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North Brazil Current retroflection eddies

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Abstract. During 1989–1992, six different anticyclonic eddies were observed to translate up the coast of South America between 7°N and 12°N. These eddies, which are similar to those recently observed with coastal zone color scanner images, current meters, and altimetry, are inferred to have formed from pieces of the North Brazil Current, which retroflects or veers offshore near 7°N to flow eastward. The maximum near-surface diameter of the eddies when newly formed is estimated to be 400 km. The retroflection eddies were identified in trajectories of four surface drifters and three SOFAR floats at depths from 900–1200 m that looped as they translated northwestward with a mean velocity of 9 cm/s. The two longest trajectories were (1) by a 900-m float beginning near 7°N in August 1989 that looped 14 times over 151 days with a maximum diameter of 140 km and (2) by a surface drifter beginning near 7°N in October 1990 that looped 9 times over 116 days with a maximum diameter of 250 km and maximum swirl speed of 80 cm/s at that diameter. The mean rotation periods of these two eddies were 11 and 13 days, respectively, with the rotation period of small loops at 900 m around 7 days. Three of the eddies were observed during the period August 1989 to April 1990. Retroflection eddies are considered to provide significant northward volume transport, ~3 Sv, along the western boundary even during the months when the North Brazil Current has been observed to retroflect into the countercurrent.

1. Introduction

Using coastal zone color scanner (CZCS) images from 1979–1980, *Johns et al.* [1990] discovered that pieces of the North Brazil Current retroflection pinch off from the main current as large, 400-km-diameter, anticyclonic eddies which drift northwestward along the coast of South America (Figures 1 and 2). During the period July 1979 to January 1980, three eddies were observed to form. Later current meter records from 1987 and 1988 in the vicinity of the retroflection implied that the retroflection eddies extended coherently down to 500–1000 m and could be important in transporting South Atlantic water northward and into the Caribbean [*Johns et al.*, 1990]. A recent study of satellite altimetry identified five retroflection eddies that translated up the coast between November 1986 and April 1989, adding confirmation to the Johns et al. observations [*Didden and Schott*, 1993].

These new CZCS and altimetry observations of the eddies raised many questions about their numbers, life histories, and significance to the general circulation. Do these eddies translate significant amounts of upper layer South Atlantic water up the coast during fall, when the North Brazil Current retroflects into the North Equatorial Countercurrent and flows eastward (Figure 1)? Is their associated transport confined primarily to the near-surface layer, or does it extend deeply into and below the thermocline, as suggested by the current meter observations?

During 1990–1991 we tracked a retroflection eddy by launching a surface drifter into the center of the North Brazil Current retroflection. This drifter was trapped in a retroflection eddy as it pinched off and translated 700 km northwestward along the coast. During these same years, three additional surface drifters launched near the Amazon River as part of A Multidisciplinary Amazon Shelf Sediment Study (AMASSEDS) [*Nittrouer et al.*, 1991] became briefly trapped in two eddies. In addition, two SOFAR floats in this region became caught in three retroflection eddies and translated northwestward in them during 1989, 1990, and 1992.

This paper uses these seven trajectories to describe the characteristics of the six retroflection eddies. The implication is that all the eddies pinched off from the retroflection, although no CZCS or other measurements document the actual formation of the eddies. Data from the drifters, floats, CZCS images, altimetry, and current meters agree remarkably well in revealing the characteristics of the eddies even though most of these different data did not overlap in time.

This introduction is followed by a brief description of the floats and drifters and the methods used to determine eddy characteristics. Next is a description of eddy case histories, followed by a summary of the eddies' general characteristics. These characteristics are then discussed and briefly compared with other ocean eddies. The main results are reiterated in the final summary.

2. Methods

2.1. Surface Drifters

The longest looping drifter trajectory (71) was made by a refurbished mini-TIROS Oceanographic Drifter (TOD) buoy

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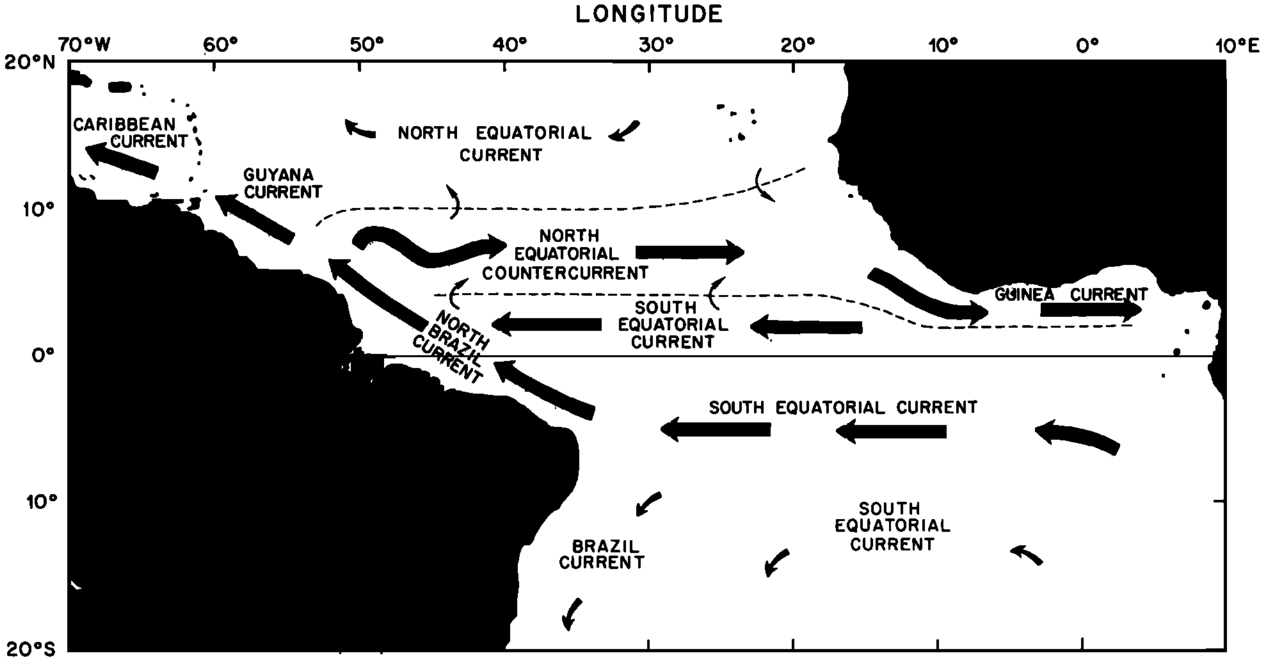

Figure 1a. Schematic map showing the major tropical currents between July and September, when the North Brazil Current (NBC) retroflects and feeds into the eastward flowing North Equatorial Countercurrent [from *Richardson and Walsh*, 1986]. From January through July the countercurrent disappears in the western tropics, and westward velocities are seen in this area. The new data discussed in this paper suggest that eddies pinch off from the NBC retroflection near 7°N and translate northwestward toward the Caribbean in the vicinity of the Guyana Current.

originally used to track currents in the tropical Atlantic during 1983–1985 [*Richardson and Reverdin*, 1987]. A 10 m^2 holey sock drogue was attached to the drifter by a 15-m-long wire-jacketed tether. There was no drogue sensor, but most other similar drogues and tethers on drifters survived longer than the 119 days discussed here. The other three drifters (42, 45, 57) were part of an array launched near the Amazon River during AMASSEDS [*Nittrouer et al.*, 1991; R. Limeburner et al., Lagrangian flow observations of the Amazon River discharge into the North Atlantic, submitted to *Journal of Geophysical Research*, 1993]. These Draper Lab drifters were attached by a wire-jacketed tether to a 2 m^2 drogue centered at depths of 2–5 m. Typically, five positions per day were obtained for each drifter by orbiting satellites.

2.2. SOFAR Floats

The SOFAR floats discussed here were a subset of an array launched in January and February 1989 at nominal depths of 800, 1800, and 3300 m off the coast of French Guiana near 7°N and off Brazil near the equator. Daily positions were obtained acoustically for 4 years from moored listening stations (see *Richardson et al.* [1992] for details). Four of the 800-m floats looped in five anticyclonic eddies, three of which are interpreted to be retroflection eddies. Some of these looping trajectories were briefly discussed by *Richardson and Schmitz* [1993] and are further analyzed and discussed here in combination with the drifter trajectories. The depth of the floats is somewhat greater than the 800-m nominal depth due to their slow sinking caused by creep of their pressure housings.

