Interhemispheric Water Exchange in the Atlantic Ocean
edited by G.J. Goni and P. Malanotte-Rizzoli

North Brazil Current rings and the variability in the latitude of retroflection

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An array of 14 inverted echo sounders (IES) were deployed as part of the North Brazil Current Rings (NBCR) experiment, to study the dynamics of the ocean in the region. Synoptic maps of dynamic height were produced from the data collected with the IES. After validating these maps with hydrographic data collected during the four NBCR cruises, they were analyzed to determine the variability of the latitude of retroflection of the North Brazil Current (NBC) and the number of rings shed during this process. Results from this analysis indicate that there is no obvious seasonality in the variability of the latitude of penetration of the NBC and, with the exception of one event, each time that the NBC reaches its northward position a ring is shed at the retroflection. A total of 11 rings were shed during the period of the observations November 1998 to June 2000. The mean diameter of the rings was estimated to be approximately 390 km, and the mean speed of propagation 12.4 km/day. The rings transported an average of 8Sv (1Sv = 10^6 m^3s^{-1}) of water and 0.54 PW of heat per year. These estimates are much larger than previous results, both in the number of rings shed per year and in the contribution of the rings to the inter-hemispheric exchange of mass and heat.

1. INTRODUCTION

In the Atlantic Ocean, the cold, deep, southward export of 15 ± 2 Sv net production of far northern hemisphere waters must be balanced by a

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compensating warm, shallow, northward flow of southern hemisphere waters (Ganachaud and Wunsch, 2000; 1 Sv = 1 x 10^6 m^3s^{-1}) as part of the global meridional overturning circulation (MOC). In the equatorial region, the North Brazil Current (NBC) is thought to be the only substantial pathway that can complete the upper limb of the interhemispheric loop by moving warm, shallow waters of South Atlantic origin across the equatorial region to the North Atlantic. From its origin near the easternmost protrusion of the South American continent (5°S, 35°W), the NBC flows northwest off the Brazilian coast continually increasing its transport with input of South Equatorial Current (SEC) waters while becoming more surface intensified (Stramma and Schott, 1996). After crossing the equator, a component of the NBC retroflects eastward into the Equatorial Undercurrent (EUC), and then recirculates within the equatorial region. The remainder of the NBC continues northwestward until approximately 7°N, 48°W. At this point, there is both a direct and an indirect NBC route to the north Atlantic: 1) directly, by flowing northwestward along the coast to the Caribbean; or 2) indirectly, with substantial potential for recirculation, by flowing eastward with the North Equatorial Countercurrent (NECC), then westward with the North Equatorial Current (NEC), and then finally entering the Caribbean at a more northern latitude than the direct route (Stramma and Schott, 1996; Stramma and Schott, 1999).

Historically the direct route of the NBC to the North Atlantic was named the Guyana Current. This current was interpreted as an extension of the SEC and defined as a broad northwestward flow from the vicinity of the Amazon River mouth to the Caribbean (Metcalf, 1968). However, with more varied types of measurements, as well as higher spatial and temporal resolution of these observations, the fundamental description of the NBC flow has been greatly modified and enhanced. Guided by the more recent observations, the "Guyana Current" has generally been reclassified as a series of anticyclonic rings translating westward after detaching from the eastward retroflecting NBC as it joins the NECC. Theory supports the presence of these rings, as it is shown that the momentum flux of the approaching and retroflecting NBC can only be balanced by anticyclonic rings forming, shedding, and drifting to the west (Nof, 1996; Nof and Pichevin, 1996). In previous studies (i.e. Didden and Schott, 1993, Richardson *et al.*, 1994, Fratantoni *et al* 1995) the presence of these rings has been documented. Recently, Goni and Johns (2001) detected the presence of 5.3 rings per year accounting for approximately 1Sv each, or ~5.3 Sv/year from altimeter derived sea height anomaly data. Fratantoni and Glickson (2001) observed 6 rings per year (~6 Sv/year) from ocean color derived chlorophyll gradients which are correlated with sudden and large southeastward retractions of the NBC retroflection. Nonetheless, observations still suggest the existence of a component of the NBC flow to the Caribbean by way of a more-or-less steady coastal current. In order to study the precise mechanisms which contribute to NBC ring formation, the structure and dynamics of the rings themselves, and the role that they play in the inter-ocean exchange of heat and salt, a multi-institutional program, the North Brazil Current Rings Experiment (NBCR), was

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conducted Fratantoni *et al.*, 1999). The extensive NBCR field program started in November 1998 and ended in June 2000.

In what follows, a subset of the data collected during the NBCR Experiment is analyzed to quantify the contribution of the rings to the transfer of southern hemisphere waters to the northern hemisphere. These time series are unique, in that they are the only in situ measurements of the program that integrate the full depth signal of the rings. The relationship of the migration of the NBC retroflection to ring generation will also be investigated in order to characterize the dynamics of the ring shedding.

During the NBCR Experiment an array of 14 inverted echo sounders (IES) were deployed and recovered in the region of NBC retroflection and ring formation region (Figure 1, Table 1), to provide a three dimensional (time/space) field of the dynamic height with which the NBC variability and the related eddy field could be studied. In particular, the array was designed 1) to monitor the displacement of the front associated with the retroflection of the NBC (IES 2, 6, 10, 12, and 16); 2) to monitor the passage of rings and study the process of eddy formation and propagation (IES 1 to 13); and 3) to provide an estimate of the strength of the NBC transport (IES 14 to 17), and determine its relation to the number of rings shed. Herein, data collected with the array of IES will be analyzed to study the variability of the latitude of penetration of the NBC, and the number of rings shed at the retroflection.

