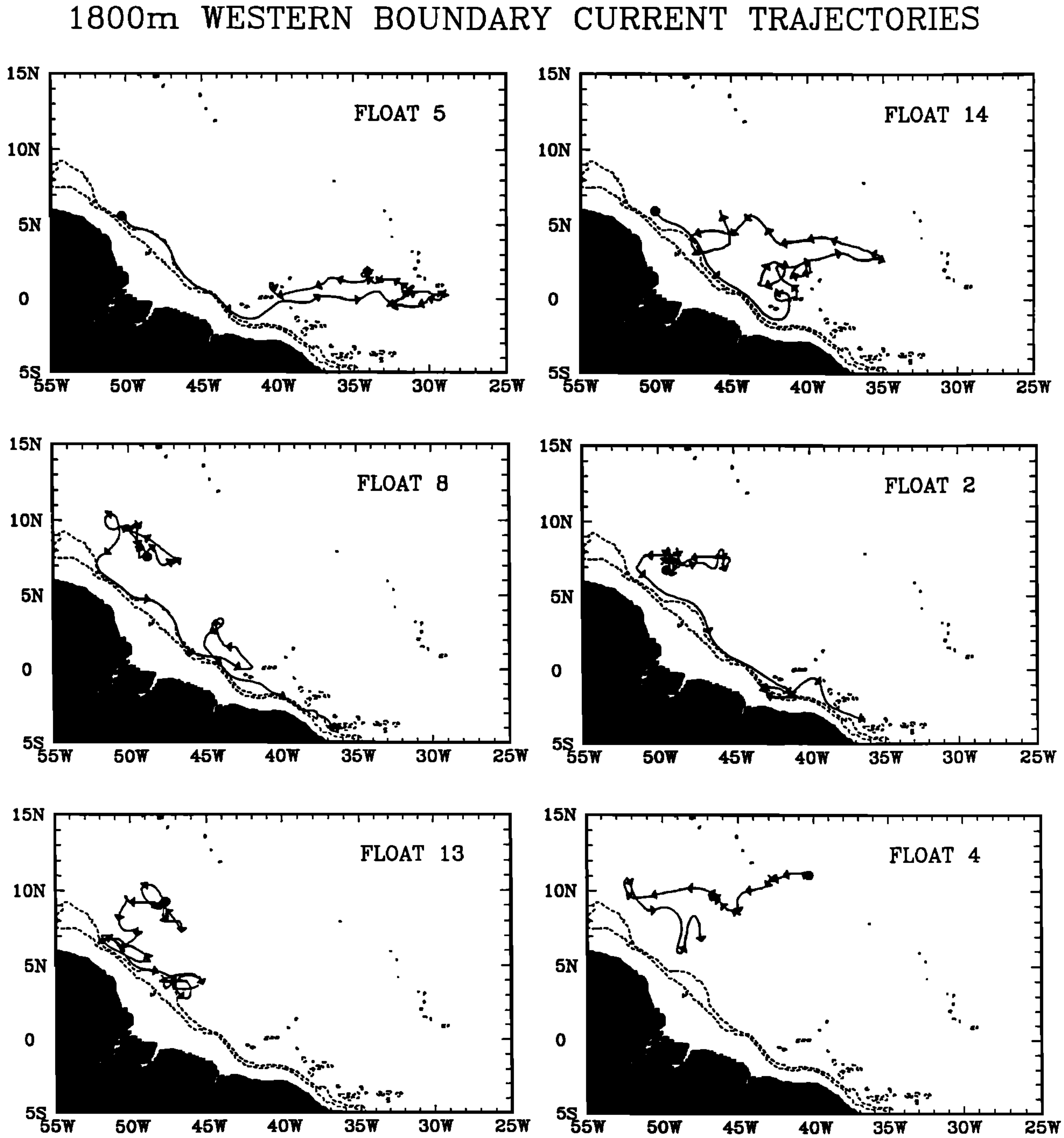

Fig. 3. Individual 1800-m float trajectories along the western boundary from February 1989 to November 1990. Arrowheads are spaced at 30-day intervals. Top panels show floats 5 and 14 launched directly into the deep western boundary current (DWBC) in early February 1989. Middle panels show floats 2 and 8 that were entrained into the DWBC in January 1990 (8) and March 1990 (2). Bottom panels show float 13, which remained in the vicinity of the western boundary from February 1990 to November 1990, and float 4, which meandered southeastward offshore of the mean DWBC. Dashed contours are 200-m and 2000-m depths.

recirculation; the width of the DWBC is 100 km as measured between points of zero velocity.

3.3. *DWBC Transport*

The transport per unit depth of the 1800-m DWBC was calculated to be 13.8 × 10^3 m^2/s by integrating across its width. Estimated standard error is around 3 × 10^3 m^2/s (Table 2). The volume transport of the portion of the DWBC measured by 1800-m floats was estimated to be 14.7 × 10^6 m^3/s (Table 2) by coupling the horizontal profile of velocity from floats with the vertical profile of velocity given by current meters moored near the axis of the DWBC in 2800 m of water [*Colin et al.*, 1991]. The volume transport was integrated over the 100-km width and from 900 m to 2800 m in depth. This transport value represents the upper core of the DWBC, not the whole DWBC, as discussed in section 6.

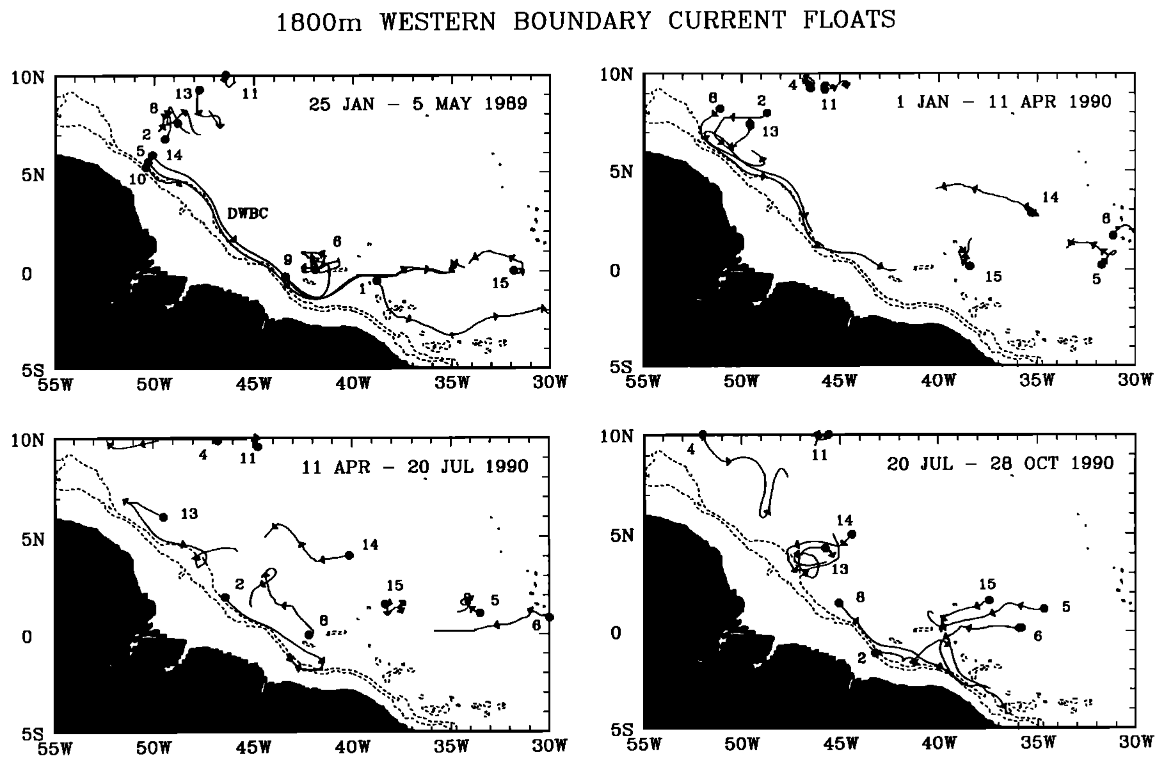

Fig. 4. Summary of 1800-m western boundary current trajectories. Each panel shows 100-day subsets of data. No floats drifted in the western boundary current from April to December 1989.

In order to search for time variations in the upper DWBC, the float data were subdivided into three subsets containing roughly similar numbers of observations, and the mean velocity and transport were recalculated (Table 2). Although each of the float subsets provided data across the width of the DWBC, the small number of observations make conclusions about time variations somewhat subjective. Maximum speeds and transport came from the first year, due to the swift floats launched in January and February 1989. Speeds and transport decrease monotonically over the three subsets, suggesting low-frequency variability. Coinciding with the decreasing speeds and transport is an increasing complexity in the character of trajectories in the DWBC; floats in the third subset loop and meander where earlier ones drifted southeastward parallel to bathymetric contours (Figure 4). One float (4) in August and September 1990 meandered southeastward 350 km offshore of the mean location of the DWBC jet, implying that the DWBC had become detached from the western boundary at that time or had split into filaments. This was the only float to do so. It is possible that the flow regime during the third subset was related to the seasonal retroflection, meandering, and eddy shedding of the North Brazil Current.