2.3. Calculations

Each of the looping trajectories (loopers) was interpreted to reveal the characteristic motion of a particle in a discrete eddy, a rotational or swirl velocity around the eddy center plus its translation through the ocean. Thus each trajectory gave the path of an eddy plus information about its size, period of rotation, translation rate, and swirl speed. The number and size of loops were estimated visually and used to calculate the diameter D and period of rotation T. The mean translation rate of the inferred eddies $\bar{v}$ was estimated by calculating the mean velocity of each looper. The characteristic swirl velocity V_θ was estimated as being equal to the root mean square (RMS) velocity of the looper about its mean velocity: $V_\theta = [\overline{u'^2} + \overline{v'^2}]^{1/2}$, where $u' = u - \bar{u}$, u is the velocity in the eastward direction, $\bar{u}$ is the average velocity, u' is thus the departure from the average velocity, and $\overline{u'^2}$ is the variance, similarly, for v in the northward direction.

In addition, each of the longer trajectories was used to calculate time series consisting of radius, translation velocity, and a rotation velocity. The translation velocity was obtained by smoothing the velocity series with a low-pass Gaussian-shaped filter whose length was around 3–4 times the typical rotation period. The rotational motion and radius were obtained by subtracting the low-passed trajectory and velocity series from the original ones, which left the trajectory and velocity relative to the center of rotation. Velocity was decomposed into radial and tangential (swirl) components.

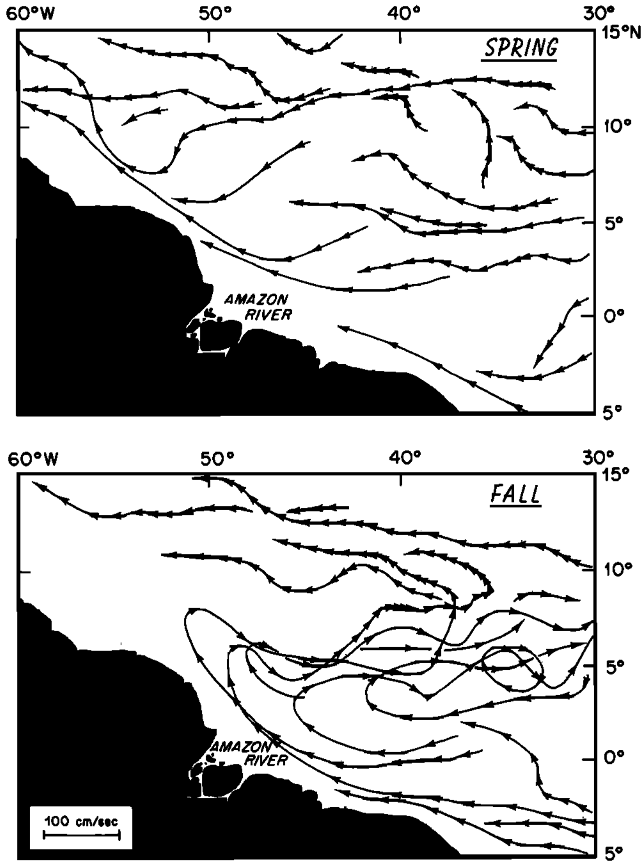

Figure 1b. Segments of surface drifter trajectories in the vicinity of the North Brazil Current retroflection during 1983–1985 [from *Richardson and Reverdin*, 1987]. Arrowheads are spaced at 5-day intervals. Some trajectories were omitted to reduce clutter. (top) Trajectories for January to June show a continuous current along the coast. (bottom) Trajectories for July–December show a complete retroflection of the North Brazil Current. CZCS images tend to confirm the presence of a complete retroflection by showing Amazon Water being carried continuously around the retroflection and into the countercurrent [*Muller-Karger et al.*, 1988].

3. Results

3.1. Case Studies

The best information about retroflection eddies comes from a surface drifter (71) and a float (28B) near 900 m (Figure 3 and Table 1). Both of these looped for long times and gave a good measure of surface and subsurface velocities in two retroflection eddies. One other float and three other drifters looped for shorter periods of time and gave supplemental information about four retroflection eddies. Three floats (22A, 28A, 63) looped in slower rotating eddies that we believe are different from but may be causally related to retroflection eddies (more about this later).

3.1.1. Drifter 71. In late October 1990 we launched surface drifter 71 into the central region of the retroflection as estimated by an earlier shipboard survey [*Wilson and Routt*, 1992]. The drifter looped anticyclonically 9 times over 4 months as it translated 1200 km northwestward up the coast (Figure 3 and Table 1). When the eddy separated from the retroflection is not known, but the second loop near 7°N is less regular than later ones, possibly as a result of the formation process. Although the last two inferred loops appear only as cusps, this part of the trajectory does loop when the translation of the eddy is subtracted. Some smaller-scale (~10 km diameter) anticyclonic loops near 9°N and 10°N with period near the local inertial period (~3 days) are superimposed on the larger loops. The larger loops are interpreted as showing the swirl velocity of the eddy. The looping stopped in February 1991 near 12°N, 59°W as the eddy approached the Caribbean Islands. This drifter trajectory is significant because it provides the best evidence to date that a whole piece of the retroflection separates as a coherent eddy which then translates northwestward along the coast.

3.1.2. Float 28. Float 28 was launched into a weak eddy near 0°N, 39°W in January 1989 and looped in it for 4 months as 28A (Figures 3 and 4 and Table 1). Float 28 was temporarily detrained from the eddy in May. In June, float 63 was apparently entrained into the same eddy. Later, in August near 7°N, float 63 was detrained from the eddy and float 28 was apparently entrained back into it, where it looped until January 1990 as 28B. We interpret the three looping trajectories to have been in a single eddy that translated northwestward along the coast from the equator to 11°N a distance of 2600 km. If this is correct, the eddy was tracked almost continuously for a year, from January 25, 1989, to January 22, 1990. These trajectories show that South Atlantic Water at depths of 600–900 m as well as above can be carried directly northward from the equator to the vicinity of the Caribbean by eddies like this one. As further evidence, water property measurements near Tobago on January 31, 1990, clearly showed the presence of Antarctic Intermediate Water at the appropriate depths (around 700 m) in a structure consistent with this eddy [*Bub*, 1993].

The loops of the first two trajectories near the equator are not very regular and the period of rotation is much longer (26–40 days) than the third trajectory (11 days). We interpret the data to show a weak, slowly rotating eddy that became much stronger as it briefly stalled near 7°N in September 1989. The increase in rotation rate and swirl speed coincided with the location of the retroflection. Thus only the third trajectory (28B) north of 7°N is considered to be in a retroflection eddy (Figure 3). The retroflection eddy is inferred to have split off from the retroflection in late September 1989 when the eddy began to translate northwestward. It drifted 1100 km northwestward during 4 months at an average velocity of around 10 cm/s. The float stopped looping near 11°N, 59°W, near the same location that drifter 71 stopped looping.

3.1.3. Additional trajectories. The next two longest looping trajectories were by float 22 in two different retroflection eddies (22B and 22C). Float 22B was near a depth of 940 m and made 7.5 loops over 53 days as it translated northwestward at 12 cm/s from 9°N, 52°W in January 1990 up to 11.5°N, 56.5°W where the eddy stopped (Figure 5). Float 22C was near 1220 m and made 6.0 loops over 80 days as it translated westward at 4 cm/s from near 10°N, 55°W in March 1992. The 1220-m estimated depth of 22C is in agreement with the general drift of float 22. After leaving eddy 22B and before entering eddy 22C, float 22 drifted gradually northward to a position near 16°N, 60°W then gradually southward, speeding up along the western boundary near 8°–9°N, 56°–59°W. This general pattern is likely due

