Velocity structure of North Brazil Current rings

W. Douglas Wilson,[1] William E. Johns,[2] and Silvia L. Garzoli[1]

Received 1 August 2001; accepted 8 November 2001; published 30 April 2002.

[1] High-resolution shipboard surveys of four North Brazil Current rings are presented, which are the first such dedicated surveys to be made of these features. Of the four rings surveyed, three fundamentally different types of ring structures are found: (1) a shallow, surface-trapped structure with velocities confined to the top 200 m (two rings), (2) a deep-reaching structure with significant swirl velocities (~0.2 m/s) extending to 2000 m (one ring), and (3) a thermocline-intensified structure with almost no detectable surface signature (one ring). The results of this study indicate that North Brazil Current rings can have highly variable vertical structures, and that assessing their overall role in cross gyre exchange in the tropical Atlantic will require a careful combination of remote sensing and in-situ observations. *INDEX TERMS:* 4520 Oceanography: Physical: Eddies and mesoscale processes; 4532 Oceanography: Physical: General circulation; 4231 Oceanography: General: Equatorial oceanography

1. Introduction

[2] The North Brazil Current is a major western boundary current in the Atlantic Ocean that transports upper ocean waters northward across the equator. It plays an important role in the wind driven circulation of the tropical Atlantic, and provides a conduit for cross-equatorial transport of South Atlantic upper ocean waters as part of the Atlantic meridional overturning cell (MOC). The transport of the NBC reaches a maximum in boreal summer and a minimum in spring *Johns et al.* [1998]. During the summer and fall months the NBC retroflects sharply from the coast near 6° or 7°N to feed into the North Equatorial Countercurrent (NECC). During this retroflection phase the NBC occasionally curves back upon itself so far as to pinch off large anticyclonic current rings. These features then move northwestward toward the Caribbean Sea, roughly paralleling the South American coastline. NBC ring shedding may account for as much as one-third of the net warm water transport across the equatorial-tropical gyre boundary into the North Atlantic in compensation for the southward export of North Atlantic Deep Water, *Johns et al.* [1990], *Didden and Schott* [1993], *Richardson et al.* [1994], *Fratantoni et al.* [1995], *Goni and Johns* [2001].

[3] The precise mechanisms that contribute to NBC ring formation, and the structure and dynamics of the rings themselves, are not well understood. A lack of direct measurements, most notably of the vertical structure of the rings, has hindered attempts to quantify their overall importance in the Atlantic MOC. One of the main objectives of a recent observational program (the North Brazil Current Rings Experiment, NBCRE) was to carry out purposeful sampling within several rings to better determine their three-dimensional structures. Using guidance from near-real-time altimeter analyses, the NBCRE conducted detailed shipboard surveys and float deployments in several North Brazil Current rings. This paper describes the velocity structure observed in four different NBC rings that were surveyed between November 1998 and June 2000.

2. Data

[4] Data analyzed in this paper were collected during three cruises on the *R/V Seward Johnson* in December 1998, February 1999, and June 2000. Rapid underway surveys of the NBC rings were performed using a hull-mounted 150 kHz narrowband shipboard Acoustic Doppler Current Profiler (SADCP), and expendable bathythermographs (XBTs). Once the ring center and approximate radial dimensions were determined, one or more cross-sections were made across the diameter of the ring using a SeaBird 911+ CTD and 300 kHz lowered ADCP (LADCP). Station spacing on these transects averaged 20 nm. Figure 1, top panels, show maps of the SADCP current vectors for each of the four rings that were surveyed; the bottom panels show the velocity sections across each ring derived from the LADCP data. Main isotherms from the CTD profiles concurrent with the LADCP'S are superimposed on the velocity maps.