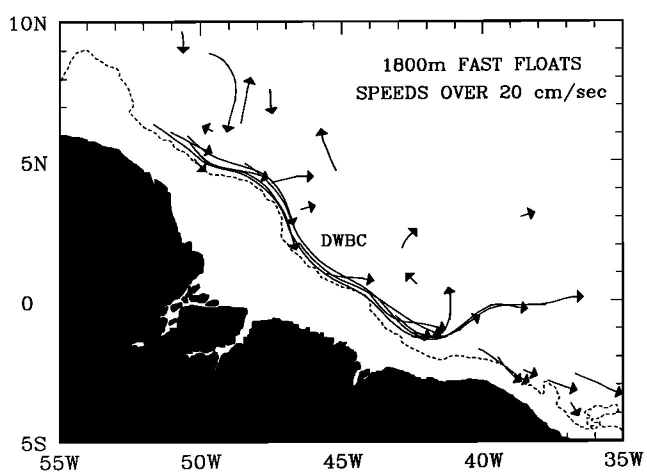

Fig. 5. Segments of 1800-m trajectories of floats that drifted faster than 20 cm/s. Fastest speeds, reaching 55 cm/s, were along the western boundary near the equator (float 5). Three floats overshot the equator in the DWBC by around 150 km before going east along the equator (5, 9) or recirculating northward (14). The dashed contour is 1800 m from the ETOPO5 data base (1989) obtained from the National Geophysical Data Center, Boulder, Colorado.

3.4. *Eddy Kinetic Energy*

Estimates of eddy kinetic energy (EKE) show that the highest energy clearly coincided with the DWBC (Figure 6). EKE peaked in the DWBC jet with values around 150 cm^2/s^2 and decreased in the offshore direction to around 5–10 cm^2/s^2 at 600–700 km from the western boundary. EKE decreased further in the eastern Atlantic, to 2.4 cm^2/s^2, as calculated from the two floats near 11°N there. The values in the DWBC are as large as peak values at 2000 m near the axis of the Gulf Stream [*Owens*, 1991; *Richardson*, 1985].

3.5. *DWBC Recirculation*

Floats offshore of the DWBC reveal (1) a northwestward recirculation between the DWBC and the Mid-Atlantic Ridge and (2) an inflow to the DWBC in the region 5°–10°N. Evidence consists of four floats (2, 4, 8, and 13) launched

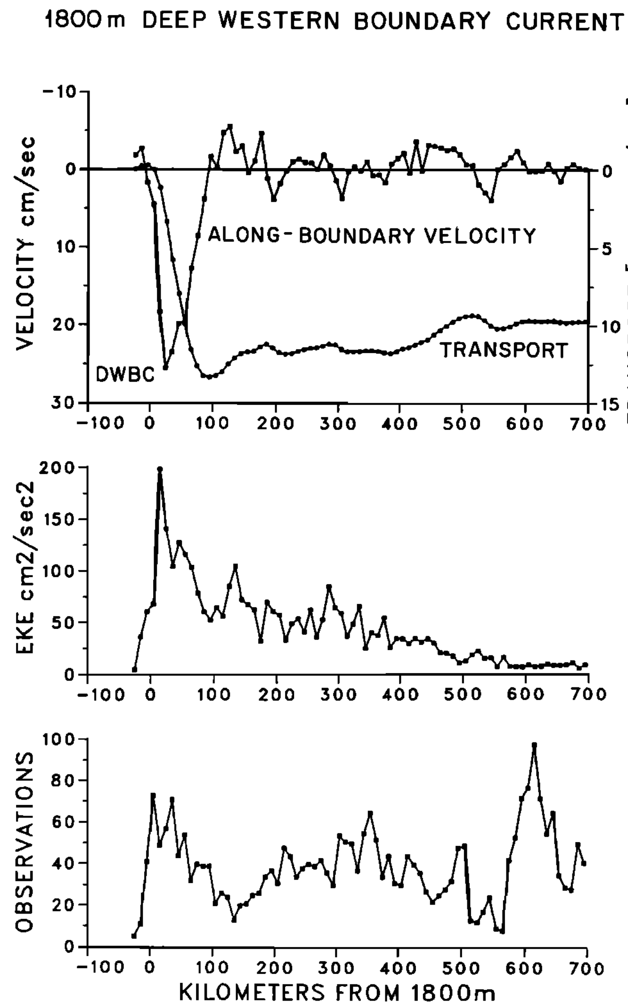

Fig. 6. Average along-boundary velocity, transport, and eddy kinetic energy, and the number of observations at 1800 m in the vicinity of the DWBC west of 43°W. All available individual daily velocities were grouped and averaged in 10-km-wide bins parallel to the 1800-m depth contour, which is from the ETOPO5 data base. Nine different floats were used to obtain this composite, which consists of roughly 3000 daily velocity observations. Eight floats drifted in the region of the mean DWBC jet and provided 500 daily observations. Transport per unit depth (10^3 m^2/s) was obtained by summing, in the seaward direction, the product of bin width and the average velocity in each bin. Eddy kinetic energy (cm^2/s^2) was calculated using $\frac{1}{2}(\overline{u'^2} + \overline{v'^2})$ where $\overline{u'^2}$ and $\overline{v'^2}$ are the variances of the velocity values parallel and normal to the 1800-m contour.

offshore of the DWBC in latitudes 6°–10°N. These floats gradually drifted westward and were entrained into the DWBC with a mean velocity of $u = -1.5 \pm 0.5$ cm/s, $v = -0.2 \pm 0.2$ cm/s. In addition, after floats 8 and 14 had reached the equator in the DWBC, they recirculated northwestward offshore of the DWBC. In contrast to these floats in the west, the easternmost floats (7 and 12) near 11°N drifted very slowly, implying very weak or zero recirculation east of the Mid-Atlantic Ridge. The combined mean velocity of floats 7 and 12 was $u = -0.11 \pm 0.19$ cm/s, $v = 0.02 \pm 0.21$ cm/s, not significantly different from zero. Evidence for recirculation is also seen in Figure 6. Although bin-averaged velocity values fluctuate around zero as a function of distance seaward of the DWBC, the integrated transport gradually decreases in the offshore direction.

Recirculation velocity and transport were estimated two ways. First the average velocities in 10-km bins seaward of the DWBC (Figure 6) were grouped and averaged, which gives a mean recirculation speed of 0.61 ± 0.25 cm/s. Second, all individual float velocities in the 90-km to 700-km band seaward of the DWBC (west of 43°W) were grouped and averaged, which gives a mean northwestward recirculation velocity parallel to the 1800-m contour of 0.47 ± 0.52 cm/s and inflow velocity toward the DWBC of 0.73 ± 0.55 cm/s. When multiplied by the 1000-km distance between the DWBC and Mid-Atlantic Ridge, these two mean recirculation velocities suggest that around 39% of the 1800-m DWBC transport per unit depth recirculated west of the ridge. Assuming that this percentage is representative of volume transport implies that around 5.8×10^6 m^3/s of the upper DWBC recirculated, leaving 8.9×10^6 m^3/s to cross the equator. However, given the estimated standard error of about one-half the magnitude of the recirculation, caution is required.

3.6. *Equatorial Currents*

A vertical profile of velocity was measured with a freely falling velocity profiler near the equator when the floats were launched there (Figure 7). The profile revealed a well-developed pattern of alternating eastward and westward currents or jets over the upper 2200 m. The most prominent eastward jets were (1) the Equatorial Undercurrent, reaching 76 cm/s at 70 m, (2) a 28-cm/s jet at 1000 m, and (3) an 11-cm/s jet at 2000 m. Four 1800-m floats appeared to be located in this third jet, which extended from around 1600 m to 2200 m.

Three floats launched near the equator (1, 6, and 9) plus another (5) that peeled off from the DWBC into the equatorial band drifted long distances in this 1800 m current (Figures 3 and 8). Float 1 drifted along 2°–3°S from 39°W to 14°W, a distance of 2750 km over 310 days at a mean velocity of 10 cm/s. This float shows that the F-11 tongue near 1700 m could have been advected to its observed location near 17°W, 2°S [*Weiss et al.*, 1989], from the western boundary in around 8 months. *Weisberg and Horigan* [1981] reported fast (~20 cm/s) eastward currents at 1800 m near 0°N, 4°W, implying that the longitudinal extent of the equatorial current is probably larger than the trajectory of float 1. Float 6 drifted eastward along 1°–3°N from 42°W to 27°W and then back to 40°W, where it turned and headed south in the DWBC.

