Oceanus 37(1), 19-21, 1994

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Phil Richardson hefts a RAFOS float aboard R/V Knorr.

Giant Eddies of South Atlantic Water Invade the North

Disrupted Flow and Swirling Waters

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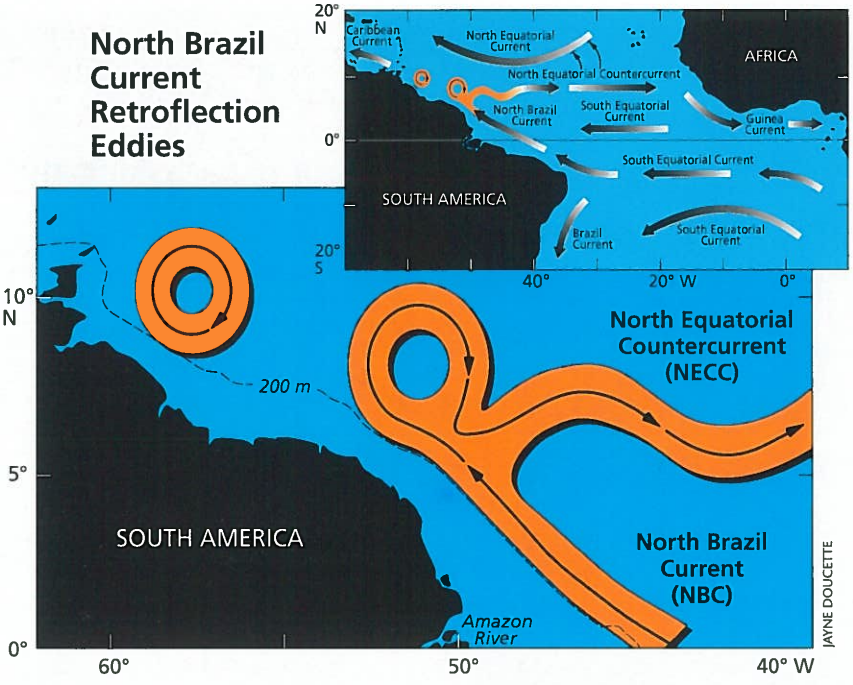
In the equatorial region of the Atlantic, the North Brazil Current follows the Brazilian coast northwestward before turning sharply to the right between 5°N and 10°N to cross the Atlantic as the North Equatorial Countercurrent. In 1990, satellite ocean color images were used to identify large, 400-kilometer-diameter, clockwise-rotating eddies that appeared to be separating from the North Brazil Current as it turned sharply to the east, much as warm-core Gulf Stream rings form from northward meanders. Because these eddies originate from retroflections or sharp changes in current direction, they are called North Brazil Current retroflection eddies. Satellite observations show them to be some of the largest eddies in the Atlantic and raise many questions about their numbers, life histories, and importance in the general circulation. Do these eddies provide a path for significant amounts of upper-layer South Atlantic water to travel up the coast? Do they transport water primarily in the near-surface layer or do they extend deeply into and below the thermocline? Do they drive recirculating flows in the underlying deep water as eddies are thought to do in the Gulf Stream system?

From 1989 to 1992 we were able to track six retroflection eddies for the first time using surface drifters and subsurface floats that were trapped in the eddies' closed circulation and looped in them for as long as five months (see lower figure on page 20). The

Retroflection eddies (orange) are water parcels that pinch off from the North Brazil Current and continue up the South American coast instead of remaining with the North Equatorial Countercurrent. Approximately three of these eddies form each year starting in July, when the North Brazil Current takes a sharp right turn, or retroflection. After an eddy pinches off near 8°N, the retroflection forms again farther south, near a latitude of 5°N to 6°N. Retroflection eddies are about 400 kilometers in overall diameter near the surface and drift northwestward at around 10 centimeters per second. They are thought to be responsible for carrying significant amounts of South Atlantic water northward into the Caribbean Current.