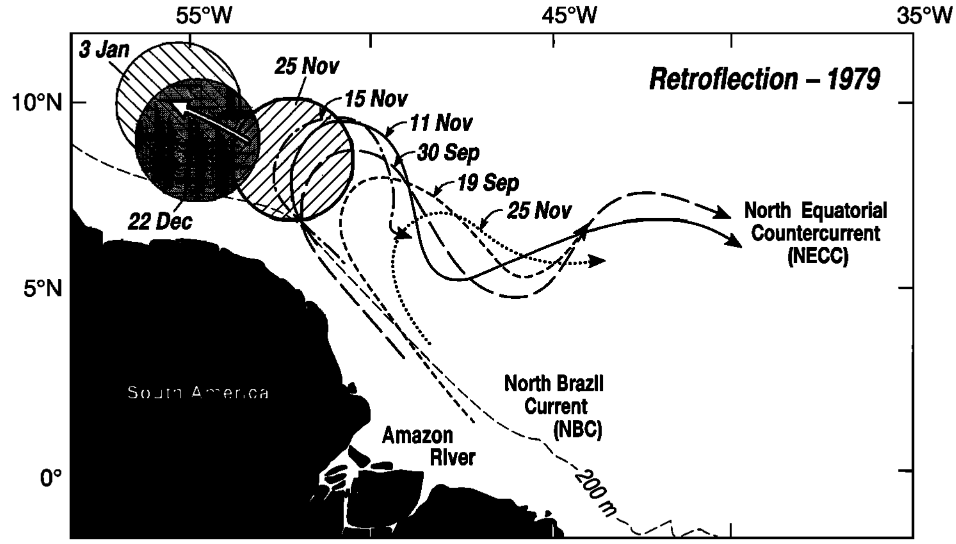

Figure 2a. The formation of a retroflection eddy as inferred from CZCS images shown by *Johns et al.* [1990]. The boundary of the North Brazil Current was detected by a color change between deep-sea water and Amazon River Water entrained into the left-hand edge of the North Brazil Current. The retroflection pinched off to produce a closed eddy by November 25, 1979, near 8°N, 52°W. The retroflection eddy appeared to translate northwestward during December and into January, after which it became difficult to see on CZCS images.

to the float gradually descending from 900 m in northward flowing Antarctic Intermediate Water into depths below 1000 m in southward flowing North Atlantic Deep Water.

All seven AMASSEDS drifters launched near the mouth of the Amazon initially drifted northwestward. Four of these were entrained into the North Brazil Current and retroflected; three others continued up the coast to 8°N–10°N, where they were entrained into two retroflection eddies. Drifter 42 looped twice in one eddy in December 1991 and January 1992, and two drifters, 45 and 57, each looped once in another eddy in March and April 1990.

One additional float in this region looped cyclonically near 9°N, 56°W in a rather weak stationary eddy, which was not a retroflection eddy and is not discussed further.

3.2. Summary of Characteristics

A summary plot of all the looping trajectories and the inferred trajectories of the eddy centers is shown in Figure 5.

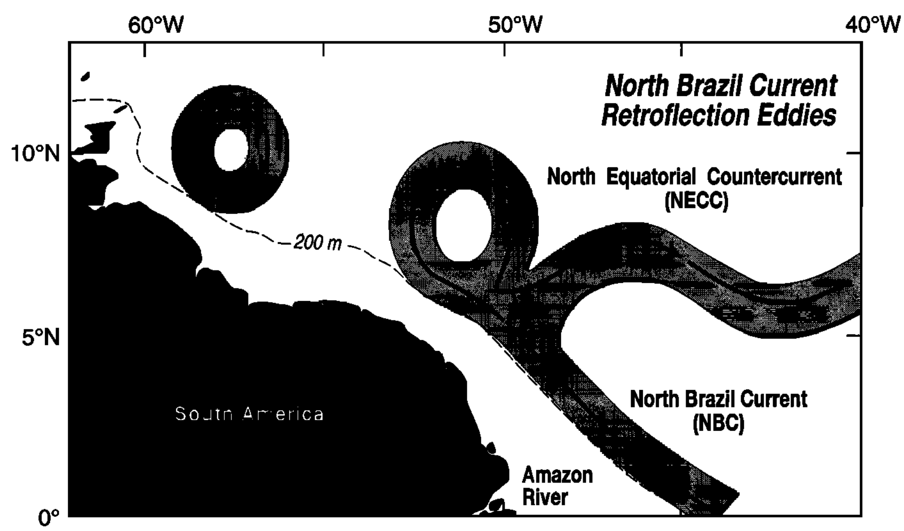

Figure 2b. Schematic diagram showing the formation of a North Brazil Current (NBC) retroflection eddy based on the CZCS images shown by *Johns et al.* [1990]. Three to four times each year starting in July the NBC retroflection advances northwestward along the boundary to about 9° to 10°N forming a current loop. The sides of the loop come together, and the current loop pinches off from the main current to form a discrete eddy. As the eddy separates, the retroflection reforms farther south near 5°–6°N. Retroflection eddies are about 400 km in overall diameter and drift northwestward at about 10 cm/s.

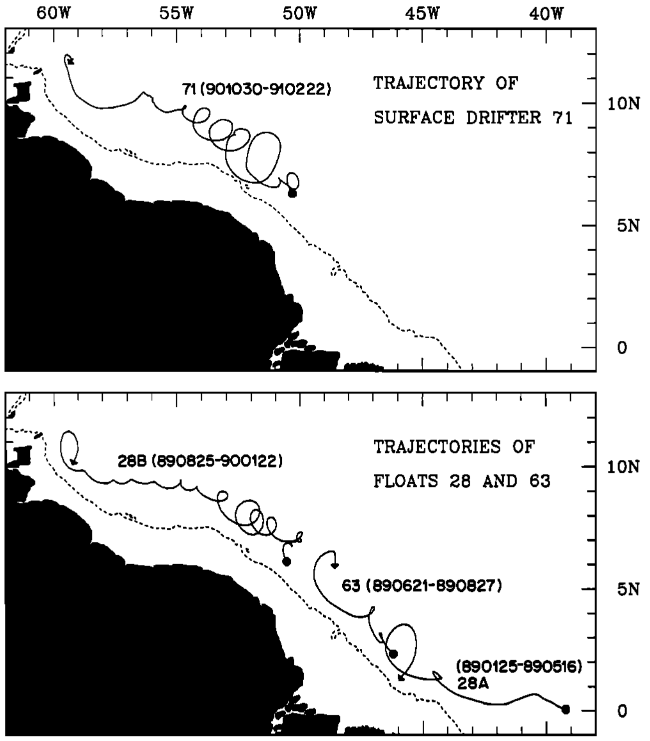

Figure 3. (top) Trajectory of surface drifter 71 from October 30, 1990, to February 22, 1991. This drifter looped roughly 9 times with a mean period of rotation of 13 days, a mean swirl velocity of 38 cm/s and a mean translation velocity of 11.6 cm/s toward 301° (Table 1). (bottom) Trajectories of SOFAR floats 28 and 63 at depths from 650 to 900 m trapped in an anticyclonic eddy as it translated northwestward along the coast of South America from the equator to 11°N a distance of 2600 km. The eddy was tracked almost continuously from January 25, 1989, to January 22, 1990 (Table 1). The northernmost trajectory, 28B, is interpreted to have been in a retroflection eddy. This float (28B) looped for 151 days with a mean period of rotation of 11 days, a mean swirl velocity of 24 cm/s, and a mean translation velocity of 8.2 cm/s toward 295°.

The trajectories give a relatively clear picture of retroflection eddies forming near 7°N, running northwestward roughly parallel to bathymetry, and ending near 12°N. In the following sections, the observations of retroflection eddies by float and drifter trajectories are augmented by information provided by CZCS images as described by *Johns et al.* [1990] and altimetry as described by *Didden and Schott* [1993].

3.2.1. **Diameter.** The loops of the longest trajectories varied considerably in diameter, from 10 km to 140 km for float 28B and from 55 km to 250 km for drifter 71 (Figure 3). The largest loops by drifters 71, 45, and 57 in two different eddies, were approximately 250 km in diameter (Figure 5). This diameter coincided with the fastest swirl speeds, ~80 cm/s, which implied that the overall size of the eddies near the surface was somewhat larger than 250 km (Figures 6 and 7). These observations are consistent with the overall diameter of 400 km estimated from CZCS images and altimetry.

The largest loops by float 28B, 140-km diameter, also coincided with the fastest swirl speed, ~35 cm/s, which suggests an overall size larger than this at 900 m. The loops of float 22B were all less than 40 km, which might mean a smaller eddy, but not necessarily so.

3.2.2. **Path.** The two longest trajectories (71 and 28B) both started in the vicinity of the retroflection near 7°N, 50°W (Figure 5). From here they seemed to follow the continental slope northwestward, running roughly 200 km offshore of the gradual S-shaped 200-m contour. The other four shorter trajectories were similar to these two, although float 22B was about 100 km farther offshore. These trajectories are also very similar to the paths of eddies inferred from altimetry.

The best CZCS images of the formation of a retroflection eddy show it to have separated from the retroflection in November 1979 [*Johns et al.*, 1990]. The images from November 23–29, 1979, reveal a nearly circular eddy centered near 8°N, 52°W northwest of the retroflection (Figure 2). This location, while based on observations more than a decade earlier, coincides with the first regular loops of drifter 71 and float 28B as they drifted northwestward. Thus the agreement between CZCS images and trajectories concerning retroflection eddies is excellent. These results suggest that the less regular loops of the trajectories southeast of this point could have been associated with incipient eddies before they had separated from the retroflection.