Three of the floats (5, 6, and 9) that first drifted eastward along the equator turned and then drifted back westward along the equator. Grouping all available velocities into a large equatorial box, 2.5°S to 2.5°N, 20°–40°W, and calculating monthly mean velocity values (Figure 9) shows the mean flow near 1800 m was 4.1 cm/s eastward from February 1989 to February 1990, and then 4.6 cm/s westward from March 1990 to October 1990. These values include float 15, which differed by slowly drifting westward over the 21 months. A further complication, which implies meridional structure in the current, is a boundary near 1°N; floats north of 1°N went eastward from August 1989 to January 1990; floats south of 1°N went westward during that period. Further confirmation of the time variation of the equatorial current system is seen in a second velocity profile near 0°N, 30°W, in June 1991 that showed a westward current from 1600 m to 2000 m where the profile stopped [*Böning and Schott*, 1993].

TABLE 2. Summary of 1800-m Deep Western Boundary Current Observations, 2°S to 12°N West of 43°W

Date	Number of Floats in Current	Number of Observations in Current	Peak Velocity, cm/s	Maximum Velocity (10-km Average) and Standard Error,* cm/s	Current Width, km	Transport per Unit Depth,* 10^3 m^2/s	Total Volume Transport,† 10^6 m^3/s
Composite, Jan. 1989 to Oct. 1990	8	500	50–60	26 ± 5	100	14 ± 3	15
Jan. 1989 to Oct. 1989	4	124	50–60	39 ± 5	100	23 ± 4‡	
Nov. 1989 to Apr. 1990	3	188	40–50	30 ± 4	100	16 ± 3	
May 1990 to Oct. 1990	3	177	30–40	19 ± 6	100	8 ± 2	

*The standard error of maximum velocity was estimated from individual observation in 10-km bins. The standard error of transport was estimated in two ways: first as listed from the average velocities in 10-km bins, second, from the three values of transport over the 21 months, which imply a standard error for the composite of around 4 × 10^3 m^2/s.

†The total transport of the upper core of the DWBC was estimated to be 14.7 × 10^6 m^3/s by combining the horizontal velocity profile from floats with the vertical profile from a current meter array [*Colin et al.*, 1991] that was moored near the center of the DWBC jet as observed at 1800 m. The mooring was located at 6.2°N, 51.0°W, from March 31, 1990, to November 18, 1990, a duration of 230 days. The depth of the meters and southward along-boundary mean velocities were 800 m, −1.6 cm/s; 1400 m, 11.4 cm/s; 2000 m, 18.9 cm/s; and 2700 m, 15.6 cm/s. The velocity was assumed to be zero at the seafloor at 2800 m. The total transport was calculated from the width and thickness of the DWBC, by assuming it was elliptical in shape, and by integrating between 900 m and 2800 m.

‡Floats sampled the DWBC in January–March 1989. A data gap occurred offshore of the DWBC between 90 and 130 km; the transport is up to the data gap. The width and transport could have been larger than given here.

In summary, of the floats that were launched on the equator (1, 6, 9, and 15) or that drifted there in the DWBC (2, 5, 8, and 14), one (14) recirculated, two (2 and 8) crossed the equator in the DWBC, and one (6) entered the DWBC from the equator, leaving four near the equator at the end of tracking in October 1990.

4. THE 3300-M TRAJECTORIES

The 3300-m float trajectories look very different from the 1800-m ones (Figure 10); no obvious DWBC is seen despite the 3300-m floats having been launched near the western boundary in the lower North Atlantic Deep Water. Four trajectories (floats 36, 39, 40, and 42) were obtained near 7°N, 50°W, from February 1989 to February 1990, but none of these looks like those in the DWBC at 1800 m. Thus the 3300-m floats suggest that there was either no DWBC or a very weak one at this depth and geographical location. It is possible that the DWBC at 3300 m was located offshore of the float measurements, but this seems unlikely considering that the floats spanned a 500-km distance seaward of the continental margin and that current meters near 8.5°N show a southward flowing core of lower deep water located significantly below 3300 m and adjacent to the continental margin [*Johns et al.*, 1990]. The mean velocity calculated by summing over the four float records near 7°N, 50°W, a total of 1164 daily velocity observations, was $u = 0.37 \pm 0.55$ cm/s, $v = 0.37 \pm 0.62$ cm/s. The mean velocity component directed along the nearby bathymetry was southeastward at only 0.15 cm/s, but since the mean velocity values are smaller than the estimated standard errors, we cannot attach much significance to this along-boundary flow. The EKE of the four 3300-m floats was 18 cm^2/s^2, lower than the roughly 50 cm^2/s^2 observed at 1800 m (Figure 6). The 3300-m floats near the equator did not drift far eastward, unlike the 1800-m floats. This lack of significant flow along the equator at 3300 m is consistent with the equatorial velocity profile (Figure 7) that showed weak flow below 2200 m.

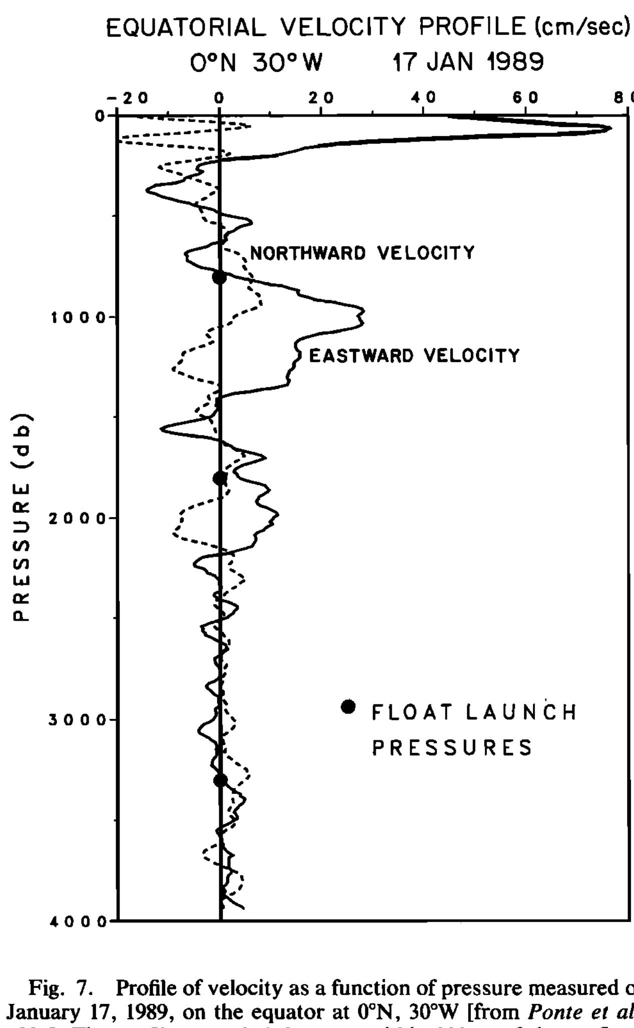

Fig. 7. Profile of velocity as a function of pressure measured on January 17, 1989, on the equator at 0°N, 30°W [from *Ponte et al.*, 1990]. The profile extended down to within 200 m of the seafloor. The solid line represents the eastward velocity component, and the dashed line is northward velocity; large dots show nominal float depths at launch.

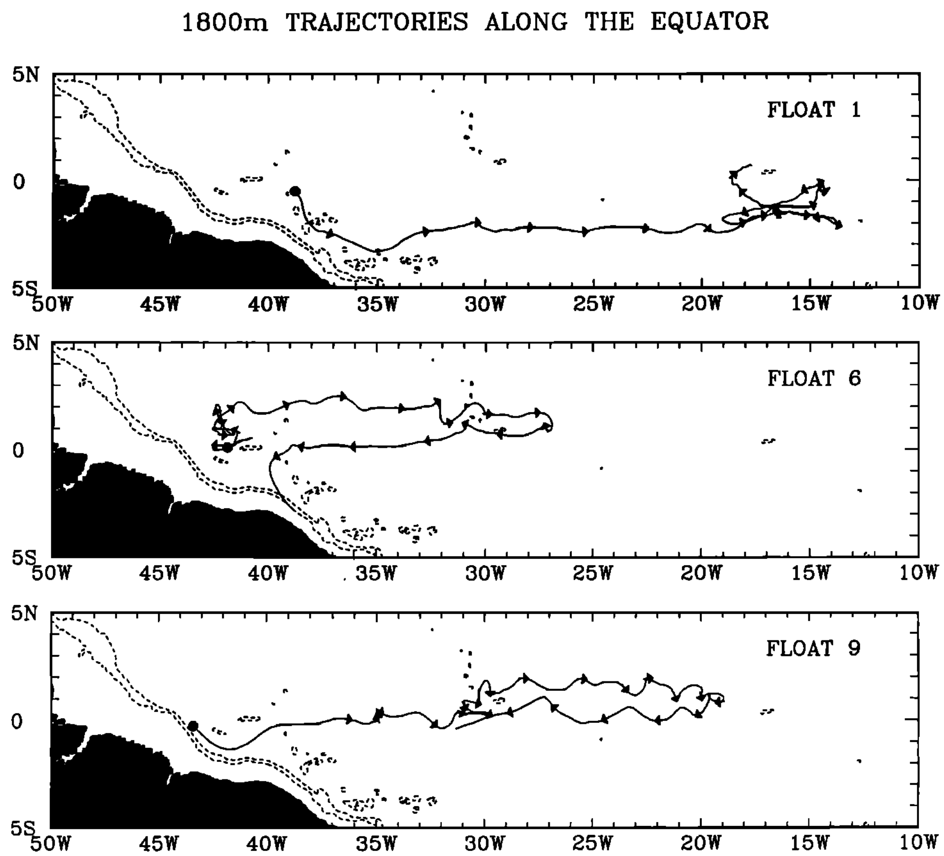

Fig. 8. Individual 1800-m float trajectories along the equator from January 1989 to October 1990. Arrowheads are spaced at 30-day intervals. Dashed contours are 200-m and 2000-m depths.