[5] The SADCP data shown are one-minute ensemble currents, corrected for ship speed and heading using P-code GPS positions and Ashtech 3DF attitude measurements, and binned in 10 km segments along the trackline. The velocity sections are contoured from the LADCP profiles below 25 m, averaged into 10 m vertical bins, merged with the hull-mounted SADCP data above 25 m. Velocities at each station along the ring transects were rotated into parallel and perpendicular components; the component perpendicular to the ring transect is shown.

3. Results

3.1. Ring 1

[6] Ring 1 is clearly seen in (Figure 1a), centered near 9°N, 56°W. This ring has an unusual (and previously unobserved) vertical structure; its velocity core is located just below the thermocline, at about 150 m, and the magnitude of the ring swirl velocity decreases both upward and downward from that level. The resulting compensation in the upper ocean thermal field leads to a very small dynamic height signal measured by satellite altimetry (not shown). In fact, this ring was not identified in our initial near-real-time altimeter analysis. Thus it is difficult to tell exactly when this ring was formed. Significant swirl velocities extend to 500 m depth, and the base of the ring structure appears to penetrate to about 700 m. The ring shows an asymmetry typical of most of the rings observed, in which the tangential velocities are greater on the southern side of the ring. This effect, analogous to the well-known wind intensification in the northeast quadrant of tropical cyclones, occurs because the forward (westward) motion of the ring adds to the clockwise swirl velocity on the southern side of the ring. At 150 m, the difference between the southern and northern velocities is 30 cm, (Figure 1d) a value consisted with the translation velocity (15 cm/sec). In the case of Ring 1 this is evidenced as an intensification of the westward flow along on the southern leg of the transect. The characteristic core velocity maximum of the ring is 0.8 m/s, and the ring is of average size with an edge diameter of about 370 km (defined as the location where the swirl velocity

[1]NOAA/Atlantic Oceanographic and Meteorological Laboratory, Miami, Florida, USA.
[2]University of Miami, RSMAS, Miami, Florida, USA.

Copyright 2002 by the American Geophysical Union.
0094-8276/02/2001GL013869$05.00