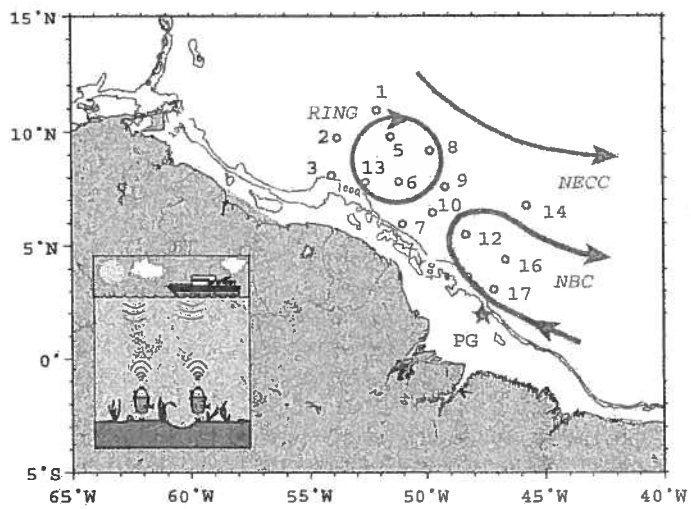

Figure 1. Map of the study region and location of the inverted echo sounder (IES) deployments (o). ★ indicates the location of the pressure gauge deployed by W. E. Johns (RSMAS/UM). The insert is a schematic of IES deployed on the ocean bottom.

Table 1.
Location, depth and deployment history of the moored instruments.

	Latitude (°N)	Longitude (°W)	Depth (m)	Date of deploymer	Date of recovery
PG	01°54.583	47° 38.223	68	5-Mar-99	9-Jun-00
1	10° 54.612	52° 04.802	4137	12-Nov-98	19-Jun-00
2	09° 44.572	53° 46.802	4570	13-Nov-98	19-Jun-00
3	8° 06.046	54° 02.461	1115	14-Nov-98	18-Jun-00
5	09° 45.764	51° 29.081	4843	16-Nov-98	16-Jun-00
6	07° 47.947	51° 09.229	4395	17-Nov-98	14-Jun-00
7	5° 56.99	51° 00.08	2700	24-Feb-99	13-Jun-00
8	09° 09.014	49° 48.530	4653	17-Nov-98	16-Jun-00
9	07° 35.589	49° 10.831	4288	18-Nov-98	12-Jun-00
10	06° 27.699	49° 42.522	3858	18-Nov-98	12-Jun-00
12	05° 29.900	48° 19.210	3442	21-Nov-98	11-Jun-00
13	7° 47.05	52° 34.026	2012	25-Feb-99	14-Jun-00
14	06° 46.009	45° 44.603	4200	22-Nov-98	10-Jun-00
16	04° 24.890	46° 39.185	3273	23-Nov-98	10-Jun-00
17	03° 04.703	47° 09.045	1802	23-Nov-98	09-Jun-00

2. METHODOLOGY

Inverted echo sounders (IES) measure the round trip travel time of an acoustic pulse from the sea floor to the surface and back. By definition, travel time, TT, is a function of the sound velocity, c,:

$$TT = \int dz / c\,(T, S, P) \qquad (2.1)$$

where c is a direct function of the temperature (T), salinity (S) and pressure (P). Travel time measurements can be empirically correlated to a number of different integrated or discrete oceanic parameters such as thermocline depth or dynamic height. Correlations vary over different regions due to the circumstances of local stratification or how T and S co-vary in the region. IES measurements have been used successfully in several regions, for example to study the Gulf Stream dynamic height variability (Watts and Rossby, 1977), to study the transports and frontal motions at the Brazil-Malvinas Confluence (Garzoli and Garraffo, 1989; Garzoli, 1993) and the Benguela Current (Garzoli *et al.*, 1995) and to examine the generation and propagation of rings in the South Eastern Atlantic (Garzoli and Gordon, 1996; Duncombe-Rae *et al.*, 1996; Goni *et al.*, 1997). IES measurements

have also been used in the equatorial Atlantic to study the North Equatorial Counter Current (Garzoli and Richardson, 1989), and in the Pacific to study the ENSO cycle in the Central Equatorial Pacific (Wimbush *et al.*, 1990, Miller *et al.*, 1985). Dynamic height time series derived from IES have also been used in comparison with altimeter data to study ring propagation and transports (see Garzoli and Goni, 2000, for a review).

For the purpose of this paper, IES acoustic travel time series were scaled to dynamic height. Using all 220 CTD stations collected during the four NBCR Experiment cruises the relationship between travel time and dynamic height was obtained as follows. Travel time and dynamic height were estimated from T, S and P for each CTD station at different depths and reference levels, and correlations between the two parameters were computed. Results of the analysis indicated that the correlations were different in the area of ring formation (west of 50°W) than in the area of the retroflection (east of 50°W), probably due to different vertical stratifications. A very good agreement was observed between travel time and the dynamic height at the surface referenced to 300 m. This depth was therefore adopted as the reference level, and it also contains the core of the NBC flow defined as above the 26.8 isopycnal (e.g. Bourles *et al.*, 1999). Results of the correlation analysis are given in Figures 2a and 2b.

The following relations were used to obtain changes in dynamic height from changes in travel time:

West of 50°W (rings area):

$$\Delta DH = -0.054\ \Delta TT \pm 0.0367 \text{ dyn m} \qquad R^2 = 0.70$$

East of 50°W (retroflection area)

$$\Delta DH = -0.061\ \Delta TT \pm 0.0270 \text{ dyn m} \qquad R^2 = 0.89$$

Where ΔDH and ΔTT are relative changes in dynamic height and travel time between two consecutive times respectively. From these relations, time series of relative dynamic height were calculated at the 14 IES locations. In order to obtain absolute values of the dynamic height, hydrographic data collected at the deployment sites during the NBCR cruises for the purpose of calibration were used. Dynamic heights at the surface referenced to 300 m were calculated at each CTD station and used to add a constant to the dynamic height anomaly specific to each site to best fit the observations. Trends observed in the time series were not altered, as they are believed to be a real part of the signal. The 14 time series of dynamic height at the surface referenced to 300 m obtained by this method are given in Figure 3. The difference in the length of the records is due to technical difficulties during the deployment cruise. The IES sites are numbered 1 to 17. IES instruments were not deployed at site 4, 11 and 15 due to malfunction at the time of deployment. IES 7 and 13 were deployed after the instruments were repaired during the second cruise. The series have been passed through a 40-hour lowpass filter to eliminate all frequencies higher than about 0.5 days^{-1}. The longer time series started in November 1998 and ended in June 2000, and the shorter series started in February 1999 and also ended in June 2000. In Figure 3,

circles indicate the dynamic height calculated from the CTD stations. These values are shown for the purpose of comparison and to indicate the agreement in dynamic height between the time series obtained with the IES and the CTD data.