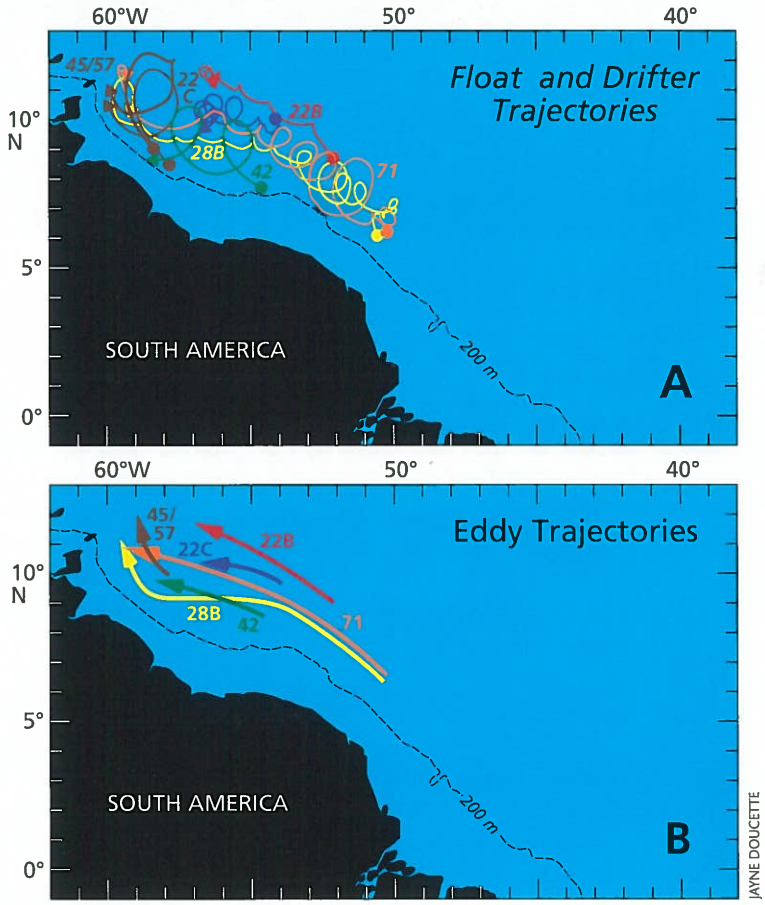


The inset schematic map shows the major tropical currents between July and September, when the North Brazil current retroflects and feeds into the eastward flowing North Equatorial Countercurrent. In contrast, from January through July the countercurrent disappears in the western tropics, westward velocities are observed in this area, and the North Brazil current continues up the coast as the Guyana Current.

looping trajectories were used to describe the number, movement, and characteristics of these eddies.

Looping surface trajectories had diameters up to 250 kilometers with swirl speeds as fast as 80 centimeters per second, dropping to diameters of 140 kilometers at 900 meters with swirl speeds of 35 centimeters per second. The deepest looper was at 1,200 meters with a maximum diameter of 100 kilometers and a swirl speed of 20 centimeters per second. The eddy shape, determined from the loop diameters, appears to be an inverted cone. The data suggest that at least three such eddies form each year from July to March. They move northwestward along the South American coast with a mean velocity of 10 centimeters per second, and seem to disintegrate when they encounter a 1,000-meter ridge between Barbados and Tobago. The water advected northward by the eddies probably then enters the Caribbean Current.

Retroflection eddies appear to carry a significant volume of South Atlantic water northward into the North Atlantic, short-circuiting the longer route around the gyre formed by the North Equatorial Countercurrent and the North Equatorial Current. Each eddy transports about a million cubic meters of water per second; three eddies per year account for as much as a quarter of the total northward transport in the upper limb of the thermohaline (temperature and salinity driven) circulation cell.