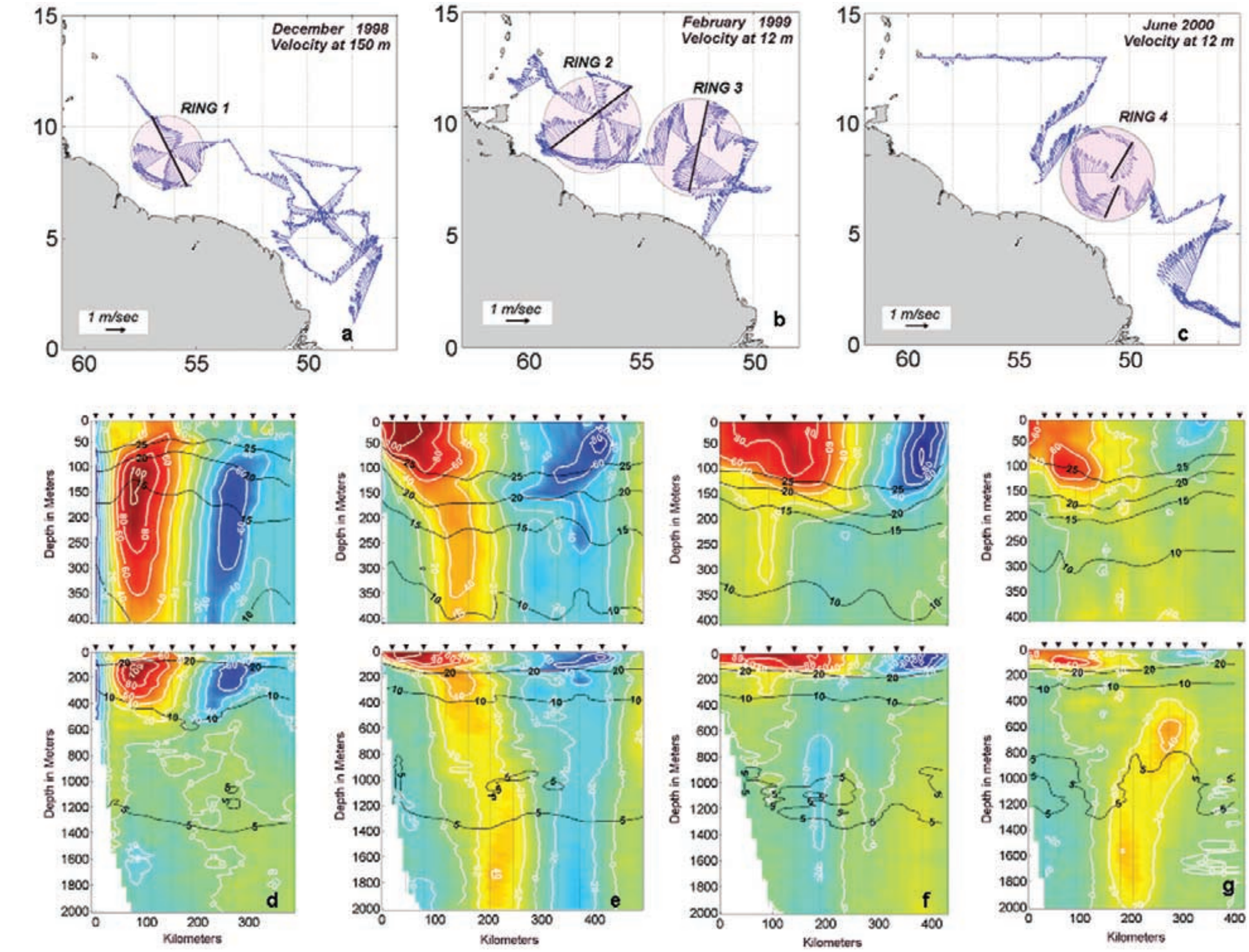

Figure 1. (a–c) Velocity vectors along cruise track at 150 meters (a) and 12 meters (b–c) derived from 150 kHz hull-mounted ADCP on the R/V Seward Johnson during cruises in December 1998 (a), February 1999 (b), and June 2000 (c). Approximate location of rings 1–4 as described in the text are shown by shaded circles. The location of CTD/LADCP sections (d–g) are shown by dark lines. (d–g) Velocity and Temperature sections associated with Rings 1–4. Velocity component is perpendicular to mean sections shown in (a–c), in cm/s. Stations shown by triangles, distance in kilometers from the southern end of the section. Velocities are based on LADCP data below 30 m and Shipboard ADCP from 8–30 m. Velocity contour level is 20 cm/s, Temperature contour level is 5°C.

drops below 0.1 m/s), and a radius of maximum velocity of approximately 110 km.

3.2. Rings 2 and 3

[7] Ring 2, centered near 10°N, 57°W, (Figure 1b) was surveyed in February 1999. Velocities at the surface are between 0.8 to 1.0 m/s, and the velocity field above 200 m is very similar to that of Ring 3 (Figure 1b) to the southeast. Rings 2 and 3 were formed within about a month of each other, on approximately Dec 24, 1998 and February 10, 1999 respectively, as estimated from the analysis of the IES array deployed as part of the NBCRE (Garzoli, personal communication). Thus Ring 2 was about 4 weeks old when surveyed and Ring 3 was only about 1 week old. The average formation rate of NBC rings is once every 2 months *Goni and Johns* [2001], and the smaller interval between the formations of these two rings appears to be linked to an unusually far northward extension of the retroflection, to near 10°N, before the pinch-off of Ring 2 occurred. Both Rings 2 and 3 are large rings, with edge diameters of 500 km, and radii of maximum velocity of 150 km. The northwestward surface flow in Ring 2 is intensified near the coast for the same reasons as noted above, and possibly also due to interaction between the upper ocean ring velocity field and northwestward coastal currents. Ring 3 also shows a larger cumulative flow on its shoreward side and appears broader on this side than the return flow on the offshore side of the ring (though the offshore edge was not fully resolved by the survey). The unique feature of Ring 2 is its deep velocity structure; at depths close to 1600 m velocities of up to 0.4 m/ sec are still observed; at 2000 m they are larger than 0.2 m/s. The axis of the ring appears to tilt slightly offshore with depth. One explanation for this vertical misalignment could be a shift of the deeper velocity field towards the interior due to the deep southward boundary current e.g., *Fine and Molinari* [1988], seen here with maximum values of 0.2 m/s at 1200 m. Each of the first two ring cross-sections shows a similar southward deep flow near 1200 m near the western boundary. Ring 3 does not exhibit the same deep velocity structure as Ring 2, and appears to be confined mainly above 200 m. The deep velocity field below Ring 3 has a banded structure that is not clearly related to the ring in any way or to the presence of a southward boundary current. Both Rings 2 and 3 actually show a mild subsurface intensification on their offshore sides, with maxima between depths of 50–100 m, though nowhere near as pronounced as in Ring 1.