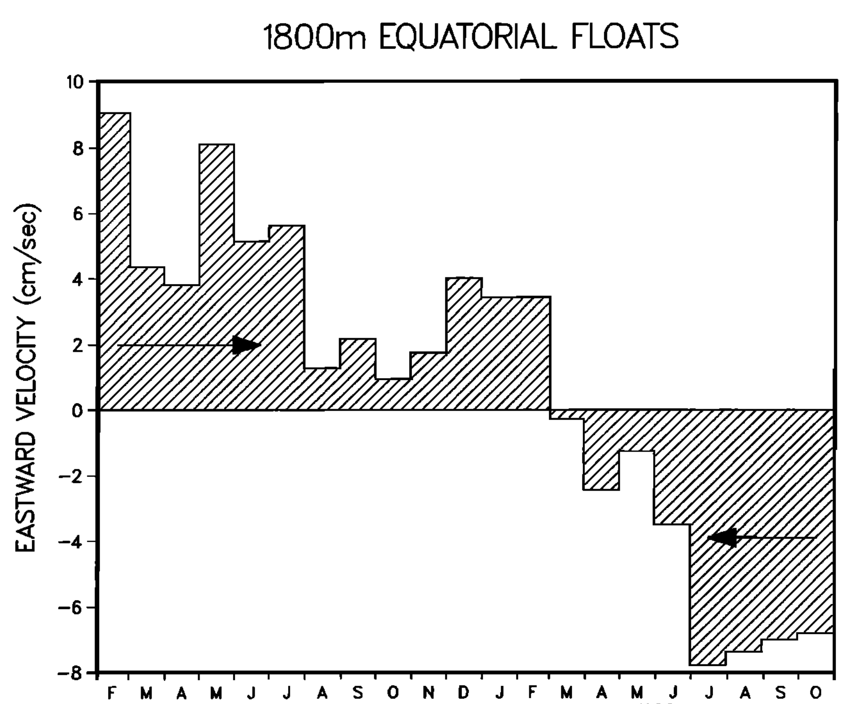

Fig. 9. Time series of 1800-m eastward velocity along the equator, calculated by grouping individual velocity values in a box whose limits are 20°–40°W, 2.5°S to 2.5°N. Plotted values are monthly averages. On average, there were approximately four floats and 120 daily observations per month in the box. Arrows pointing left and right indicate westward and eastward velocity, respectively.

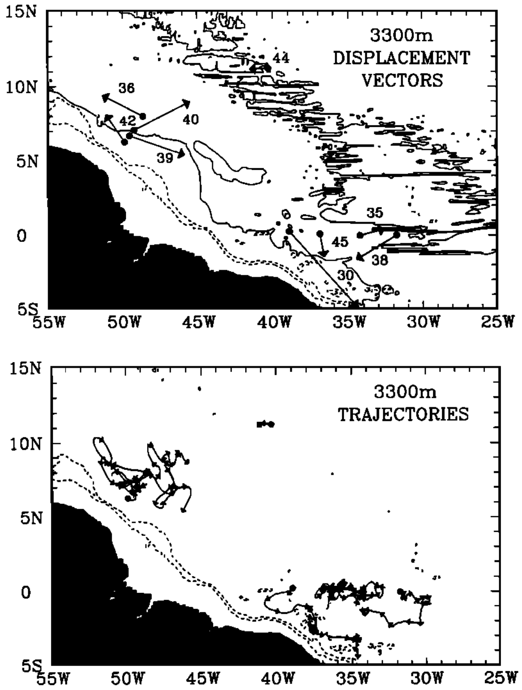

Fig. 10. Summary of 3300-m float trajectories and displacement vectors from January 1989 to October 1990. Arrowheads are spaced at 30-day intervals. Dashed contours are 200-m and 2000-m depths, the solid contour is the 4000-m depth.

5. THE 800-M TRAJECTORIES

5.1. *Intermediate Western Boundary Current*

Two 800-m floats launched near 6°N (22 and 23) and a third near the equator (28) clearly translated in a mean northwestward direction along the boundary (Figures 11 and 12). One of these (28) is inferred to have entered the Caribbean through the Grenada Passage at the end of April 1990. In addition, a 650-m bobber float (B63) launched near the equator translated up the boundary. The mean velocity of these four floats was 3.5 ± 0.8 cm/s toward 307°, with the standard error calculated from the four velocity values. Two floats (16 and 25) drifted southeastward near the boundary for various amounts of time and a few others (20, 21, and 26) translated eastward and southeastward. Floats 19 and 26 drifted southward and then eastward long distances in equatorial currents. They are discussed below. For now, the point is that some of the water in a countercurrent or recirculation offshore of the intermediate western boundary current (IWBC) fed into the equatorial current.

Individual trajectories along the western boundary are complex, as is a superposition of them (Figures 11 and 12). Although box averages of along-boundary velocity are noisy, there is a general trend of northwestward velocity within 200–300 km of the 800-m contour. This northwestward flow is bounded by generally southeastward velocity. The northwestward along-boundary transport (per unit depth), integrated seaward from the boundary, increased to

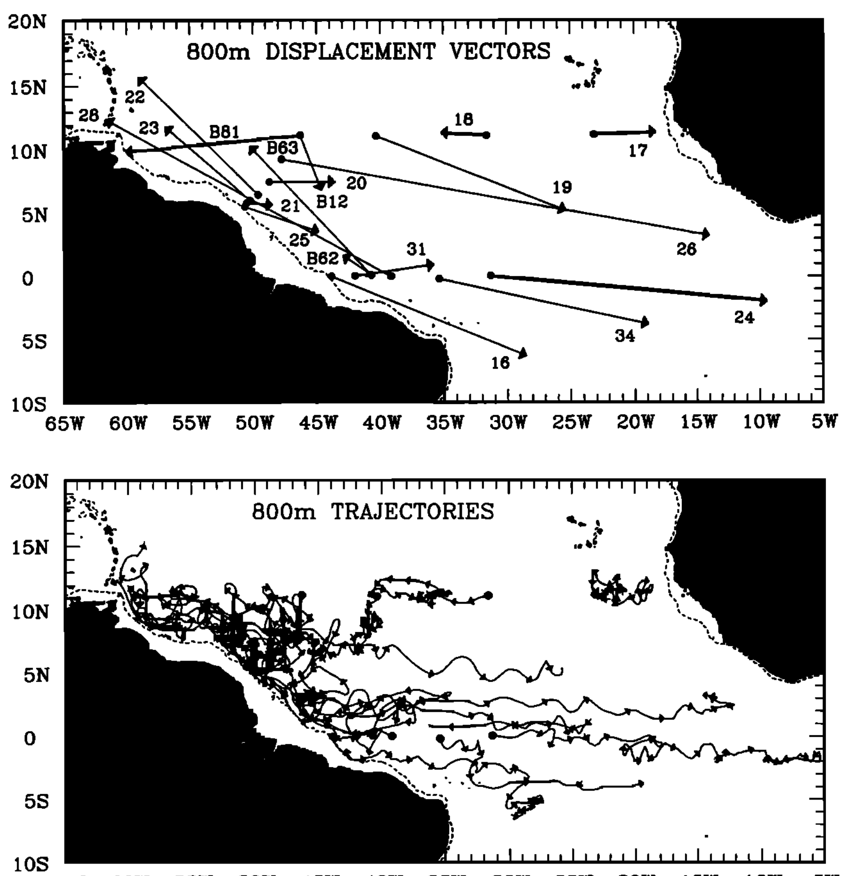

Fig. 11. Summary of 800-m trajectories and displacement vectors from January 1989 to October 1990. Float 34 was tracked up to July 25, 1989, when it stopped being heard, and float 28 was tracked up to April 22, when it is inferred to have entered the Caribbean. Four bobber (B) floats at shallower depths were included; three of these were short records. Arrowheads are spaced at 30-day intervals. The dashed contour is the 200-m depth.