In addition to the 14 IES, W. E. Johns (RSMAS/UM) deployed a pressure gauge (PG) during the second cruise. The decision to make this deployment was made after the first cruise when it became evident that a large amount of water was flowing north to the west of IES 17. The PG data were made available for this study.

A PG measures the total pressure of the overlying water column. At the very shallow 68 m location on the continental shelf, the water column can be assumed to be homogeneous in density, and therefore the PG effectively monitored all the pressure changes at its location. On the other hand, by measuring the integrated temperature of the water column, the IES estimate only the pressure variations within the water column (baroclinic). At these deep locations (all greater than 1000 m), any full-depth barotropic flows are most likely quite small relative to the 20 to 100 cm s^{-1} NBC near-surface currents. Therefore, both the PG and the IES are assumed to measure the total variability of the flow. A time series of dynamic height was obtained from the pressure record as follows. First the pressure variability ($\Delta P = P - \bar{P}$, $\bar{P}$ = mean pressure) was transformed into dynamic height variability by using the relation between dynamic height (DH) and pressure (P) ($\Delta DH = \Delta P / \rho$) when ρ is the water density. To obtain an absolute value for dynamic height the same method as for the IES was used, except that in this case the CTD cast only reached a depth of 60 m. Data were extrapolated to 300 m using a historic T, S profile from Levitus *et al.*, 1994, located closest to the site at 300 m depth. This method may add an unknown error to the dynamic height series obtained from the PG. Nevertheless, given the location of the PG, the data serve to enhances the maps without affecting array of the key results. The time series of dynamic height obtained with this procedure is also shown in Figure 3. The three near coastal sites (IES 3 and 7 and PG) show more variability at high frequencies than the other time series.

3. DYNAMIC HEIGHT FIELD

From the dynamic height time series, synoptic maps were produced every 3 days using an interpolation routine with a weighting factor, WF *(i, j, k),* for *k* dynamic height data values at each grid point *(i, j)*, (Figures 4c and f, 5c and f). The WF used is 1 / R where R is the distance between the grid points and the observed values. Two different series of maps were created: one with 12 time series from November 27, 1998 through June 1, 2000, and a second one with 15 time series from February 25, 1999 through June 1, 2000. From the dynamic height time series, it is possible to calculate the geostrophic velocity. The geostrophic velocity between two stations is given by: from February 25, 1999 through June 1, 2000.

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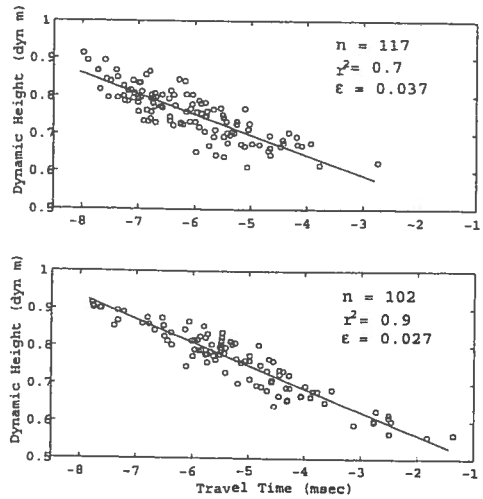

Figure 2. Results of the correlation analysis between dynamic height at the surface (referenced to 300 m) and travel time. Both variables are obtained from CTD cast collected during the NBCR cruises, a) for the region west at 50°W (rings area) and b) for the region east of 50°W (retroflection area).

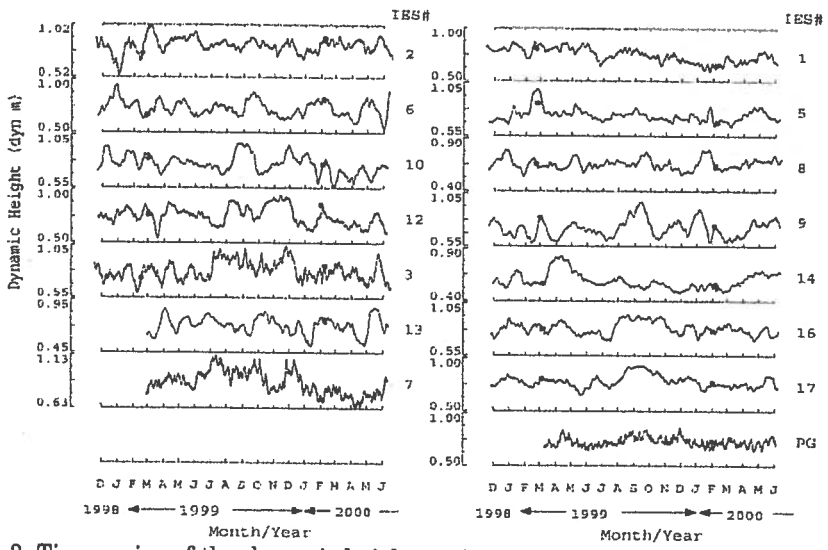

Figure 3. Time series of the dynamic height at the surface referenced to 300 m, obtained from data collected from the 14 IES and the PG deployed as part of the NBCR experiment. The circles indicate the value of dynamics high obtained with the CTD data.