3.3. Ring 4

[8] Ring 4 (Figure 1c) was observed almost at the same location as Ring 3 during June 2000. It is similar to Ring 3 in

that it is surface trapped above 200 m and has about the same diameter and radius of maximum velocity (500 and 150 km, respectively), but it is considerably weaker, with maximum surface velocities just over 0.6 m/s. This ring was formed on May 20, 2000. The weaker overall structure of Ring 4 may be due to seasonal variation in the transport and vertical penetration of the NBC, which reaches its minimum strength in April to May. A strong deep northwestward flow exists below the ring, offshore of the deep southward boundary current, which is not obviously correlated with the ring velocity field. During this survey it appears that a considerable amount of flow from the NBC is passing shoreward of the ring and turning offshore near 10N, rather than retroflecting south of the ring at about 5N. No evidence of this NBC flow returning to the southeast is found in the survey, suggesting that it may have deflected back toward the coast and continued northwestward toward the Caribbean Sea. The structure of this ring may therefore be somewhat obscured by interaction with the NBC.

4. Discussion and Summary

[9] The observations described above indicate that the rings shed by the NBC retroflection can have dramatically different vertical structures and characteristics. Out of a total of four rings surveyed, two were strongly surface-trapped, with their identifiable velocity structure confined above 200 m. Another ring presented almost no surface expression, with its velocity core located just below the thermocline near 150 m. Finally, one ring presented a strong barotropic structure with 2000 m velocities larger than 0.2 m/s. All of the rings showed a relatively weak thermocline depression of only about 50–75 m at their center, except for Ring 1, which had the reversed sense of displacement (a doming of the upper thermocline) due to its subsurface-intensified nature, and a larger compensating depression of the deeper isopycnals ($\sim$10°C) of nearly 200 m.

[10] Previous observations have suggested that NBC rings can have variable vertical structures and sizes. Studies using altimetric data *Didden and Schott* [1993], *Goni and Johns* [2001] found that NBC rings could have a radius of maximum velocity anywhere between 70 to 150 km, with on average value of 100–120 km. Early studies of NBC rings *Johns et al.* [1990] assumed that these rings were all shallow features with a vertical scale on the order of 200 m. *Richardson et al.* [1994] analysis of surface drifters and subsurface floats in several NBC rings showed substantial swirl velocities of $\sim$0.2 m/s at 900 m depth, which was the first clear evidence that NBC rings can penetrate through the thermocline to depths of 1000 m or greater. At the surface, they found maximum swirl velocities ranging from 0.4 to 0.8 m/s. *Fratantoni et al.* [1995] study combining current meter data with the *Didden and Schott* [1993] altimetry analysis suggested that at least two different classes of NBC rings are formed, ones with relatively large size (radius of maximum velocity $\geq$100 km) and deep-reaching velocity structure (>0.1 m/s at 1000 m), and a class of smaller (radius of maximum velocity 70–100 km), shallower ($\leq$250 m) rings. However, ours is the first study to show clearly that rings of the thermocline-intensified variety (e.g., Ring 1) exist.