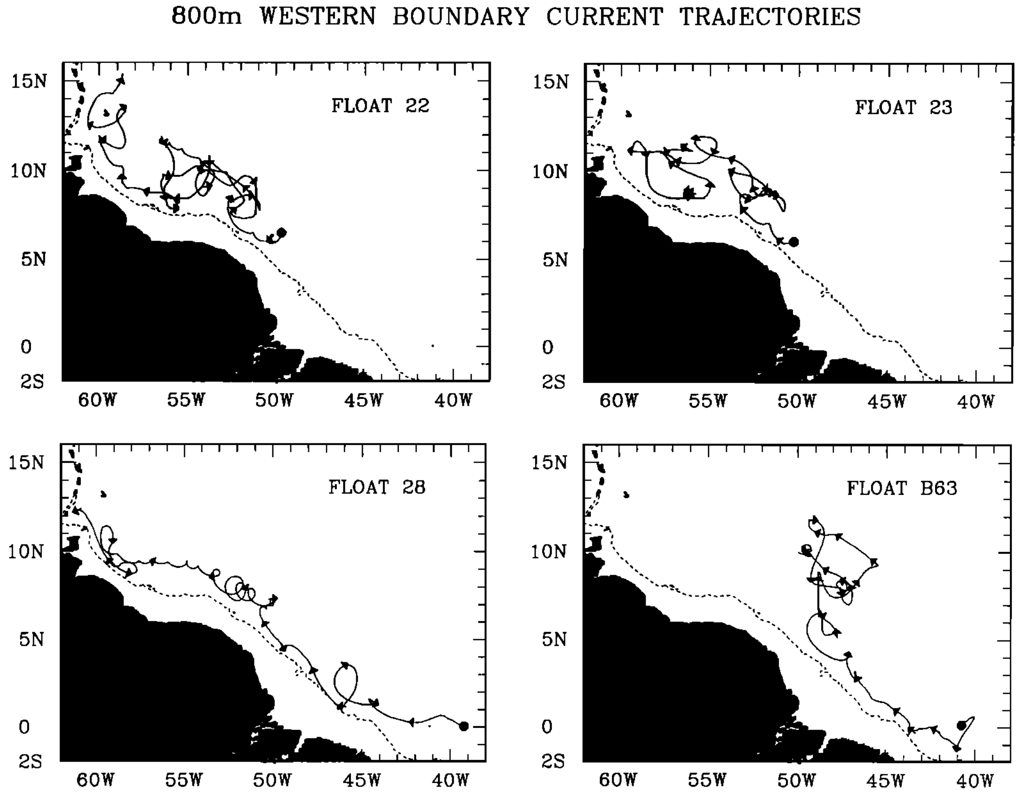

Fig. 12. Trajectories of four 800-m floats that drifted, on average, northwestward along the western boundary. Floats 22, 28, and B63 (at 650 m) looped in anticyclones that translated northwestward.

a maximum near a distance of 300 km and then decreased farther offshore (Table 3). The northward transport of the IWBC estimated from this maximum was 5.8×10^3 m^2/s $\pm$ 1.8×10^3 m^2/s (Table 3). The amount of recirculation offshore of the IWBC is ambiguous considering the complicated flow structure there and the implied connections to equatorial currents, which have low-frequency fluctuations.

Eddy kinetic energy was around 150 cm^2/s^2 near the boundary. It decreased seaward to around 30 cm^2/s^2 near a distance of 700 km and to around 16 cm^2/s^2 in the eastern Atlantic near 11°N (floats 17 and 18).

5.2. *Anticyclonic Eddies*

Three of the four floats (22, 28, and B63) that drifted northwestward the farthest looped for various amounts of time in three different anticyclonic eddies as the eddies translated up the western boundary (Figure 13, Table 4). The mean velocity of the eddies, northwestward at 8.1 $\pm$ 1.0 cm/s, contributed significantly to the mean velocity and transport in the IWBC (Table 3). Approximately 50% of the total northward transport in the IWBC was accounted for by the measurements of these floats looping in anticyclones.

TABLE 3. Northwestward Intermediate Western Boundary Current (IWBC) at 800 m

	Number of Observations in IWBC	Maximum Velocity (20 km average) and Standard Error, cm/s	Width, km	Transport per Unit Depth,* 10^3 m^2/s
I (All floats including bobbers)	1833	7.1 ± 3.8	300	5.8 ± 1.8
II (No loopers)†	1606	4.5 ± 3.6	300	2.7 ± 1.6
III (No bobbers)‡	1091	6.8 ± 3.8	180	4.2 ± 1.6
IV (No bobbers or loopers)	782	4.5 ± 3.6	160	2.2 ± 1.6

*Float velocity values were grouped in 20-km bins as a function of distance seaward of the 800-m depth contour. Only floats within the rectangle 4°–13°N, 43°–55°W, were included in order to screen out floats in equatorial currents. The northwestward transport in the IWBC was estimated by integrating the mean velocity in 20-km bins seaward from the western boundary to the point of maximum transport, near a distance of 200–300 km from the 800-m contour. The standard error of IWBC transport was estimated from the different 20-km mean velocity values within the region of the IWBC. Total transport did not vary much when the size of the 4°–13°N, 43°–55°W, rectangle was varied, except for increasing somewhat as the western edge was shifted farther to the west to include more of the northwestward going trajectories.

†Loopers are floats looping in anticyclonic eddies (see Table 4).

‡Two bobber floats located near 650 m were included in I and II.

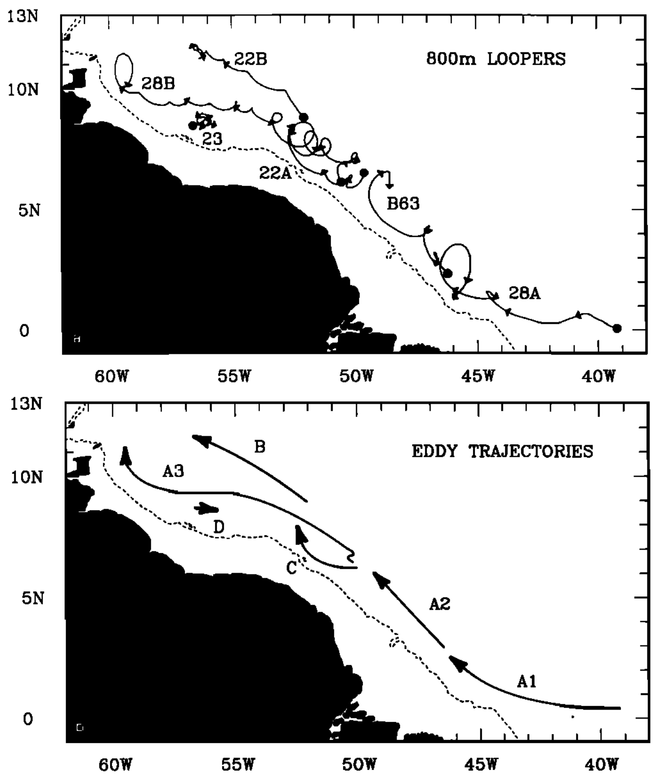

Fig. 13. (*a*) Trajectories of 800-m floats trapped in eddies as inferred from looping trajectories (see Table 4). In each case shown, a float made at least two consecutive loops in the same direction, implying it was trapped in an eddy. Anticyclone A was tracked by floats 28 and B63 almost continuously from January 25, 1989, to January 22, 1990. An early meander in the trajectory of 28 was found to be a loop when the mean translation of this float was subtracted from the trajectory. Anticyclone B was tracked with float 22 from January 21 to March 14, 1990. Anticyclone C was tracked with float 22 from February 8 to April 23, 1989. Cyclone D was tracked with float 23 from April 30 to July 15, 1990. (*b*) Trajectories of the eddies, estimated from the looping float trajectories.

Anticyclone A, most remarkable for its long life and the long distance it traveled, was tracked with floats 28 and B63 for over a year as it translated from the equator up to 11°N, a distance of 2600 km. Float 28 was launched into the eddy by chance on January 23, 1989, and looped in it for 4 months. This float was temporarily detrained from the eddy in May and float B63 was entrained into it in June. Later, in August near 7°N, float B63 was detrained from the eddy and 28 was entrained back into it, remaining there until January 1990. South of 7°N the period of rotation was 26–40 days, much larger than north of 7°N, where the period was ~11 days. Anticyclone A is interpreted to have been a weak eddy that translated up the boundary and became much stronger as it briefly stalled near 7°N in September 1989. The eddy's increase in rotation rate, swirl speed, and EKE coincided with the North Brazil Current retroflection, which occurs near 7°N during the last half of each year. Floats in the other two anticyclones began to loop near 6°N in February 1989 (anticyclone C) and near 9°N in January 1990 (B), when the retroflection was weakening. The diameter of the three anticyclones, estimated from looping trajectories, was 100–200 km.