The last loops of three trajectories (71, 28B, 45/57) were centered near 11°N, 59°W, coinciding closely with the last positions of four eddies tracked by altimetry. One of these trajectories (57) had loops of 250-km diameter and swirl speeds of 80 cm/s near this spot, suggesting that the eddy was still large and energetic at this point. Northwest of 11°N, 59°W is a ridge between Barbados and Tobago with depths of near 1000 m. We speculate that the relative shallowness and narrowness (220 km) of the gap between Barbados and Tobago caused the disintegration of the eddies as they approached the Caribbean. The even smaller gaps between islands farther west represent a greater barrier to the translation of a discrete eddy.

3.2.3. **Translation velocity.** The mean translation velocity of all six retroflection eddies, weighted by the length of time each was tracked, is 9.2 cm/s toward 296° (Table 1). The fairly small standard deviation of mean velocity values suggests that the mean is well determined. This mean is somewhat smaller than the 15 cm/s estimated from tracking with altimetry [*Didden and Schott*, 1993] and the 11–17 cm/s from CZCS images [*Johns et al.*, 1990].

The translation velocity of two trajectories (28B, 22B) varied considerably around their mean values. Float 28B seemed to have stalled near 7°N before it gradually accelerated and translated northwestward. This could have been due to the float looping in the retroflection before the eddy separated. Between 9°N and 10°N, and during the latter part of its trajectory, this eddy accelerated to speeds of 18 cm/s. The average velocity of float 28B, after it started translating northwestward in September, was 9.6 cm/s, close to the velocity of the others. If we use the latter value, rather than the 8.2 cm/s given in Table 1, the mean translation velocity of the six retroflection eddies becomes 9.7 cm/s toward 296°.

At first float 22B translated northwestward at a relatively fast 25 cm/s. Later, however, it stopped, actually reversing course at the very end (the only one to do so). At the time of the reversal this float was 220 km northeast of looping drifters 45/57 (Figure 8). We hypothesize that the anticyclonic circulation of eddy 45/57 could have extended into the

Table 1. Characteristics of Retroflection Eddies

	Retroflection Eddies						Other Eddies		
	Float 28B	Float 22B	Drifters 45/57	Drifter 71	Drifter 42	Float 22C	Float 28A	Float 22A	Float 63
Depth, m	900	940	3.5	15	2.3	1220	800	800	650
Start date	Aug. 25, 1989	Jan. 21, 1990	March 16, 1990	Oct. 30, 1990	Dec. 17, 1991	March 2, 1992	Jan. 25, 1989	Feb. 8, 1989	June 21, 1989
Stop date	Jan. 22, 1990	March 14, 1990	April 10, 1990	Feb. 22, 1991	Jan. 14, 1992	May 22, 1992	May 16, 1989	April 23, 1989	Aug. 27, 1989
Duration, days	151	53	26	116	29	80	112	75	68
Number of loops	13.7	7.5	(2)	8.8	1.8	6	2.8	3.0	2.6
Period of rotation, days	11	7.6	13	13	16	13	40	25	26
Diameter, km	10–140	15–40	250	55–250	210	20–100	55–200	25–160	35–150
Swirl velocity V_0, cm/s	−24	−17	−84	−38	−58	19	−16	−12	−18
Translation velocity V									
Speed, cm/s	8.2	11.6	9.4	11.6	16.4	4.1	7.9	5.7	8.2
Direction, deg	295	302	306	301	286	269	281	299	326
Ro	0.29	0.36	0.20	0.24	0.20	0.22	0.41	0.16	0.25

Each trajectory listed here consists of two or more consecutive anticyclonic loops except for 45/57, which consists of two single loops made by two drifters. The letters A, B, and C designate different looping trajectories when the same float looped in more than one eddy. The set of inferred eddies was subdivided into retroflection eddies and other eddies based on the trajectories and characteristics. Retroflection eddies (ordered by start date) rotated twice as fast as the other eddies, and the loops were more regular than those of the other eddies. Depth is the drogue depth for surface drifters. For floats 22 and 28, the depth is the equilibrium depth at launch (800 m) plus a slow downward velocity estimated to be 0.37 m/d due to the creep rate of the pressure housing. Float 63 was a bobber float that each day bobbed between two depths around 200 m apart and equilibrated halfway between them. The depth given for 63 is the mean equilibrium depth during the loops. The number of loops was estimated visually and used to calculate the period of rotation. Diameter of loops was estimated visually from the trajectories. The mean swirl velocity (V_θ) was estimated as being equal to the root mean square (RMS) velocity of a float about its mean velocity. The mean translation velocity V of each eddy was estimated by calculating the mean velocity of each looping trajectory. Characteristics of 45/57 were estimated from two drifters, each of which made one loop at different but overlapping times. *Ro* is the Rossby number, estimated from the relative vorticity (2 times the rotation rate) divided by the planetary vorticity f at the mean latitude.

vicinity of eddy 22B, thus reducing its translation velocity, disrupting its circular flow, and resulting in float 22B leaving the eddy. The circulation of eddy 22B seems to have had little influence on the translation velocity of eddy 45/57, which was translating northwestward at 9 cm/s at that time. The loops in eddy 45/57 were much larger than those in eddy 22B which is consistent with eddy 45/57 being the dominant one. These data suggest that there is a range of eddy sizes and strengths and that not all eddies are 400 km in diameter.

3.2.4. Swirl speed and period of rotation. The fastest surface swirl speeds, 80 cm/s, were measured by surface drifters 57 and 71 at a radius of 125 km. The Figure 7 plot of the swirl velocity versus radius of 71 suggests that the eddy could have been in solid body rotation out to this radius. However, the scatter is so large that other functional relationships are possible. Since the mean radius of the smallest drifter loop was around 25 km, there is no information about surface velocities in the central core region. The mean period of rotation of these two trajectories (42 and 71) was 13 days; the period of the fastest loop of 71 was around 11 days.

The fastest 900 m swirl speed, 35 cm/s, was measured by float 28B near a radius of 70 km. The rotation period for the larger loops was around 13 days. However, the period of the smaller (<40 km) loops of 28B and those of 22B was around 7 days, suggesting that the eddy core was rotating twice as fast as the eddy periphery. This can be seen in the time series (Figure 6) and in large-scale plots of the trajectories (not shown). One interpretation of the 28B results is that at a depth of 900 m the eddy was not in solid body rotation out to a radius of 70 km. An alternative interpretation of 28B, but one we think less likely, is that the solid body rotation rate of the eddy increased with time, giving the impression of an increased rotation rate at smaller diameters. Without further data we cannot rule out this alternative interpretation.

3.2.5. Population statistics. The combined evidence suggests that roughly three retroflection eddies form per year during the months of July to March, with most looper observations occurring during November to March (Table 2 and Figure 9). Three eddies were observed during the winter of 1979–1980 by CZCS images, three during the winter of 1987–1988 by altimetry, and three during the winter of 1989–1990 by floats and drifters. There could have been more eddies than were observed, so the three per year is probably a lower bound. The eddies typically required three months to drift northwestward from near 8°N, 52°W to 11°N, 59°W. May is the last month of the eddy season (Table 2 and Figure 9).

The trajectories and altimetry showed that often two eddies coexisted. Pairs of eddies were observed by loopers in January 1990 separated by 850 km and in March 1990 separated by 220 km (Figure 8). The extrapolation of looper 45/57 two months back in time, to January 1990, suggests that this eddy could have coexisted with the other two eddies associated with loopers 22B and 28B. Coexisting pairs of eddies were also observed by altimetry during the months of January to April 1988.

3.2.6. Volume transport. The volume transport associated with the alongcoast translation of one eddy per year is estimated to be 0.9 Sv (10^6 m^3/s) by considering each eddy to be an inverted cone truncated at 1000 m. The eddy diameter was assumed to be 250 km at the surface and 140 km at 900 m. If we had included the extension of the cone below 1000 m, it would have reached 2045 m and the transport would have increased to 1.0 Sv; we excluded this portion because the deep western boundary current flows southward at depths below around 1000 m in this region, although the evidence from one float (22C) suggested that closed circulation in retroflection eddies can extend as deep as 1220 m. The overall diameter of the eddies was larger than the largest float and drifter loops, so the above value of transport is probably an underestimate. It also is fairly crude, since eddies probably vary in size. Our estimated transport per eddy is similar to the 0.8 Sv estimated by *Johns et al.* [1990], who assumed each eddy was 400 km in diameter and 200 m thick, and somewhat smaller than the 1.4 Sv estimated by *Didden and Schott* [1993], who assumed each eddy was 400 km in diameter and 350 m thick.