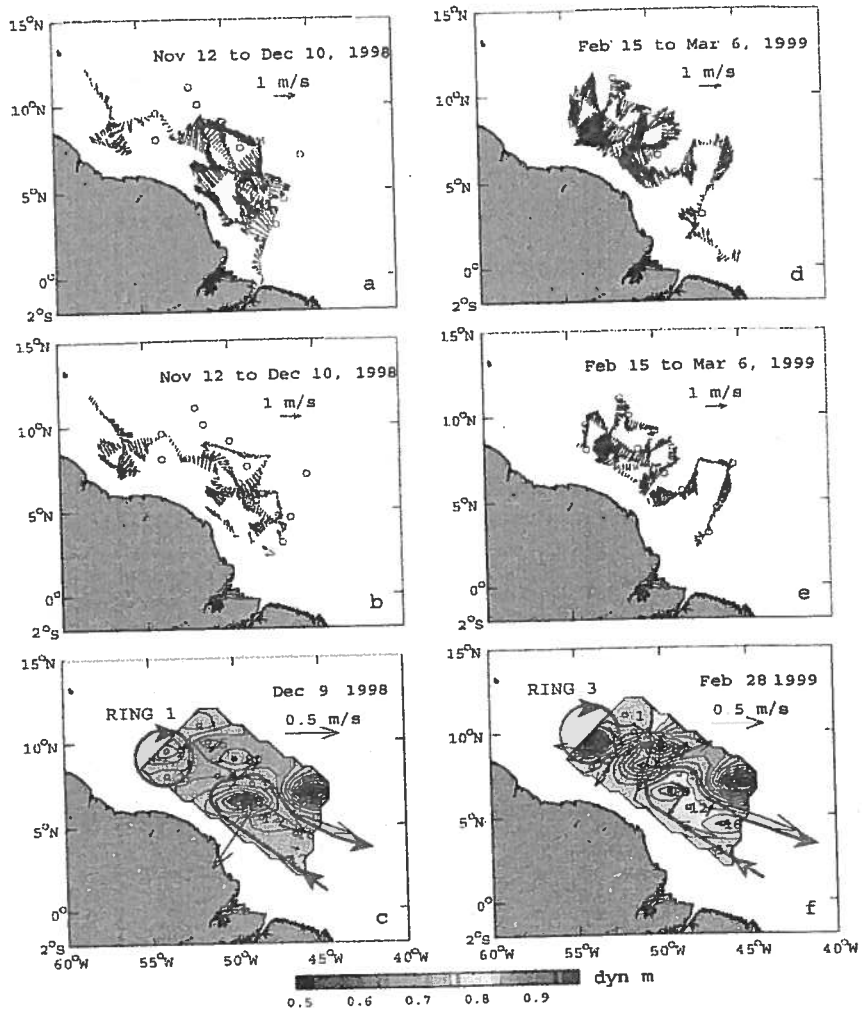

Figure 4. Left panel: Velocity field collected with the hull-mounted ADCP during the first NBCR cruise: (a) at 20 m and (b) integrated velocity from 20 to 250 m. Data is from November 12 to December 10, 1998. Data is compared (c) to the objective map of the dynamic height from the IES array for December 9, 1998. Right panel: Same as Figure 4 (a, b) but for the second NBCR cruise from February 15 to March 6, 1999. Data is compared to (f) the objective map dynamic height field obtained from the IES array for February 28, 1999. Black arrows are geostrophic velocities between station pairs, in m sec^{-1}. The thicker, red lines and arrows highlight the ring and NBC structures revealed by the dynamic height field.

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From the dynamic height time series, it is possible to calculate the geostrophic velocity. The geostrophic velocity between two stations is given by:

$$Vg = (1/f)\,(\delta DH/\Delta x) \tag{3.1}$$

where g is gravity, f the Coriolis parameter, and δDH the difference of dynamic height between two stations separated by a distance Δx. Assuming no error in the distance between stations, the error incurred by equation (2) is then due solely to errors in dynamic height. The error in the estimate of dynamic height is ±0.0033 dyn m west of 50°W, and ± 0.0022 dyn m east of 50°W. Therefore, the errors in the geostrophic velocity are on the order of ± 3 to ± 5 cm/sec. The black arrows superimposed on the dynamic height contours (Figures 4c and 4f, and 5c and 5f) indicate the magnitude of the geostrophic velocities calculated between station pairs using relation (2). The dynamic height maps display structures that can be associated with rings and with the location of the retroflection. To provide a quantitative validation of our results, comparisons will be shown between dynamic height maps and velocities obtained from the hull-mounted Acoustic Doppler Current Profiler (ADCP) data collected during the four NBCR cruises. During the cruises, intensive hydrographic surveys were also performed in four rings (Wilson *et al.*, 2002). Results from these surveys will also be compared with the IES synoptic dynamic height maps.

The first cruise, NBCR1 took place from November 7 to December 11, 1998. Figure 4 (left panels) compares the ADCP velocities at 20 m (Figure 4a) and the integrated velocities from 20 to 250 m (Figure 4b) from this cruise with the surface dynamic height referenced to 300 m (Figure 4c), measured on December 9, 1998. The dynamic height field shows that the retroflection reaches 53°W, in agreement with the ADCP survey. During NBCR1 a ring was surveyed (Ring 1, Wilson *et al.*, 2002, WEAR1 from now on). WEAR1 was a subsurface ring, with a weak surface signal. The dynamic height map shows a rotational structure west of 54°W that is the expression of WEAR1.

The second cruise, NBCR2, took place during February 1999. The top right side panels of Figure 4 (d and e), shows the surface velocity and the integrated velocities from the ADCP data collected along the track. The lower panel (Figure 4f) shows a map of dynamic height created from the IES data for February 28, 1999. The retroflection can be observed reaching 51°W, and a ring appears to have shed farther north, west of 53°W. The ring observed from the dynamic height field is the same one surveyed during the cruise (WEAR3). WEAR2 was outside of the IES domain, but was observed when it was formed in December 1998.