We tentatively conclude that the three anticyclones (including A north of 7°N) were subsurface manifestations of retroflection eddies that have been observed in satellite altimetry (N. Didden and F. Schott, Eddies in the North Brazil Current retroflection region observed by Geosat altimetry, submitted to *Journal of Geophysical Research*, 1992), coastal zone color Scanner images, and current meter records [*Johns et al.*, 1990]. The current meters show that the eddies extend coherently down to at least a depth of 900 m, where the velocity is reduced somewhat but consistent with the swirl speeds of 12–24 cm/s calculated from the float loops (Table 4). The southern part of anticyclone A's trajectory and some other anticyclones observed along the boundary south of 7°N [*Johns et al.*, 1992] suggest that a train of anticyclones propagates up the boundary starting near the equator. As was suggested by *Johns et al.* [1992], these northward-propagating eddies may somehow interact with the retroflection, causing eddies to be shed from it periodically near 7°N. The eddies could be generated by instability waves resulting from the wind-driven near-equatorial currents. These waves and accompanying anticyclones have been observed to form near the equator during the northern summer and to propagate westward toward the western boundary and then northward along the boundary [*Carton*,

TABLE 4. Summary of Eddy Characteristics Estimated From Looping Float Trajectories at 800 m

	Float	Dates	Duration, days	Number of Loops	Period of Rotation, days	Swirl Velocity, cm/s	Diameter, km	Mean Velocity, cm/s u	Mean Velocity, cm/s v	EKE, cm^2/s^2
					Anticyclones					
A1	28A	890125–890516	111	2.8	40	−15.8	173	−7.8	1.5	125
A2	B63	890621–890827	67	2.6	26	−17.7	125	−4.6	6.8	158
A3	28B	890825–900122	150	13.7	11	−14.0	72	−7.4	3.5	288
B	22B	900121–900314	52	7.5	7	−16.9	32	−9.9	6.1	144
C	22A	890208–890423	74	3.0	25	−11.7	79	−5.0	2.8	68
					Cyclone					
D	23B	900430–900715	76	2.9	26	7.6	55	1.5	0.1	29

The mean translation velocity of the anticyclones from the five individual estimates is $u = -6.9 \pm 1.0$ cm/s $v = 4.2 \pm 1.0$ cm/s, or 8.1 cm/s toward 301°. The number of loops was estimated visually and used to calculate the period of rotation. Swirl velocity was estimated as being equal to the root-mean-square velocity of a float about its mean velocity. Diameter (D) of the loops was estimated from the mean period of rotation (T) and mean swirl velocity (V_θ) with the relation $D = (V_\theta T)/\pi$. The mean translation velocity of each eddy was estimated by calculating the mean velocity of each float while it was looping in the eddy. Eddy kinetic energy (EKE) was estimated from the average of the u and v velocity variances about their respective mean velocity values.

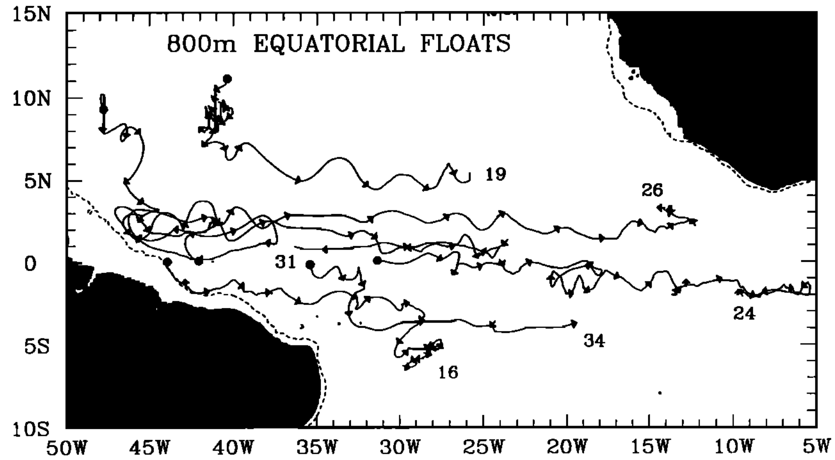

Fig. 14. Trajectories of six 800-m floats that drifted eastward in equatorial currents. Float 24, which was ballasted to lie near the center of the eastward jet (Figure 7), equilibrated near 1125 m.

1992; *Weisberg and Weingartner*, 1988]. The eddies may also be generated by instability of the cross-equatorial thermohaline flow; *Thompson et al.* [1992] have observed anticyclonic eddies propagating up the western boundary in simulations from a numerical model when the forcing was a steady 13×10^6 m^3/s thermohaline circulation, without winds or wind-driven currents.

In summary, three anticyclones were observed to translate up the western boundary and to account for a significant amount of the mean northwestward velocity and transport in the IWBC at 800 m. The implications are that (1) these eddies extend coherently from the sea surface to at least 800 m, (2) north of 7°N they are subsurface manifestations of retroflection eddies that pinch off from the North Brazil Current retroflection, and (3) they carry sizable amounts of South Atlantic water from the equator to around 11°N.

5.3. *Equatorial Currents at 800 m*

The 800-m trajectories in a band from around 5°S to 6°N (Figures 11 and 14) indicate a long, visually striking, eastward drift of floats. These floats equilibrated at a depth near the top of an eastward equatorial jet that had a peak speed of 28 cm/s and thickness of 500–600 m (Figure 7). The floats apparently descended into the jet and were carried eastward by it. Most remarkable is the broad width, ~11° in latitude, of the dominantly eastward equatorial currents. Peak speed along eastward trajectories was ~40 cm/s, and the average eastward velocity calculated by grouping all eastbound floats in the box 5°S to 6°N, 5°–40°W was 10.6 ± 0.9 cm/s. Coupling this value with the 11° width and 500-m thickness gives an eastward transport per unit depth of 128×10^3 m^2/s and a volume transport of 64×10^6 m^3/s. Of course, regions of westward flow could be embedded in the eastward current, which would reduce the mean velocity, and a few are seen. Still, the trajectories imply that very large amounts of water can flow in equatorial currents at this depth.

Six different floats drifted eastward in the equatorial currents; two of these drifted southward into the equatorial band and then eastward. Float 24, launched on the equator at 30°W, went 26° east along 0°–2°S to 5°W, the farthest east of any float. This float was ballasted to equilibrate near 1125 m, near the center of the jet (Figure 7). Assuming that the eastward jet began near the western boundary implies that the current extended coherently eastward about 38° of longitude, to at least 5°W.

5.4. *Reversal*

Three of the four floats (24, 26, and 31) that were still in the 5°S to 6°N band at the end of the 21 months reversed direction shortly before the end. The fourth float (19) looked as if it had just stopped near 5°N, 26°W, and was perhaps about to reverse direction. This reversal of the equatorial current is inferred to be primarily a temporal change because the 800-m floats would have still been well within the equatorial jet seen in Figure 7. The one deeper float (24) would have been near 1350 m when it reversed, close to the lower limit of the jet. The mean westward velocity of the westbound trajectories in the box 5°W–40°W, 5°S–6°N was 7.8 ± 1.4 cm/s, roughly equal to the eastbound velocities.

5.5. *Southward Velocity*

Three of the five 800 m floats launched near the equator (16, 24, and 34) plus two others launched near 9°N (26) and 11°N (19) drifted on average southward between Brazil and Africa. This can be seen in the southward tilt of their trajectories and displacement vectors (Figure 11). The mean southward velocity of these five floats was 1.3 ± 0.3 cm/s, with the standard error estimated from the five individual mean velocity values. Although the mean southward velocity of all observations in the box 5°W–40°W, 5°S–6°N was 0.8 ± 1.0 cm/s, not significantly different from zero, the southward trend of the trajectories and displacement vectors suggests that the southward velocity might be of importance.

The southward cross-equatorial transport implied by this velocity is large, considering the great width of the Atlantic where the floats drifted. For example, a 1 cm/s southward velocity over a 30° longitudinal width gives a southward transport per unit depth of 33×10^3 m^2/s, twice that observed in the DWBC at 1800 m and dwarfing the northward transport along the western boundary at 800 m.