Three eddies per year would transport 2.8 Sv northward. Larger eddy transports than this would probably occur during winter when most eddies were observed and smaller transports during summer when fewer eddies were observed. These eddy transports are significant in comparison to the ~13 Sv thought to flow northward as part of the thermohaline circulation cell [*Schmitz and Richardson*, 1991; *Schmitz and McCartney*, 1993].

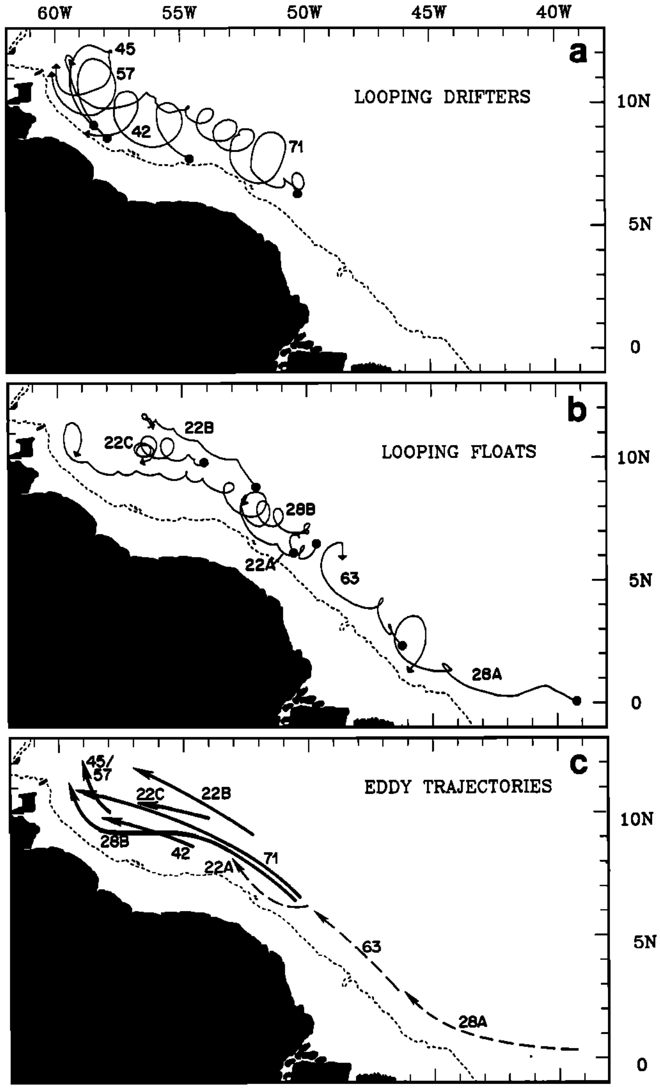

Figure 5. (a) Composite of four looping surface drifter trajectories during March 1990 to January 1992. (b) Composite of six looping float trajectories measured during the period January 1989 to May 1992. (c) Inferred trajectories of the eddy's centers. Solid lines represent retroflection eddies; dashed lines are weaker eddies thought to be different from retroflection eddies. The average translation velocity of the six retroflection eddies is 9 cm/s toward 296°. Three eddies translated up the boundary during early 1990 (28B, 22B, 47/45).

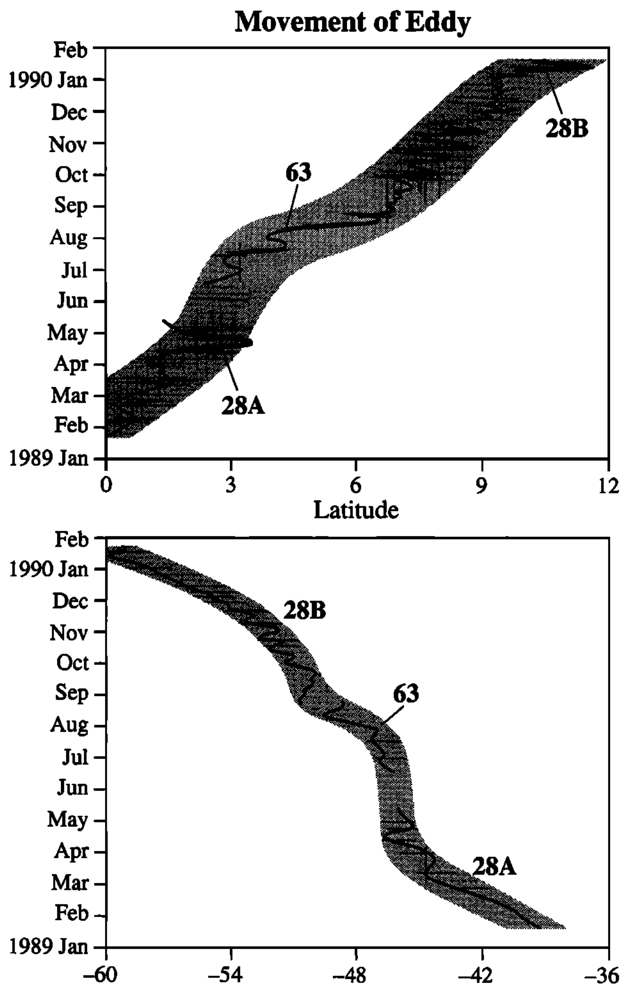

Figure 4. Plots of latitude and longitude versus time for floats 28 and 63 that were interpreted to have been in an eddy as it translated northwestward. The inferred movement of the eddy is shown by shading which represents a diameter of approximately 250 km.

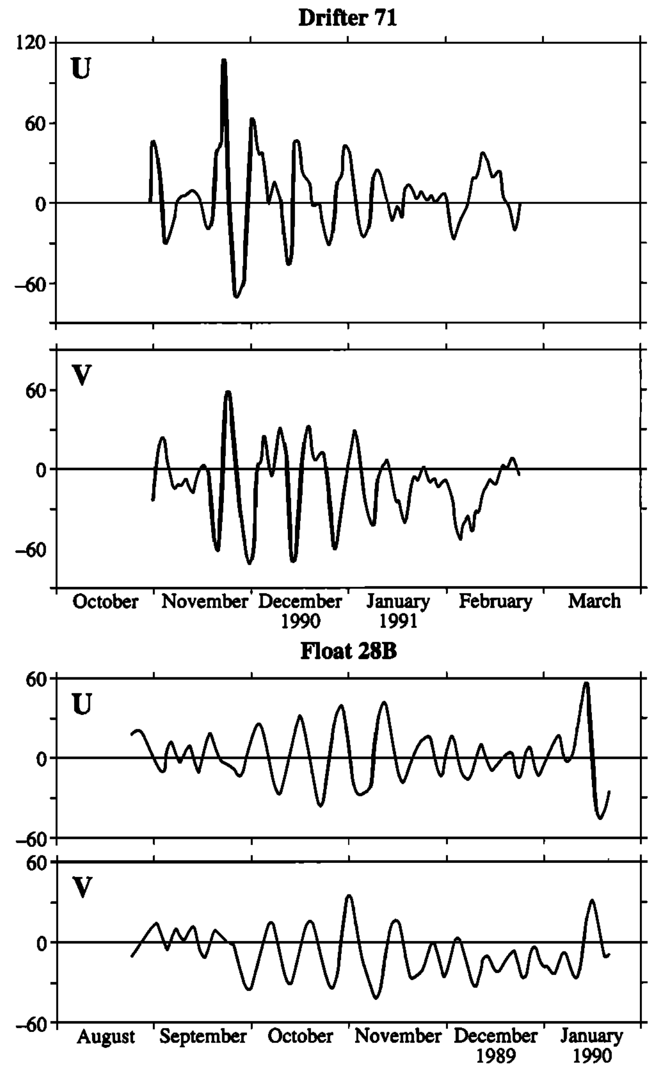

Figure 6. Velocity time series (cm/s) of drifter 71 and float 28B as they looped in two retroflection eddies. The trajectories are shown in Figure 3.