[11] The results of these surveys raise several important new questions about NBC rings. First, how prevalent are the thermocline-intensified rings, and how are they formed? For example, are they a product of a fundamentally different process than most NBC rings (i.e., do they pinch off from the Equatorial Undercurrent retroflection at a latitude closer to the equator than the NBC retroflection)? Second, how does the deep barotropic structure present in some of the rings develop? And third, is there any kind of seasonal pattern in the types of rings that are formed, perhaps related to the seasonal cycle of the NBC and the related retroflection dynamics? If such a patterns exists, it is not yet clear from the available studies. Finally, the variable structure associated with these rings means that determining their overall role in the MOC will be a challenging problem. This preliminary analysis suggests that NBC ring formation is a complex process, and a much more detailed synthesis of all experimental data collected during the NBCRE (ship surveys, altimetry, moored observations, Lagrangian measurements, and models) will be required to fully understand it.

[12] **Acknowledgments.** The authors thank the crew of the R/V Seward Johnson for their able assistance and cooperation. Ryan Smith processed the LADCP data. Roberta Lusic prepared the manuscript for publication. This research was supported by NOAA/AOML and by NSF Grants OCE 97-30322 and OCE 97-32389.

References

Bourles, B., R. L. Molinari, E. Johns, and W. D. Wilson, Upper layer currents in the western tropical North Atlantic (1989–1991), *J. Geophys. Res.*, *104*(C1), 1361–1375, 1999.
Didden, N., and F. Schott, Eddies in the North Brazil Current Retroflection Region Observed by Geosat Altimetry, *J. Geophys. Res.*, *98*, 20,121–20,131, 1993.
Fine, R. A., and R. L. Molinari, A continuous deep western boundary current between Abaco (26.5°N) and Barbados (13°N), *Deep-Sea Res.*, *35*(9), 1441–1450, 1988.
Fratantoni, D. M., W. E. Johns, and T. L. Townsend, Rings of the North Brazil Current: Their structure and behavior inferred from observations and a numerical simulation, *J. Geophys. Res.*, *100*(C6), 10,633–10,654, 1995.
Goni, G., and W. E. Johns, A Census of North Brazil Current Rings Observed from TOPEX/POSEIDON Altimetry: 1992–1998, *Geophys. Res. Let.*, *28*(1), 1–4, 2001.
Johns, W. E., T. N. Lee, R. Beardsley, J. Candela, and B. Castro, Annual Cycle and Variability of the North Brazil Current, *J. Phys. Oceanogr.*, *28*(1), 103–128, 1998.
Johns, W. E., T. N. Lee, F. A. Schott, R. J. Zantopp, and R. H. Evans, The North Brazil Current Retroflection: Seasonal Structure and Eddy Variability, *J. Geophys. Res.*, *95*(C12), 22,103–22,120, 1990.
Richardson, P. L., G. E. Hufford, R. Limeburner, and W. S. Brown, North Brazil Current retroflection eddies, *J. Geophys. Res.*, *99*(C3), 5081–5093, 1994.
Wilson, W. D., E. Johns, and R. L. Molinari, Upper layer circulation in the western tropical North Atlantic Ocean during August 1989, *J. Geophys. Res.*, *99*(C11), 22,513–22,523, 1994.

W. Douglas Wilson and S. L. Garzoli, NOAA/AOML, 4301 Rickenbacker Causeway, Miami, Florida 33149, USA. (Doug.Wilson@noaa.gov; Silvia.Garzoli@noaa.gov)
W. E. Johns, University of Miami, RSMAS, 4600 Rickenbacker Causeway, Miami, Florida 33149, USA. (wjohns@rsmas.miami.edu)