During the third cruise, NBCR 3, January 30 to February 7, 2000, no ring was observed or surveyed. The velocity field shows a series of rotations that are the expression of meandering of the NBC (Figure 5a and b) both for the surface and the integrated value. A ring was starting to form but was not cut off from the main NBC during the time of the cruise. The same situation is observed in the surface dynamic height map for February 5, 2000 (Figure 5c).

A final comparison is made between the data collected during the fourth cruise, NBCR 4, June 7 to June 19, 2000, and the surface dynamic height map for June 1, 2000 (Figure 5, right panels). The dynamic height map is for a date six days earlier than the cruise, but it is the latest one available after filtering and truncating the files to the same length. The dynamic height shows the NBC retroflection between 47° and 48°W and a ring farther north (Figure 5f). The location of this ring is southeast of the location of the ring surveyed during NBCR 4 (WEAR4). This difference is due to the time lag. The position of the ring during the cruise (12 days later) is consistent with the location it had on June 1 and a propagation speed of 14 km/day. A second ring is also observed towards the northwest in the dynamic height field. Although the presence of this ring was noted during the recovery cruise, it was not surveyed due to lack of time.

4. LATITUDE OF PENETRATION AND NUMBER OF RINGS SHED

A careful subjective analysis of all the dynamic height maps was conducted to determine the latitude of the northward penetration of the NBC retroflection and to determine the number of rings shed. The latitude of penetration was measured as the distance between the northernmost point of the retroflection and an arbitrary set of geographical coordinates (0°N, 42°W) to allow the description of motions occurring at the same latitude. Thus, during the northward motion, the distance between 0°N, 42°W and the northern extension of the NBC is measured. Once the flow closes upon itself and a ring is shed, the location of the new position of the NBC, to the southeast of the new ring formed, is measured. Therefore, the northward motion can be considered as the motion of the northward penetration, which according to the record has a mean speed of 30 km day^{-1}. During the southward motion, it represents more of a resetting of the index than a continuous motion. As the ring separates, the retroflection rapidly re-forms further south. A ring (of approximately 300 to 400 km in diameter) is located between the previous northward location and the new one. As a result, southward motion cannot be inferred from the figure.

Figure 6. shows the result of this analysis. The maximum northward penetration of the NBC and its retroflection varies from 600 km to 1900 km from the 0°N, 42°W reference location. In all cases but one (August 1999), after the retroflection reaches its northward extension a ring is shed. During the 18-month period covered by the coincident time series, November 27, 1998 to June 1 2000, 11 rings were shed from the retroflection. Rings are shed at one to four month intervals, with no obvious periodicity observed. Nevertheless, there is a difference in the number of rings shed during the two overlapping periods of observation (December 1998 through May 1999; December 1999 through May 2000), with fire shed in 1998/1999 and three in 1999/2000. This may be an indication of interannual variability.

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5. RINGS VOLUME AND TEMPERATURE TRANSPORT

A simple calculation can be performed to determine the volume and temperature transport of these rings (e.g. Duncombe Rae *et al.*, 1996; Garzoli *et al.*, 1999). Rings are assumed to have a Gaussian shape in the horizontal and to carry a volume, $V = 2 \Pi L^2 h_0$, where L is the radius of maximum velocity, assumed to be half of the radius, and $h_0 = h - h_\infty$ (h is the depth of the ring signature and h_∞ is the depth of the thermocline in a region outside of the ring's influence). If we assume that all of the South Atlantic water carried by the NBC rings at the retroflection is compensated by cold, deep North Atlantic water, then each ring will transport heat in the amount of approximately $Q = \rho C_p V \Delta T$, with $\Delta T = 15°C$, the difference between the mean temperature of the two water masses and C_p the specific heat of sea water. Using these formulas, the volume and heat transported by each of the rings was calculated. The approximate diameter for the rings was obtained from the dynamic height maps, and the speed of propagation from the dynamic height time series. Results are given in Table 2, listing the number of rings observed, the dates when the rings were shed, and the parameters calculated as described above. During the period of time covered by the observations (18 months) 11 rings were observed which yields an annualized value of 7.3 rings/year. The ring diameters ranged between 300 and 400 km, and the mean speed of propagation was 12.4 cm sec^{-1}, in agreement with previous results (Fratantoni *et al.*, 1995). Results from the IES array indicate that previous calculations underestimated the component of the MOC return transport carried by NBC rings. An estimate of the long-term averaged transport can be obtained by dividing the total volume carried by the total elapsed time. The total volume transported by the 11 rings in the 18 months of observations is of the order of 40×10^{13} m^3 ($39.4. \times 10^{13}$ m^3). If this number is divided by the number of seconds in 18 months (the length of the observations), then the estimated transport is of the order of 8 Sv (8.3 Sv).

The total annual northward mean transport of the MOC is estimated to be between 14 Sv (Schmitz and McCartney, 1993) to 16 Sv (Ganachaud and Wunsch, 2000). If NBC rings transport 8 Sv/year, then they carry more than half of the total volume of upper water entering the North Atlantic through the MOC. It is interesting to compare these results with a similar previous analysis performed to estimate the contribution of Agulhas rings to the interocean exchange of mass and heat. The Agulhas rings are one of the major contributors to the upper limb of the MOC in the South Atlantic.

It is estimated that 4 to 7 rings are shed per year at the retroflection of the Agulhas Current (Garzoli and Goni 2000). The volume transport associated with these rings varies from 3.2 Sv to 9.6 Sv annually depending on the year and the volume of the ring. In a five year period (1993 to 1997) it was estimated that the Agulhas rings contributed a mean transport of 6 Sv per year. These numbers are slightly smaller than, and of the same order of magnitude, as results obtained for the NBC rings in the present study.