4. Discussion

4.1. Formation

Coinciding with the North Brazil Current retroflection and particularly well developed during summer and fall is a semipermanent anticyclone near 7°N–10°N known as the Demerara Eddy [*Bruce et al.*, 1985]. The warm core of this anticyclone was observed by two air dropped XBT surveys and by several expendable bathythermograph (XBT) sections running parallel to the coast [*Bruce and Kerling*, 1984; *Bruce et al.*, 1985; *Bruce*, 1987]. One of Bruce's XBT sections on September 22–29, 1980, coincided closely in time to a CZCS image on October 4, 1980 (F. E. Muller-Karger, personal communication, 1993). The XBT section shows an anticyclone near 8°N, 51°W; the image shows a retroflection eddy centered near 8°N, 52°W that looks as if it had nearly pinched off from the retroflection, much like the November 23–27, 1979, image shown by *Johns et al.* [1990]. We interpret the data to show that the Demerara anticyclone always coincides with the retroflection and that periodically pieces of the retroflection and of the Demerara anticyclone separate as retroflection eddies which translate up the coast. As a retroflection eddy pinches off in the northwest, the retroflection reforms in the south, coinciding with another anticyclone. On average, the retroflection and Demerara anticyclone are centered near 8°N. The scatter in their positions, as seen in the XBT data, is related to their periodic advances and retreats, which eventually become retroflection eddies.

What causes retroflection eddies to form is not known. One possibility concerns the translation of weak eddies up the western boundary, as tracked by floats 22A, 28A, and 63 (Figures 3–5) and a series of anticyclonic eddies with dominant periodicity of 50 days observed in the current meter velocity time series south of 7°N [*Johns et al.*, 1992] as well

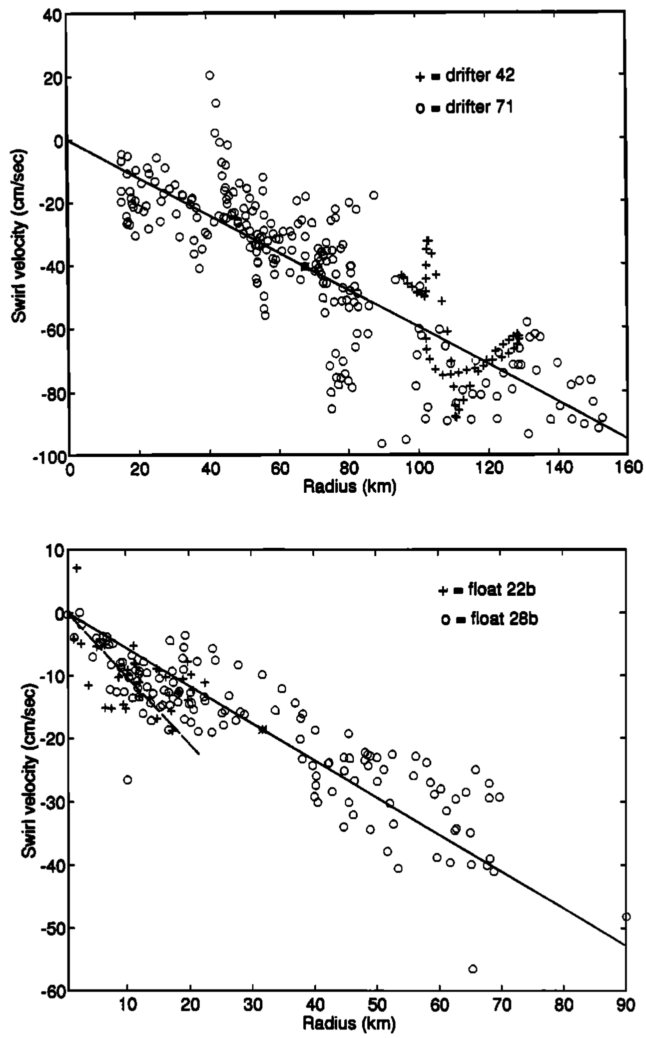

Figure 7. Swirl velocity versus radius for (top) the surface drifters and (bottom) 900-m floats in retroflection eddies. Values from different instruments are shown by different symbols. Negative values indicate anticyclonic (clockwise) rotation. The solid straight lines show the swirl speed and radius of a hypothetical eddy in solid body rotation with a period of 12 days. The dashed line shows solid body rotation with a period of 7 days. Scatter in values is due to a combination of irregularities in the translation velocity, swirl velocity, and shape of loops. Higher-frequency oscillations with a period near the local inertial period (~3 days) caused the reversals of swirl velocity and much of the scatter of surface drifter values.

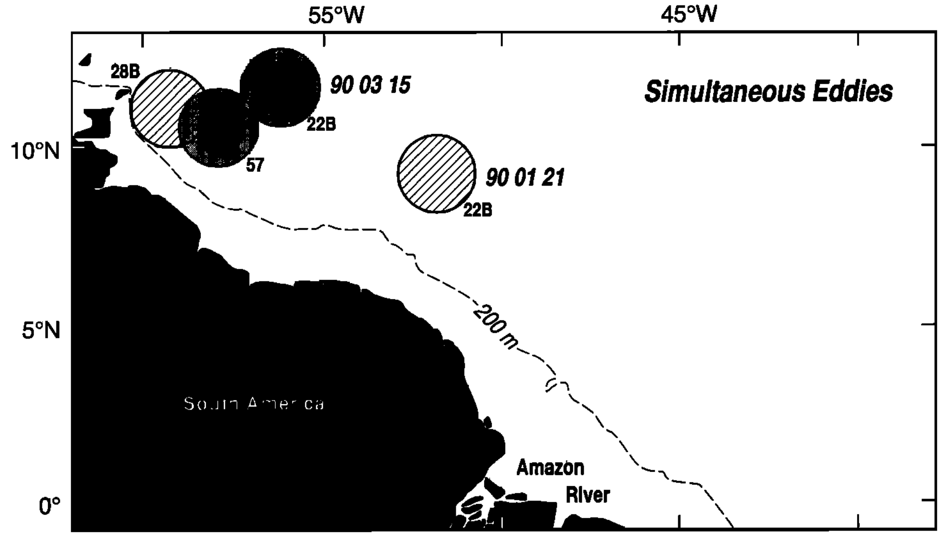

Figure 8. Pairs of retroflection eddies that coexisted; 22B and 28B in January 1990 and 22B and 45/57 in March 1990. Extrapolating the trajectory of 45/57 back in time to January 1990 indicates that the three eddies probably coexisted briefly then. Diameters of eddies in this figure are 250 km.

as north of 7°N [*Johns et al.*, 1990]. The data reveal that a train of 50-day waves and accompanying anticyclones propagates up the boundary starting near the equator. North of 7°N the maximum energy of these eddies was during fall, and the eddies were interpreted to be retroflection eddies [*Johns et al.*, 1990]. As suggested by *Johns et al.* [1990], these northward propagating eddies may somehow serve as a catalyst, causing retroflection eddies to be periodically shed near 7°N. In summary, we hypothesize that 50-day waves propagate northwestward through the region throughout the year (1) inducing the weak anticyclonic looping motion observed by floats, (2) causing the retroflection to wobble, and (3) triggering the production of retroflection eddies during August–April.

The 50-day waves and associated weak anticyclonic eddies could be generated by an instability of the cross-equatorial thermohaline flow; *Thompson et al.* [1992] observed anticyclonic eddies propagating up the western

Table 2. Retroflection Eddy Observations

Observation	Start	End
CZCS	July 1979	...
Float 28B	Oct. 1989	Jan. 1990
CZCS	Nov. 1979	...
Altimetry (A1)	Nov. 1986	Jan. 1987
Drifter 71	Nov. 1990	Jan. 1991
Altimetry (B1)	Dec. 1987	Feb. 1988
CZCS	Jan. 1980	...
Float 22B	Jan. 1990	March 1990
Altimetry (B2)	Feb. 1988	April 1988
Altimetry (C1)	Feb. 1989	April 1989
Altimetry (B3)	March 1988	May 1988

Dates are ordered by month to show seasonality. Start is the month of eddy formation near 8°N, 52°W by CZCS images or when the tracked eddies passed near this spot. End is the last month each eddy was observed (near 59°W). Dates from CZCS were given by *Johns et al.* [1990] and from altimetry by *Didden and Schott* [1993].

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. The weak eddies may also be generated in the ocean interior by instability waves resulting from the wind-driven near-equatorial currents. Instability waves with a 25-day period 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*, 1992; *Weisberg and Weingartner*, 1988]. The connection between the equatorial 25-day waves (and eddies) and the 50-day waves (and eddies) along the western boundary is not clear because of the different frequencies. Could some of the equatorial eddies merge on encountering the western boundary? A further discussion of the 50-day waves is given by *Johns et al.* [1990].

Some models of the general circulation that realistically simulate many features of the equatorial region such as the retroflection do not reproduce the formation of retroflection eddies [*Philander and Pacanowski*, 1986a; *Schott and Böning*, 1991]. In *Philander and Pacanowski*'s [1986b] model, the northward heat flux across 8°N reversed during the fall as a result of the complete retroflection of the North Brazil Current. The northward translation of observed retroflection eddies at this time suggests that the real ocean heat flux probably does not reverse. Clearly, the eddies are an important part of the northward flux of heat and water and need to be properly modelled.