A possible explanation is that the nearly east-west equatorial currents are tilted in the mean such that eastward flow is accompanied by southward velocity and westward flow is

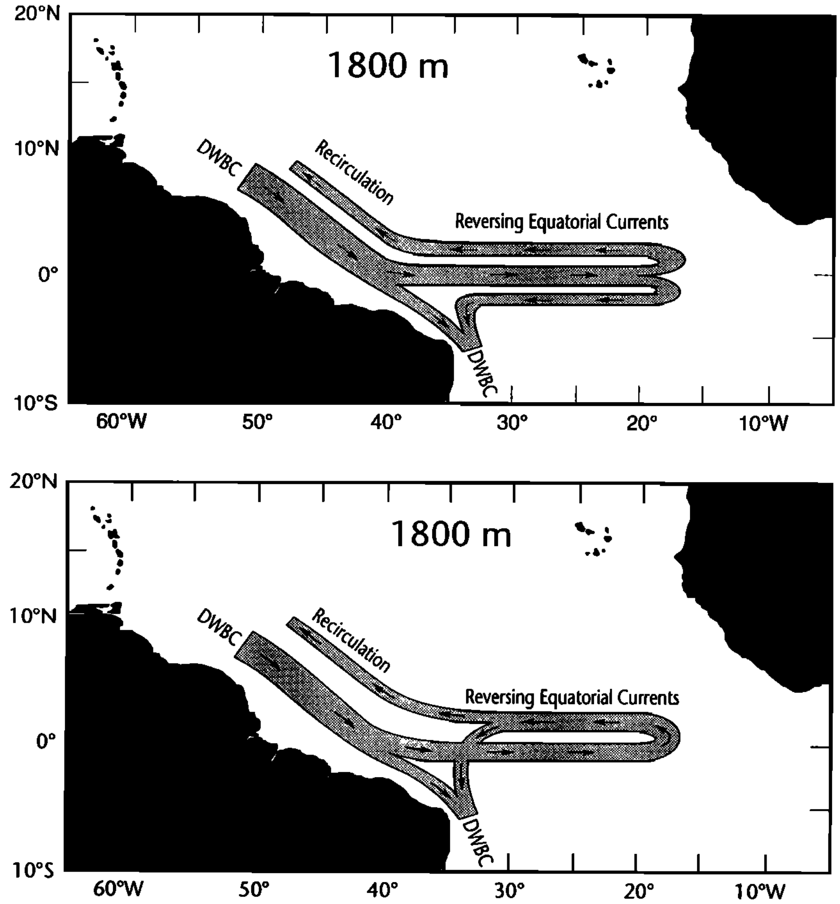

Fig. 15. Schematic diagrams summarizing the 21 months of 1800 m float data. The width of currents is roughly proportional to estimated volume transport: 15×10^6 m^3/s in the DWBC north of the equator, 6×10^6 m^3/s in the recirculation there, and 9×10^6 m^3/s in the DWBC south of the equator.

accompanied by northward velocity. If so, there would be little or no net meridional transport of this region, assuming that the eastward transport is replaced periodically by an equal westward transport. At the end of 21 months of tracking, the floats were near their eastern limit. When and if they return westward should reveal whether this explanation is valid.

An alternative explanation, and one we believe is less likely, is that narrow westward currents are sandwiched between the eastward ones shown by floats, so that the mean flow between 5°S–6°N is near zero over the 21 months. Although there is no evidence for this from our data, one could argue that only long eastward trajectories were observed because the floats were launched in the west. Had we launched floats in the east, we might have observed long westward trajectories.

6. Interpretation and Discussion

6.1. *DWBC–Equatorial Current Connection at 1800 m*

The trajectories show that when the equatorial current system was directed eastward at 1800 m, some of the DWBC water turned and flowed along the equator (floats 5 and 9). Eventually, after about a year, the equatorial current reversed and flowed westward (floats 5, 6, and 9). When the westward current along the equator reached the western boundary, some water turned southward and entered the DWBC south of the equator (float 6). At this time, two of the DWBC floats (2 and 8) crossed the equator. Thus the pattern of cross-equatorial flow in the DWBC seems to be coupled with the direction of equatorial currents. An implication is that the equatorial current system acts as a temporary reservoir for DWBC water, storing it in eastward flow and releasing it in westward flow. Virtually all net cross-equatorial flow occurred in the west near the boundary, except for temporary crossings by floats farther east trapped in higher-frequency motion within a few degrees of the equator.

Schematic diagrams of the inferred general circulation of upper North Atlantic Deep Water are given in Figure 15. Two interpretations of the currents are shown, both of which attempt to illustrate the time-dependent reversing equatorial current in a single figure. The top panel shows the eastward equatorial current to split in the east and to return westward on both sides of the equator. The bottom panel shows the westward equatorial current to split near the western boundary, with the southern part crossing the eastward current. The splitting of the equatorial current in the east (top) and the apparent crossing of two currents in the west (bottom) are artistic artifacts, not real circulation features, since the floats suggest that the main eastward and westward flows do not occur simultaneously.

Variations in the speed of the DWBC may be linked to variations in the direction of the equatorial currents. The

DWBC was observed to be fastest in February and March 1989 (Table 2), when the eastward flow along the equator was fastest (Figure 9). The DWBC was slowest during May–October 1990, when the equatorial current was westward. This raises the possibility that a pulse of above average flow in the DWBC caused eastward flow along the equator and that below average flow in the DWBC caused westward flow near the equator. The implied period of this oscillation would be around 2 times the 18 months between maximum and minimum flow in the DWBC and in the eastward velocity near the equator, or roughly 3 years.

This scenario is consistent with model studies by *Kawase et al.* [1992], who showed that the spin-up of the DWBC caused eastward flow along the equator and westward flow above and below the DWBC in jets a few hundred meters thick (after a few hundred days). Initially, most of the DWBC water turned eastward at the equator, but after around 5 years only half did so; the other half crossed the equator and continued south in the boundary current. At much greater times, virtually all the DWBC water crossed the equator in the DWBC. *Kawase et al.* [1992] suggest that transients in the DWBC draw out water along the equator, resulting in the observed F-11 tongue.

6.2. *Two Cores of the DWBC*

The float trajectories in combination with other recent data in the tropical Atlantic reveal that the DWBC is divided vertically into two distinct cores that are also displaced laterally. *Molinari et al.* [1992] occupied three hydrographic sections across the DWBC during March 1989, coinciding with the early float trajectories. These sections clearly show an upper core that matches our 1800-m floats and that contained a maximum of F-11 centered near 1500 m and a maximum in geostrophic velocity centered near 1900 m. Water properties were used to trace the origin of this core's water to the Labrador Sea [see *Pickart*, 1992] and suggest recent ventilation. The lower core lay just below the 3300-m floats and contained a maximum in F-11 centered near 3500 m and a maximum in geostrophic velocity at 4100 m. Water properties indicate that the lower core originated in the Denmark Strait. The upper and lower high-velocity cores are separated by a layer of low geostrophic velocity near 3000 m, close to the 3300-m floats, which also indicated low mean velocity. Thus the floats are consistent with the general picture of two cores, although no floats were in the lower one.

The 1800-m floats reveal a swifter mean DWBC, ~25 cm/s, than that calculated from geostrophy, ~8 cm/s, although the widths agree [*Molinari et al.*, 1992]. The estimated transport of the upper part of the DWBC from floats and current meters was 14.7×10^6 m^3/s, considerably larger than the geostrophic transport given by *Molinari et al.* [1992]: 7.6×10^6 m^3/s, where 4.4×10^6 m^3/s comes from the upper core and the remaining 3.2 is half of the 6.3×10^6 m^3/s between cores. The low geostrophic velocity and transport values might be due to the choice of the zero velocity level (4.7° isotherm) and the fairly wide station spacing (~50 km) compared with the narrow width of the high-velocity core near the continental margin. The geostrophic transport of the upper core given by *Speer and McCartney* [1991] near 10°N is 15×10^6 m^3/s, closely matching the float and current meter data. The total transport of both cores of the DWBC near the equator was estimated to be 24×10^6 m^3/s by *Molinari et al.* [1992], 25×10^6 m^3/s by *Speer and McCartney* [1991], and 35×10^6 m^3/s by *McCartney* [1993]. Since much of the DWBC is inferred to recirculate locally, these estimates do not conflict with the magnitude of the net thermohaline circulation, which is roughly 15×10^6 m^3/s [*Hall and Bryden*, 1982; *McCartney and Talley*, 1984; *Roemmich and Wunsch*, 1985; *Schmitz and Richardson*, 1991; *Schmitz and McCartney*, 1993].