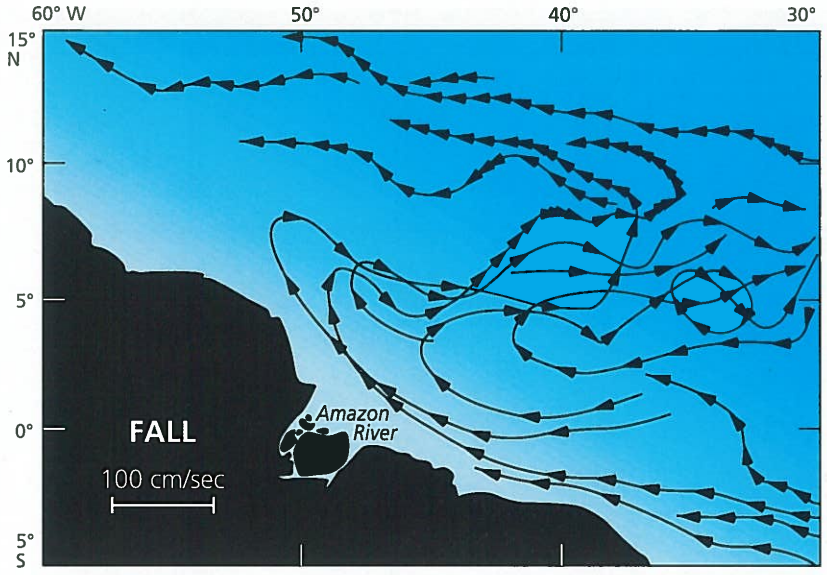


***A)** Composite of looping trajectories measured by surface drifters (42,45,57,71) and subsurface SOFAR floats (22B, 22C, 28B) in retroflection eddies from 1989 to 1992. Surface drifters' positions were recorded by orbiting satellites several times per day. Acoustic signals transmitted daily by the floats were recorded by a moored array of listening stations.*
***B)** Inferred trajectories of six retroflection eddies. Three different eddies were observed during the period August 1989 to April 1990 (28B, 22B, 45/57).*

Estimates place the total upper-layer current transport of water into the North Atlantic at about 13 million cubic meters per second. This upper-layer northward transport is balanced by the southward flow of cold North Atlantic Deep Water beneath the eddies. (See figures on pages 6 and 7.)

The discovery of numerous eddies translating up the coast helps explain a discrepancy between two earlier data sets, from drifting buoys and historical ship drifts, that show continuous flow up the coast to the Caribbean from January through June. From July through December, however, all available surface drifters (during 1983 to 1985) in the North Brazil Current retroflected into the countercurrent (see figure above). In these same months, ocean-color images also showed Amazon Water flowing around the retroflection into the countercurrent, implying a complete surface disruption of flow up the coast. These drifters and images contradict historical ship drifts, which show a continuous northwestward current there during July through December, with a branch feeding into the countercurrent. An explanation for this discrepancy involves retroflection eddies. The continuous current seen in ship-drift maps is probably an artifact of averaging many years of velocity measurements on the inshore side of the mean path of eddies, where eddy swirl velocity is northwestward. This is demonstrated by a map of surface-drifter velocity, including newer trajectories in retroflection eddies (see figure to right), that agrees with the earlier ship-drift data. The Guyana Current, if it exists during the months of July through December, is not a smoothly flowing current but instead consists primarily of a train of retroflection eddies.