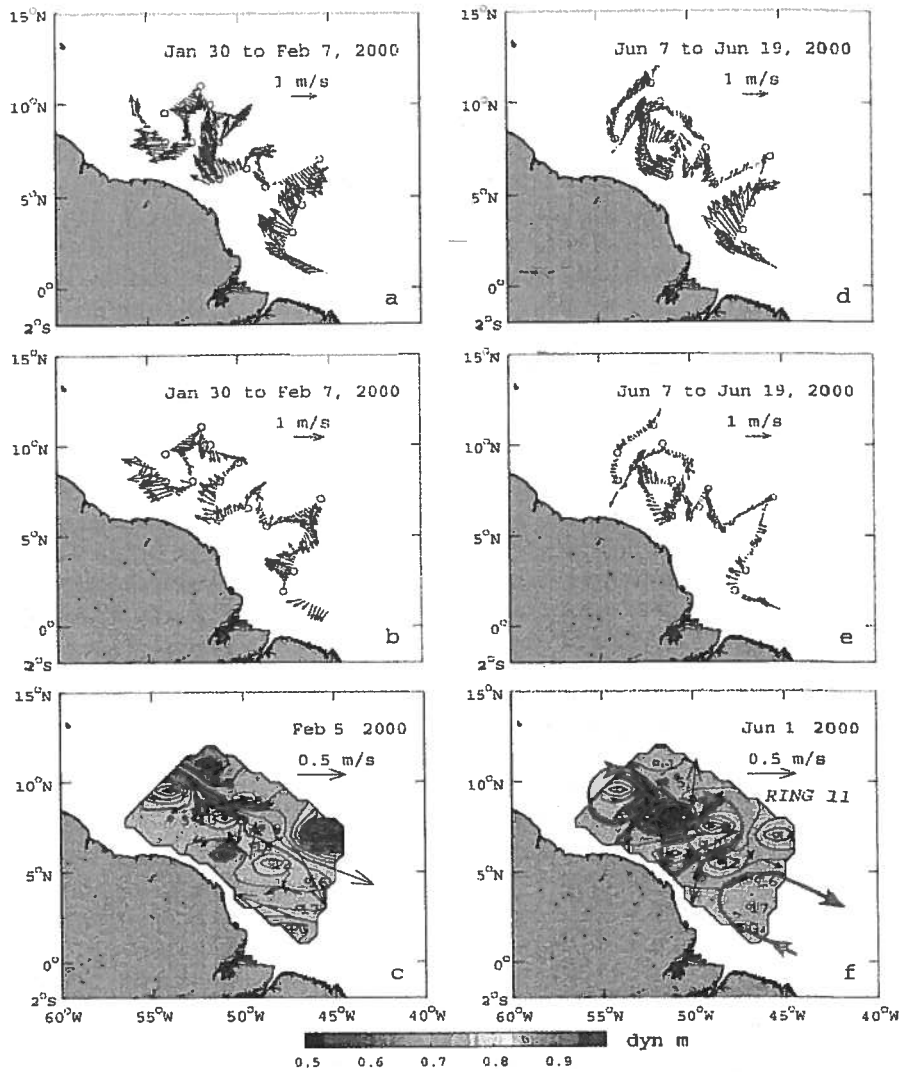
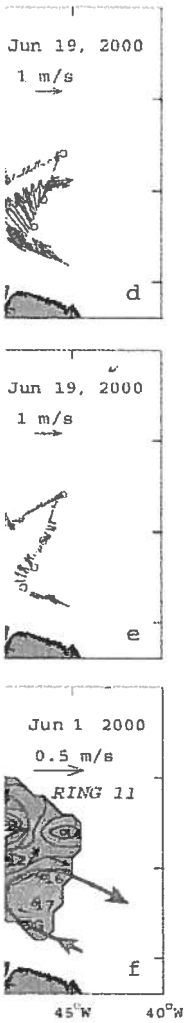


Figure 5. Left panel: Same as Figure 4 (a, b), but for the third NBCR cruise from January 30 to February 7, 2000. Data is compared to (c) the objective map of the dynamic height field obtained from the IES array for February 5, 2000. Right panel: Same as Figure 4 (a, b) but for the fourth NBCR cruise from June 7 to June 19, 2000. Data is compared to (f) the objective map of the dynamic height field obtained from the IES array for June 1, 2000. Black arrows are geostrophic velocities between station pairs, in m sec^{-1}. The thicker red lines and arrows highlight the ring and NBC structures revealed by the dynamic height field.



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: and NBC structures

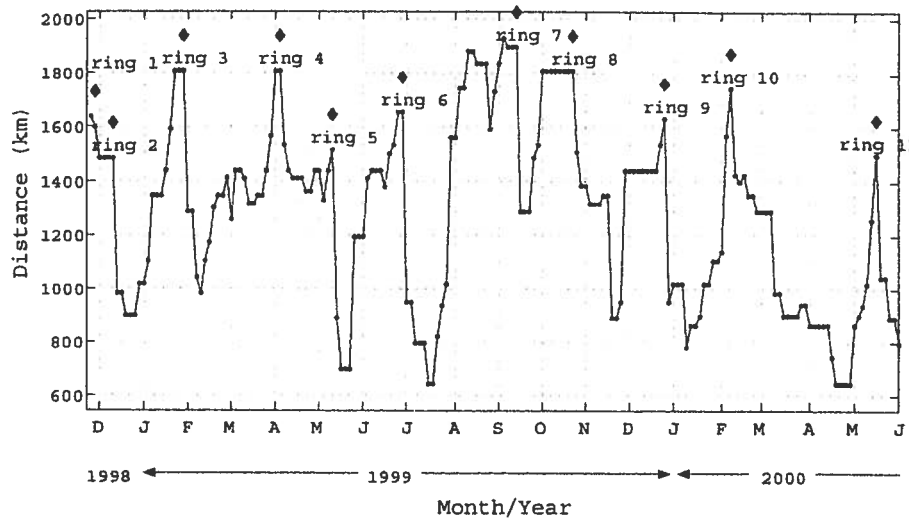

Figure 6. Time series of the latitude of penetration of the NBC retroflection observed from the dynamic height synoptic maps, defined as the distance (in km) between the northernmost point of the retroflection and a reference set of geographical coordinates. (0°N 42°W). Diamonds indicate the times when NBC rings sered.