4.2. Guyana Current

Surface drifter trajectories from 1983 to 1985 [*Richardson and Reverdin*, 1987] suggested that a continuous northwestward boundary current extended from the equator to the Caribbean during January to June. During July to December, however, all five of the available drifters retroflected into the countercurrent (Figure 1b). In addition, many CZCS images showed Amazon water to flow continuously around the retroflection into the countercurrent during July to December [*Muller-Karger et al.*, 1988]. Thus on one hand these

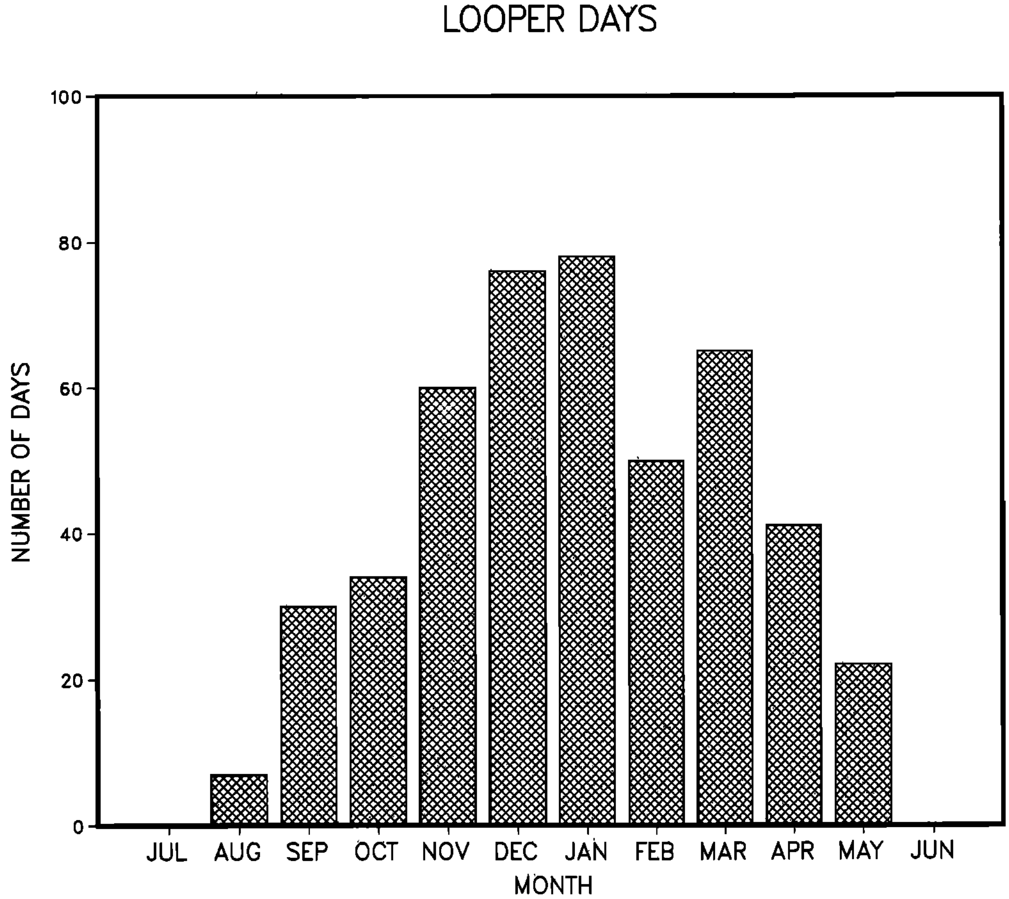

Figure 9. Histogram showing the number of days that floats and drifters looped in the six retroflection eddies. All observations were in the months of August through May, with maximum values in December and January. The looper days in August and September were included for completeness even though the eddies may not yet have separated from the retroflection, as discussed in the text.

drifters and CZCS images suggested a complete break between the along-coast North Brazil Current and along-coast Guyana Current. On the other hand and in apparent disagreement, historical ship drifts reveal a continuous northwestward boundary current throughout the year, although a portion of the current retroflects into the countercurrent during July to December (Figure 10).

A possible resolution of this disagreement is provided by retroflection eddies. When the newer drifter trajectories in retroflection eddies are added to the earlier ones (Figure 11) maps of drifter mean velocity vectors (Figure 12) look very similar to those from ship drifts. The explanation is that vector averages of many years of both ship drift and drifter measurements on the inshore side of the mean path of retroflection eddies, where the eddy swirl velocity is northwestward, show a continuous current even though the whole boundary current was observed to retroflect when eddies were not being shed. We interpret the periodic shedding of retroflection eddies and their northwestward translation along the boundary to have caused the appearance of a continuous current in the mean vectors, the Guyana Current. The Guyana Current is thus dominated by eddies, at least during July–December.

4.3. Causes of Translation

It is not known to what extent the translation velocity of retroflection eddies is due to the self-induced motion of an eddy caused by the meridional variation of the Coriolis parameter [*Flierl*, 1977; *Nof*, 1981; *Cushman-Roisin et al.*, 1990] or advection by northwestward boundary currents. Some anticyclonic eddies at similar latitudes in the eastern Pacific with characteristics rather similar to those of retroflection eddies translated westward at around 15 cm/s in the absence of any currents that could have advected them [*Hansen and Maul*, 1991]. Hansen and Maul concluded that the translational velocity was due primarily to the meridional variation of Coriolis parameter. One can imagine that the presence of a sloping western boundary like the one off South America could deflect a westward translating eddy northwestward.

A study of 103 eddies observed with SOFAR floats in the North Atlantic concluded that eddies, uninfluenced by western boundary currents, generally propagated westward at a few centimeters per second [*Richardson*, 1993]. However, when eddies were advected by flow along the western boundary or near the Gulf Stream, they were advected downstream with speeds up to 15–20 cm/s. One cold-core Gulf Stream ring tracked by a surface drifter translated up to 75 cm/s downstream when this eddy was attached to the Gulf Stream [*Richardson*, 1981]. Thus western boundary currents are capable of advecting eddies at the observed speeds of the retroflection eddies.

Evidence for northwestward surface flow along the western boundary was obtained from other drifters. A surface drifter similar in configuration to drifter 71 was launched a day before and 350 km northwest of 71 near 8°N, 53°W, a site outside the retroflection or any obvious eddies (Figure 11). Between October 1990 and February 1991, this drifter translated rather erratically northwestward at an average speed of 12 cm/s, almost exactly equal to the mean velocity of 71 over the same time interval and the velocity of the four other retroflection eddies. Several other drifters north of the retroflection and countercurrent tended to translate northwestward at around 20 cm/s, and faster speeds were measured along the western boundary during the first half of the year (Figure 11).

As discussed above, an average northwestward near-surface boundary current extends from the equator to the Caribbean. Since this current appears to be dominated by retroflection eddies at least during August–April (Figure 9), it is very difficult to clearly separate the eddy velocity component from the background velocity component. Thus the mean currents from drifters (Figure 12) and ship drifts (Figure 10) do not represent the background flow field.

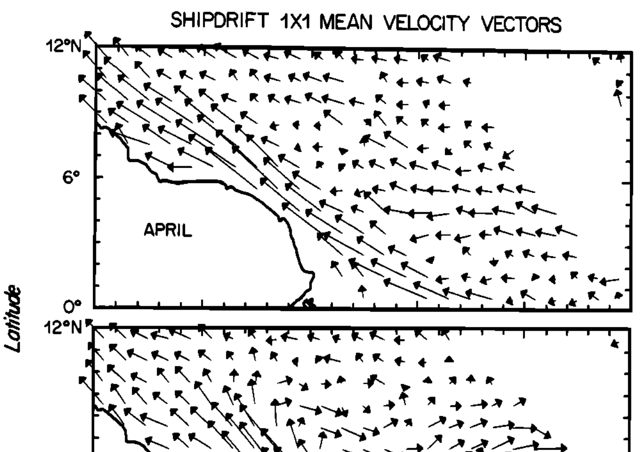

Figure 10. Map of velocity vectors from historical ship drifts off South America from the equator to 15°N [from *Richardson and McKee*, 1984]. (top) Vectors computed for August and (bottom) April (months containing the most data). Individual velocity measurements were grouped into 1° squares. Speed is given by the length of each vector. Vectors were omitted in boxes containing fewer than five observations. Ship drifts show a continuous current along the western boundary with part branching into the countercurrent during fall (bottom).