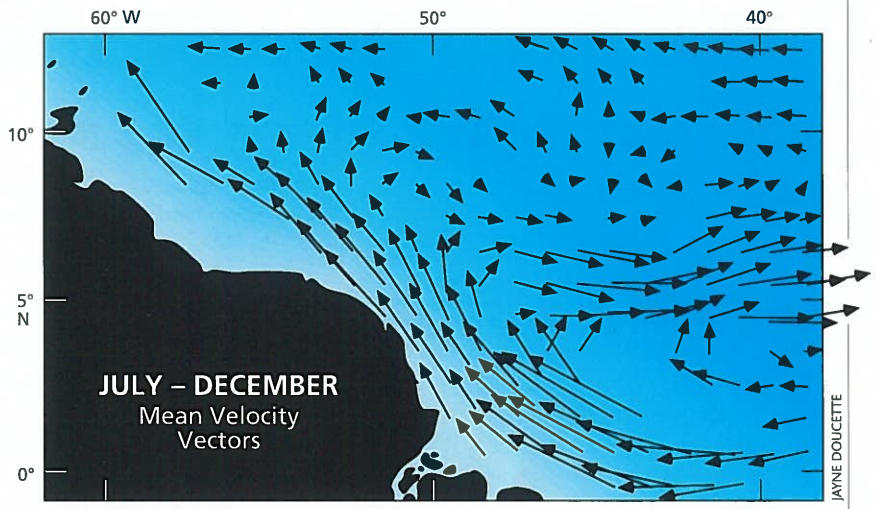
It may seem surprising that we are just beginning to understand a major current system like this. Our ignorance has been caused partially by a lack of good in situ data sets and partially by the intermittent character of these powerful eddies and their rapid movement. Our knowledge about many subsurface currents is even more rudimentary, which suggests that we will find many more surprises in our ocean-circulation studies.



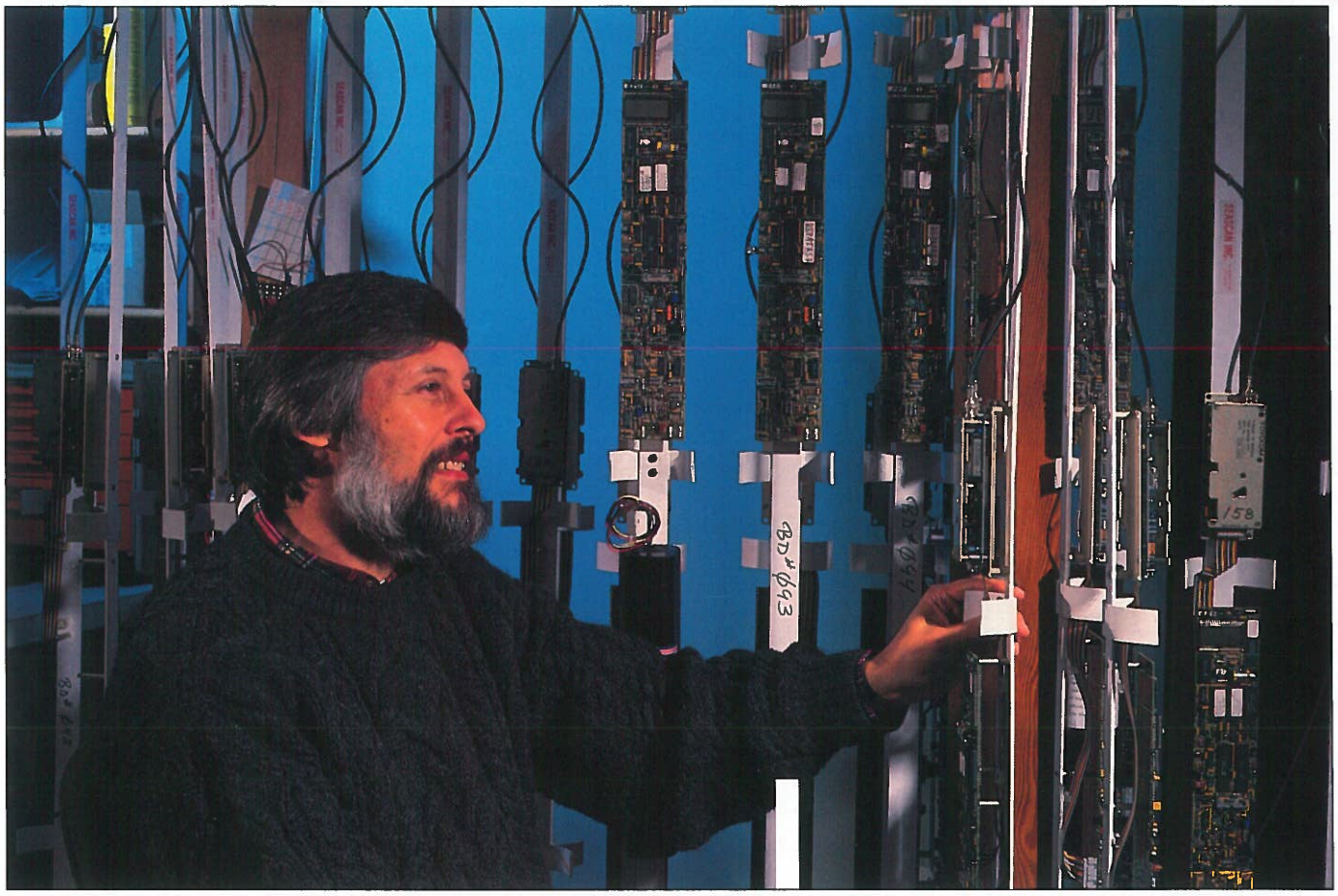
Surface-drifting buoy trajectories in the North Brazil Current retroflection during 1983 to 1985. All five available drifters retroflected during the months of July to December, implying that there was a complete break in the northwestward flow.