Table 2.
Ring parameters*

Ring #	D km	Observed	Speed km/day	Volume m3 1013	Transport Sv	T_Q (ref °C) PW	Comments Previously observed by:		
1	300	11/27/1998	11.1	2.83	0.9	0.06	NBCR1		Altimeter
2	380	12/24/1998	14.3	4.54	1.4	0.09		SeaWifs	Altimeter
3	320	2/13/1999	12.5	3.22	1	0.07	NBCR2	SeaWifs	Altimeter
4	300	4/5/1999	12.5	2.83	0.9	0.06		SeaWifs	
5	333	5/11/1999	10.7	3.48	1.1	0.07		SeaWifs	Altimeter
6	350	6/28/1999	11.3	3.85	1.2	0.08			Altimeter
7	300	9/14/1999	13.9	2.83	0.9	0.06		SeaWifs	Altimeter
8	330	11/7/1999	7.9	3.42	1.1	0.07			
9	350	12/22/1999	16.7	3.85	1.2	0.08		SeaWifs	Altimeter
10	333	2/20/2000	12.3	3.48	1.1	0.07		SeaWifs	Altimeter
11	400	5/17/2000	13.3	5.03	1.6	0.1	NBCR4		
Mean	392		12.4	3.6	1.1	0.07			

*The first column is the ring number, D is the diameter in km, Observed is the date when the ring was first observed in the dynamic height field, Speed is the translation speed of the ring and T_Q is the temperature transport. The last row, Mean, is the mean value of each parameter. NBCR 1, 2, and 4 are the NBCR cruise numbers. 1 Sv = 10^6 m³/sec.

The mean heat transported per NBC ring is 0.07 PW (Table 2). During the 18 months of observations, a total of 0.81 PW are transported by the rings. This yields a mean annualized value of 0.54 PW, which represents half of the total heat transported across the tropical Atlantic (1 PW, e.g., Ganachaud and Wunsch, 2000). Given the nature of the assumptions made to obtain these numbers, it is not possible to quantify a precise error and therefore the values should be considered only an estimate. In these simple calculations, we do not distinguish how much water transported by the rings is from the South Atlantic and how much is already mixed with other water masses. In a companion paper (Johns *et al.*, 2002, this volume) a detailed analysis of the percentage of the water transported by the rings is given using all of the CTD stations collected during the NBCR cruises. Also, a similar analysis is done using the results of a high resolution model (Garaffo *et al.*, this volume).

The last column of Table 2 compares the rings observed with the IES to those observed with other platforms during the NBCR Experiment: intensive ship surveys (Wilson *et al.*, 2002), Ocean Color (SeaWifs) images (Fratantoni and Glickson, 2001), and altimeter data (Goni, personal communication). Previous estimates for the number of rings shed at the retroflection range from 1 to 4 rings per year (for a comprehensive review see Johns *et al.*, this volume). The latest census done from altimeter data before the NBCR experiment (Goni and Johns, 2001) observed an average of 5 rings/year, with the time interval between rings ranging from 1 to 2 months.

The number of rings observed with the IES array, 11 rings shed in 18 months (7.3 rings/year), is larger than previous estimates. However, this number is similar to the number of rings observed with a current meter mooring deployed as part of the NBCR Experiment (Johns *et al.*, this volume). The number of rings observed with the IES array is larger than previous estimates, because this is the first time that a coherent array of moored instruments have been deployed in the region. Satellite observations for example can miss rings having subsurface signals (Wilson *et al.*, 2002).

6. SUMMARY

The IES array deployed as part of the NBCR experiment enables continuous monitoring of the variability in the latitude of penetration of the NBC retroflection and the number of NBC rings shed. Results indicate that after the NBC reached its maximum latitude of penetration, in almost all cases a ring was shed. The time series of the latitude of penetration did not show an apparent periodicity, nor was there a period of time when the number of rings shed was larger than another. There was, however, an indication of interannual variability observed during the two overlapping periods of observation (December 1998 through May 1999; December 1999 through May 2000), with fire rings shed in 1998/1999 and three in 1999/2000.

It was previously assumed that one third of the MOC was transported from the South Atlantic to the North Atlantic via North Brazil Current rings (Johns *et al.*, 1990; Richardson *et al.*, 1994; Fratantoni *et al.*, 1995). The results obtained in this study indicate that a portion of the MOC large than these prior estimates is actually transported by rings shed at the retroflection. During the 18 months of observations, 11 rings were shed, transporting in the mean 8 Sv or 0.54 PW per year.

It should be remembered that results from the simple calculations described in this paper do not distinguish how much water transported by the rings is from the South Atlantic and how much is already mixed with other water masses. A comprehensive analysis of the full data set collected during the NBCR experiment will provide further information on the generation and propagation of NBC rings.

Acknowledgments

The authors are indebted to the crew of the R/V Seward Johnson for their support during the four cruises and to Dr. W. E. Johns for providing the pressure gauge data. The IES were prepared for deployment, deployed and recovered by David Bitterman. Roberta Lusic prepared the manuscript for publication. Support for this project was provided by NSF Grant OCE-97-32389 and by NOAA/AOML. NOAA/OAR ship time for the cruises was funded by NSF and NOAA/OAR.

REFERENCES

Bourles, B., Y. Gouriou, and R. Chuchla. On the circulation in the upper layer of the western equatorial Atlantic, *J. Geophys. Res.*, 104, 21151-21170, 1999.

Didden N. and F. Schott. Eddies in the North Brazil Current Retroflection Region Observed by GEOSAT Altimetry, *J. Geophys. Res.,* 98, 20121-20131, 1993.