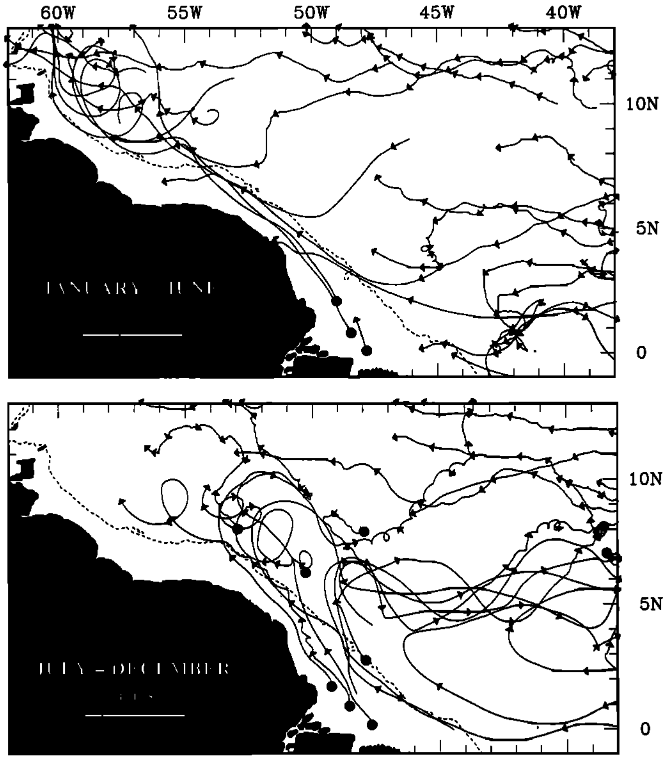

Figure 11. Composite of surface drifter trajectories including those from 1983 to 1985 [*Richardson and Reverdin*, 1987], AMASSEDS from 1989 to 1991 (R. Limeburner et al., submitted manuscript, 1993), and two new ones described in the text. Arrowheads are spaced at 10-day intervals. Large dots show launch locations. (top) Data from January to June, (bottom) from July to December.

Evidence for subsurface northwestward velocity along the western boundary exists above 1000 m, but the strong eddies and seasonal variations complicate the picture there too. *Johns et al.* [1990, p. 22,118] found from a current meter mooring 7.5°N, 53.5°W "evidence for persistent northwestward flow at 900 m over the continental slope, with an annual mean speed of 10–15 cm/s, which appears to be associated with the transport of Antarctic Intermediate Water into the North Atlantic." Since this mooring lay inshore of the mean eddy path, the mean northwestward velocity is probably strongly biased toward the northwest by the eddies, and therefore the mean velocity is probably not representative of the velocity outside the eddies. Considering the energetic fluctuations that dominate the current meter records, the notion of a general background flow outside of eddies is problematic. However, several 800-m floats not obviously trapped in discrete eddies also tended to translate northwestward along the boundary in general confirmation of the current meter records [*Richardson and Schmitz*, 1993]. We conclude that while the eddies could have been advected by background currents, it is difficult to determine what the background velocity is due to the presence of energetic eddies.

4.4. Comparison With Other Eddies

Retroflection eddies are roughly equal in size and surface swirl velocity to some of the largest and most energetic anticyclonic eddies elsewhere, Agulhas eddies in the south-

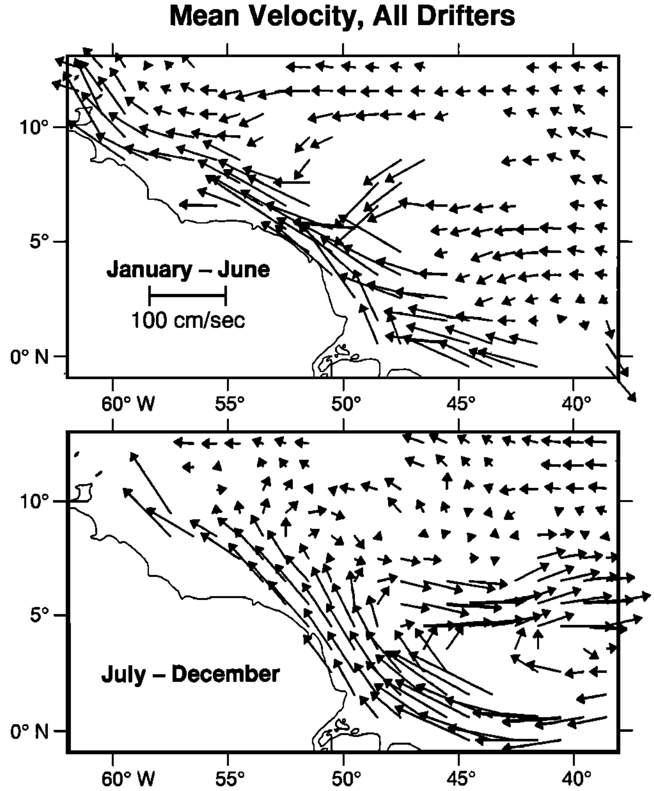

Figure 12. Maps of mean velocity vectors from the surface drifters shown in Figure 11. Individual velocity measurements were grouped into 1° squares. Speed is given by the length of each arrow. (top) Data from January to June, (bottom) from July to December. These maps agree remarkably well with those from historical ship drifts and (with Figure 11) show that when averaged in this way, retroflection eddies cause the apparent continuous northwestward current extending from the equator to the Caribbean during July–December when the North Brazil Current retroflects into the countercurrent.

eastern Atlantic [*Olson and Evans*, 1986; *Gordon and Haxby*, 1990] and Gulf Stream rings in the Gulf of Mexico [*Lewis et al.*, 1989; *Cooper et al.*, 1990]. Anticyclonic rings north of the Gulf Stream [*Brown et al.*, 1986; *Joyce*, 1991] and south of the Brazil Current [*Legeckis and Gordon*, 1982] seem to be roughly half as large as North Brazil Current retroflection eddies, although swirl speeds are comparable. All of these eddies, with the possible exception of the virtually landlocked Gulf of Mexico rings, transport water across gyre boundaries as part of the meridional fluxes of water and heat. Retroflection eddies transport water and heat from the tropics, into the subtropical gyre, across the boundary formed by the North Brazil Current retroflection and North Equatorial Countercurrent.

5. Summary and Conclusions

Looping trajectories from drifters and floats were used to infer the characteristics of retroflection eddies. To do so, we assumed that each trajectory measured a discrete eddy that originated in the North Brazil Current retroflection. Supplemental evidence from CZCS images, current meters, altimetry, and a ship survey gave credence to these assumptions. The combined data agree remarkably well in showing the pattern of movement of the eddies: their formation site near the retroflection, their paths along the boundary of South America, and their dissipation near the Caribbean.

The combined data suggest that around three retroflection eddies separated from the retroflection each year near 8°N, 52°W. Typically, two retroflection eddies coexisted during the months of January to April. During the months of July to May, the eddies translated northwestward with a mean velocity of 9–10 cm/s. Some evidence suggests that retroflection eddies could have been actively advected by background flow along the western boundary.

The largest loops of two surface drifters were 250 km in diameter, coinciding with the fastest swirl speeds, around 80 cm/s. The overall diameter of the newly formed eddies is estimated to be 400 km. The largest loops at 900 m were 140 km in diameter with swirl speeds of 35 cm/s. The estimated volume transport of three eddies per year, each 250 km in diameter at the surface, 140 km in diameter at 900 m, and extending down to 1000 m, is around 3 Sv. This is significant considering that about 13 Sv of upper layer and intermediate water are thought to flow northward across the equator as the warm water part of the thermohaline circulation cell in the Atlantic. Retroflection eddies seem to act as a short circuit, providing transport across the gap between the North Brazil Current, which retroflects near 7°N to feed the North Equatorial Countercurrent during the last half of each year, and the Caribbean Current farther up the coast.

Maps of surface velocity from historical ship drifts show a continuous current running northwestward along the boundary from the equator to the Caribbean. When the new drifter data associated with retroflection eddies are suitably averaged, the resulting picture reveals a continuous current from the equator to the Caribbean. Thus the Guyana Current seems to be dominated by retroflection eddies at least during July–December. The presence of energetic eddies explains how Amazon water can move eastward across what looks like a continuous swift northwestward boundary current on historical ship drift maps.

Although the new data have added significantly to our understanding of retroflection eddies, most of what we have learned has been pieced together from different kinds of data from different years. To more fully learn about the detailed characteristics of these eddies and their role in the large-scale circulation, several eddies should be continuously followed and extensive in situ measurements made of their physical properties.

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