Recent current meter data along the western margin of the tropical Atlantic between the equator and 9°N tend to agree with the floats in showing a continuous, narrow, swift DWBC at 1800 m and a lower-velocity layer near 3300 m. The current meters also measured a swift deep core of the DWBC at depths of 3700 m to 4600 m located seaward of the upper level DWBC. Current meters located near 1800 m at three locations spanning the high-velocity core of the DWBC recorded mean southeastward velocities of 19–24 cm/s in close agreement with the mean velocity profile from floats shown in Figure 6 [*Colin et al.*, 1991; F. J. Schott, et al., On mean and seasonal currents and transports at the western boundary of the equatorial Atlantic, submitted to *Journal of Geophysical Research*, 1992 (hereinafter referred to as Schott et al., submitted manuscript, 1992); W. Johns, personal communication, 1992]. Two other current meters at this level approximately 70 km and 85 km seaward of the 1800-m depth contour recorded mean southeastward velocities of 4 cm/s and 3 cm/s (respectively) agreeing with the narrow width shown in Figure 6 [*Johns et al.*, 1990; Schott et al., submitted manuscript, 1992]. Deeper in the water column, near 3300 m and close to the western boundary, two current meters recorded mean southeastward velocities of 2 cm/s and 4 cm/s in agreement with the inferred low mean velocities observed with floats there. Below this depth, current meters between 3800 and 4600 m near 8.5°N recorded swift southeastward mean velocities of 17–28 cm/s in the deep core of the DWBC [*Johns et al.*, 1990]. Farther south, near 1.5°N, a mean velocity of 16 cm/s was recorded at 3700 m (Schott et al., submitted manuscript, 1992) implying that at least some of the deeper DWBC reaches the equator although the path of this water is complicated by the Ceara Rise located north of this mooring.

The DWBC was extensively measured off Abaco in 1987–1988 [*Lee et al.*, 1990]. It appeared to be a single current jet there, with maximum mean velocity of 20 cm/s near 1800 m. The DWBC extended from around 1000 m down to the seafloor near 4800 m, where a velocity of 10 cm/s was observed. The horizontal velocity profile off Abaco at 1800 m seems to match closely that observed farther south by the 1800 m floats. The major difference is that Lee et al. observed a mean southward velocity of 15 cm/s at 3300 m off Abaco, instead of a velocity minimum. Thus between Abaco and northeast Brazil a major change in the structure of the DWBC takes place, from a large single jet to two jets separated in the vertical and laterally offset. What happened to the piece missing near 3300 m off northeast Brazil? *Lee et al.* [1990] and *Leaman and Harris* [1990] suggest that part of the 33×10^6 m^3/s in the DWBC off Abaco recirculated offshore of the boundary current. Perhaps the recirculation off Abaco near 3300 m is strong enough to account for the missing piece.

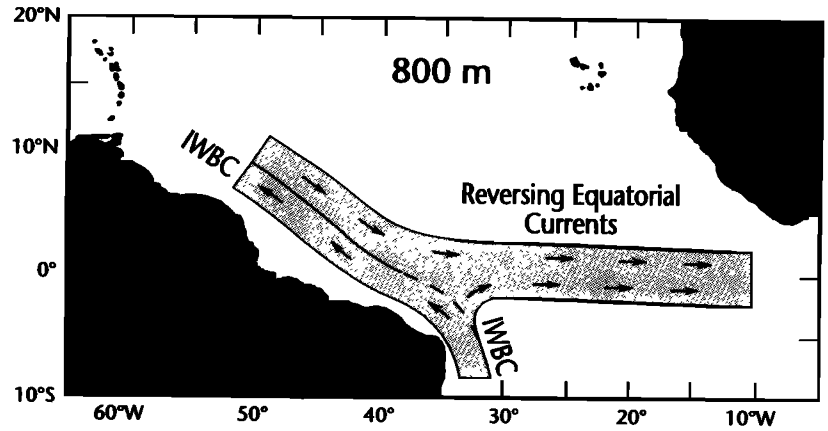

Fig. 16. Schematic diagram summarizing the 21 months of 800-m float data. The direct connection between the IWBC and the equatorial current was not obvious from the trajectories because the IWBC floats went northwestward and the equatorial floats went eastward. The schematic shown here is based partially on a consideration of continuity.

6.3. *IWBC–Equatorial Current Connection at 800 m*

A schematic diagram of the inferred mean circulation at 800 m is shown in Figure 16. The IWBC is interpreted to originate in the South Atlantic and to be continuous along the boundary with part feeding into the equatorial current. The two floats (16 and 25) that drifted southeastward along the boundary counter to the inferred mean flow are interpreted to show temporal variability of currents that are predominantly northwestward and illustrate the complexity of currents in this region. The equatorial current is interpreted to be a broad eastward flow, although there is the possibility of unresolved meridional structure and narrow counterflows embedded in the equatorial band. Since the eastward equatorial current reversed only near the end of the 21 months, the mean circulation shown here does not include a westward equatorial current. If a westward flow persists for the same duration as the eastward flow, then a schematic of the longer-term circulation at 800 m might look like Figure 15 with arrows reversed in direction.

6.4. *Meridional Structure of Equatorial Currents*

Swift zonal equatorial currents have now been observed below the thermocline in all three oceans [*Luyten and Swallow*, 1976; *Firing*, 1987; *Ponte et al.*, 1990]. The latitudinal structure of these currents was measured by *Firing* [1987] in the Pacific between 3°N and 3°S. At 800 m he found generally westward velocity within around 1° of the equator, which seems to be part of a series of stacked jets above 3000 m, each one occupying 150–400 m in the vertical. Eastward currents, the North and South Intermediate countercurrents, extended from 1.0° to 2.5° of the equator with maximum speeds of 15–20 cm/s near 700 m. Westward currents were found again outside the 2.5°S to 2.5°N region, although only the South Equatorial Intermediate Current was well resolved. These three off-equatorial currents were much thicker vertically than the equatorial jets and seemed to be part of the permanent circulation (over 16 months). At 1800 m, Firing observed a similar meridional structure of the currents, but their direction was the reverse of that at 800 m. To resolve currents of this width adequately would require more closely spaced floats than we have, which may account for the apparent discrepancy between the Atlantic float trajectories and Pacific equatorial currents at 800 m. Another possible explanation of the discrepancy could be the low-frequency variability observed in the long-term float trajectories.

There are virtually no other long-term direct velocity measurements in the Atlantic equatorial band at 800 m with which we can compare our results. It is possible that part of our observed eastward current at 800 m could be a deep extension of the subsurface geostrophic countercurrents described by *Cochrane et al.* [1979]. These countercurrents were centered near 4.5° north and south of the equator at 200 m, were 2° in latitude wide, and extended down to around 800 m. Our mean float velocities seem to be faster than these countercurrents, which were slow at 800 m.

7. SUMMARY AND CONCLUSIONS

SOFAR floats have given a first Lagrangian view of flow in the upper core of the DWBC, a connection of the DWBC to the equatorial current system, and cross-equatorial flow. The DWBC at 1800 m was found to be a narrow, 100-km-wide jet, flowing with peak speeds of 55 cm/s and peak average (10 km bin) speeds of 26 cm/s. Roughly 39% of its 14.7×10^6 m^3/s transport recirculated between the current and the Mid-Atlantic Ridge, leaving around 9×10^6 m^3/s to cross the equator. At times, DWBC water flowed eastward along the equator for long distances. At other times, when the equatorial current was westward, the DWBC crossed the equator, joined by flow turning south from the equator. Thus the equatorial current seems to serve as a temporary reservoir for DWBC water. Variations in the DWBC and its cross-equatorial flow seem to be linked to low-frequency variations of the equatorial current, in agreement with modeling studies by *Kawase et al.* [1992]. The inferred period of the variations is around 3 years based on the 21 months of data. Observations of the longer-term drift of the floats over an additional 2 years should provide a better picture of the variations of these currents and the longer-term fate of DWBC water.

The 3300-m float trajectories look very different from the 1800-m ones; no indication of a DWBC was observed, and the mean velocity was slow. We conclude that these floats were located in a low-velocity layer separating the upper and lower cores of both F-11 and velocity in the DWBC. Thus the DWBC is very different off northeast Brazil than off Abaco, where a single southward flowing jet extended from around 1000 m to the seafloor near 4700 m.

Most visually striking of the 800-m trajectories is the long eastward drift of floats between 5°S and 6°N, which suggests large transports. The reversal in direction of several floats near the end of the 21 months implies that the flow varied with a period of around 3 years. Large southward transport in the equatorial band is suggested by the southward tilt of five trajectories there. If the equatorial currents are tilted on average, their reversal could also cause a reversal of transport, which implies that the cross-equatorial flow could have large low-frequency variations at this depth.

At 800 m a northwestward-flowing IWBC was observed north of the equator, bounded in the offshore direction by counterflow which fed into the equatorial current from as far north as 11°N. Around half of the transport per unit depth in the IWBC consisted of a series of three anticyclonic eddies that translated northwestward along the boundary. One was tracked all the way from the equator to 11°N. North of 7°N the anticyclones are inferred to be subsurface manifestations of North Brazil Current retroflection eddies.

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P. L. Richardson and W. J. Schmitz, Jr., Woods Hole Oceanographic Institution, Woods Hole, MA 02543.

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