Duncombe Rae, C. M., S. L. Garzoli and A. L. Gordon. The Eddy Field of the South-East Atlantic Ocean: A Statistical Census from the BEST Project, *J.Geophys.Res.,* 101, 11,949-11,964, 1996.

Fratantoni, D. M., W. E. Johns and T. L. Townsend. Rings of the North Brazil Current: Their Structure and Behavior Inferred from Observations and Numerical Simulations, *J. Geophys. Res.*, 100, 10633-10654, 1995.

Fratantoni, D. M., P. L. Richardson, W. E. Johns, C.I. Fleurant, R. H. Smith, S. L. Garzoli, W.D. Wilson, and G. J. Goni. The North Brazil Current Experiment. *EOS, Transactions AGU*, 80, (17), 1999.

Fratantoni, D. M. and D. A. Glickson. North Brazil Current Ring Generation and Evolution Observed with SeaWiFS, *J. Phys. Ocean.*, Vol 32, No 3, March 2002.

Ganachaud, A. and C. Wunsch. Improved estimates of global ocean circulation, heat transport and mixing from hydrographic data. *Nature*, 408, 453-456, 2000.

Garzoli, S. L. and Z. Garraffo. Transports, Frontal Motions and Eddies at the Brazil-Malvinas Currents Confluence. *Deep-Sea Res.*, 36, 681-703, 1989.

Garzoli, S. L. and P. L. Richardson. Low Frequency Meandering of the North Equatorial Counter Current. J. Geophys. Res., 94, C2, 2079-2090, 1989.

Garzoli, S. L.. Geostrophic Velocities and Transport Variability in the Brazil/Malvinas Confluence. Deep-Sea Research. 40 No.7, pp.1379-1403, 1993.

Garzoli, S. L., A. L. Gordon and C. Duncombe Rae. Benguela Current Sources and Transports. U.S. WOCE Report, 1995, 17-19, 1995.

Garzoli, S. L. and A. L. Gordon. Origins and variability of the Benguela Current, *J. Geophys. Res.*, 101, 897-906, 1996.

Garzoli, S. L., P. L. Richardson, C.M. Duncombe Rae, D.M. Fratantoni, G.J. Goni and A.J. Roubicek. Three Agulhas Rings Observed During the Benguela Current Experiment. *J. Geophys. Res*, 104, 20971-20985, 1999.

Garzoli, S. L. and G. J. Goni. Combining altimeter observations and oceanographic data for ocean circulation studies. *Satellites, Oceanography and Society,chap,* 5, 79-97, 2000.

Garraffo, Z. D., W. E. Johns, E. P. Chassignet and G. Goni (2002). North Brazil rings and transports of southern waters in a High Resolution Numerical Simulation of the North Atlantic. This volume.

Goni, G., S. L. Garzoli, A. Roubicek, D. Olson and O. Brown. Agulhas Rings Dynamics from TOPEX/POSEIDON Satellite Altimeter Data. *J. Mar. Res.*, 55, 861-883, 1997.

Goni, G. J. and W. E. Johns. A Census of North Brazil Current Rings Observed from TOPEX/POSEIDON Altimetry: 1992-1998, *Geophys. Res. Lett.*, 28, 1-4, 2001.

Johns, W. E., R. Zantopp, and G. Goni (2002). Cross-gyre watermass transport by North Brazil Current Rings. This volume.

Johns, W. E., T. N. Lee, F. Schott, R. J. Zantopp, and R. H. Evans. The North Brazil Current retroflection: Seasonal structure and eddy variability. *J. Geophys. Res.,* 95, 103-221, 120, 1990.

Metcalf, W. G. Shallow Currents Along the Northeastern Coast of South America, *J. Mar. Res.*, 26, 232-243, 1968.

Levitus, S., R. Burgett, T. Boyer. World Ocean Atlas 1994, Vol. 3: Salinity. *NOAA Atlas NESDIS 3*, U.S. Gov. Printing Office, Wash., D.C., 99 pp., 1994.

Miller, L. L., D. R. Watts, and M. Wimbush. Oscillation of dynamic topography in the Eastern Equatorial Pacific, J. Phys. Oceanogr., 15, 1759-1770, 1985.

Nof, D. Why are rings regularly shed in the western equatorial Atlantic but not in the western Pacific?, *Prog. Oceanog.*, 38, 417-451, 1996.

Nof, D. and T. Pichevin. The Retroflection Paradox, *J. Phys. Ocean.*, 26, 2344-2358, 1996.

Richardson, P. L., G. E. Hufford, R. Limeburner and W. S. Brown. North Brazil Current retroflection eddies, *J. Geophys. Res.*, 99, 5081-5093, 1994.

Schmitz, W. J. Jr. and M. S. McCartney. On the North Atlantic circulation. *Rev. Geophys.*, 31, 29-49, 1993.

Stramma, L., and F. Schott. Western Equatorial Circulation and Interhemispheric Exchange. *The Warmwatersphere of the North Atlantic Ocean*, pub. Gebruder Borntraeger, ed. by W. Krauss, 195-227, 1996.

Stramma, L. and F. Schott. The mean flow field of the tropical Atlantic Ocean, *Deep-Sea Res. II*, 46, 279-303, 1999.

Watts, D. R. and H. T. Rossby. Measuring dynamic height with inverted echo sounders: Results from MODE, *J. Phys. Oceanogr.*, 7, 345-358, 1977.

Wilson, D. W., W. Johns and S. L. Garzoli. Velocity structure of North Brazil Current rings, *Geophys. Res. Lett.,* 29, 114 (1-3), 2002.

Wimbush, M., S. M. Chiswell, R. Lukas, K. A. Donohue. Inverted echo sounder measurement of dynamic height through an ENSO cycle in the central Equatorial Pacific. *IEEE J. Ocean. Eng.,* 15, 380-383, 1990.