Funding for the work described was provided by the National Science Foundation. Recent scientific journal articles on the subject of this article include "Tracking Ocean Eddies" (Philip L. Richardson, American Scientist, *May-June 1993, pages 261-271) and "North Brazil Current Eddies" (P.L. Richardson, G.E. Hufford, R. Limeburner, and W.S. Brown,* Journal of Geophysical Research, *1994, Vol. 99, pages 5081-5093).*

Phil Richardson grew up on a cattle ranch in California where he spent long hours chasing cows. He ran away to sea and eventually earned a Ph.D. in oceanography from the University of Rhode Island. His early experience on the ranch has proven valuable in his recent efforts to follow floats and drifters in the oceans.



Mean velocity vectors calculated by grouping all available surface-drifter velocity measurements from 1983 to 1993 into 1°-by-1° bins. The newer data, which are similar to historical ship drifts, include trajectories in several retroflection eddies and show that on average the North Brazil Current runs continuously up the coast into the Guyana Current, with some flow peeling off and feeding into the countercurrent. The mean northwestward current is partly an artifact of averaging the clockwise rotating swirl velocity of several eddies as they drifted northwestward along the coast.



TOM KLEINDINST

Nelson Hogg with RAFOS floats that are being serviced in the laboratory.

The Deep Basin Experiment

How Does The Water Flow in the Deep South Atlantic?

Nelson Hogg
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Fresh from his success at explaining why currents like the Gulf Stream are found along the western boundaries of all ocean basins, Henry Stommel proposed almost 40 years ago that there were similar features in the abyss. According to his scheme, these would be fed by water made dense in the polar regions during winter. This convective circulation would be completed by a slow bleed of water from the deep boundary currents into the ocean interior, and a broad rising through the ocean thermocline (a region of rapid decrease in temperature with depth) into the upper ocean where it would then be carried poleward (in, for example, the Gulf Stream) to complete the circuit.

Almost immediately, using conventional hydrography and a novel neutrally buoyant float that John Swallow (UK Institute of Ocean Sciences) had recently invented, Val Worthington (WHOI) and Swallow discovered the "Deep Western Boundary Current" part of the scheme on the Continental Rise south of Cape Cod. Then, with help from Stommel and others and using these same floats, Swallow set out to confirm the existence of the slow interior circulation that was an integral part of the scheme. Instead, they found that the deep ocean, away from the boundary, was dominated by a vigorous eddy field, much like the weather systems that dominate our day-to-day existence on land. With the ship-based technology then available, there was no hope of being