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A Census of North Brazil Current Rings Observed from TOPEX/POSEIDON Altimetry: 1992-1998

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Abstract. Six years of TOPEX/POSEIDON altimeter data are used to investigate the formation of rings and eddies shed by the North Brazil Current. Upper layer thickness maps were used to identify 34 of these features formed in the North Brazil Current retroflection region, an average of more than 5 rings and eddies per year. The ensemble of ring trajectories closely parallels the 500 m isobath, and one out of six rings penetrate into the Caribbean Sea through the southern Lesser Antilles. The rest of the rings and eddies follow a northern trajectory past Barbados once they reach 58W. Their estimated mean translation speed is 14 km/day and their mean length scale is approximately 100 km. Our results suggest that the formation rate of NBC rings and eddies is nearly twice that previously thought, and that they may account for more than 1/3 of the interhemispheric transport within the Atlantic meridional overturning cell.

1. Introduction

North Brazil Current (NBC) rings are large anticyclones that pinch off from the NBC retroflection in the western tropical Atlantic near 8°N and translate northwestward along the coast of South America toward the Caribbean Sea. Ring shedding by the NBC is one of several mechanisms that contribute to the transport of South Atlantic upper ocean waters into the North Atlantic as part of the Atlantic meridional overturning cell (MOC) (Johns *et al.*, 1998). Other mechanisms include a possible coastal current along the South American continental shelf, and a seasonal rectification of the tropical Atlantic circulation that causes warm surface waters to be stored in the North Equatorial Counter Current and released northward via Ekman transports (Mayer and Weisberg, 1993). Previous studies on NBC rings using GEOSAT altimetry (Didden and Schott, 1993) and *in situ* measurements (Johns *et al.*, 1990; Richardson *et al.*, 1994; Fratantoni *et al.*, 1995) have suggested that typically 2-4 NBC rings are generated each year and that these rings may account for up to one-fourth (~ 3 Sv) of the total upper ocean transport in the warm limb of the Atlantic overturning cell.

The objective of this study is to identify and track the NBC rings and eddies during the period October 1992 through December 1998 using TOPEX/POSEIDON (T/P)-derived sea height anomaly data. These features are identified in this work from their upper layer thickness signature as derived from the altimeter sea height anomaly data used within the context of a two-layer ocean model (Goni *et al*, 1997). The region of study extends from 40°W to 70°W, and from 0° to 20°N (Figure 1). Figure 1

2. Data and Methods

Two main data sets are used in this study: (i) altimeter-derived sea height anomaly data, and (ii) climatological hydrographic data for the region. The T/P altimeter measures the sea height anomaly along the altimeter groundtracks, which are separated three degrees longitudinally, and are repeated every approximately 10 days. The data used in this work was processed with the standard altimetric corrections (Cheney *et al., 1994*), the Cartwright and Ray (1991) tidal model, the sea height anomaly values referred to the 1992-1998 mean, and interpolated onto a 9 km alongtrack grid.

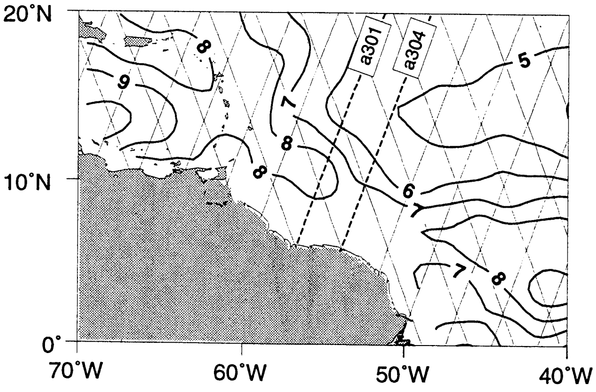

Figure 1. The region of study, with T/P groundtracks and T/P-derived rms sea height variability (in cm) during the study period. The two T/P groundtracks with dotted lines are used to extract the scale parameters of the rings.

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The sea height anomaly values in the region range from approximately -0.2 to 0.2 m, while the mean rms of the sea height is approximately 0.07 m with maximum values of 0.1 m (Figure 1). The regions with highest sea height variability correspond to the NBC retroflection region and the central Caribbean Sea. The band of elevated sea height variability along the coast of South America defines the 'ring corridor' along which NBC rings travel as they propagate from the NBC retroflection toward the southern Lesser Antilles.

The sea height anomaly is combined with historical hydrographic data to estimate the upper layer thickness (ULT), which in this study is defined to extend from the surface to the depth of the 20°C isotherm. Use of the ULT rather than just the sea height anomaly is advantageous for tracking of eddy features since it allows anomalous features to be viewed within the context of a mean background circulation. The 20°C isotherm is chosen because it lies within the center of the main thermocline in the tropics and is often used as an indicator of the upper layer flow in the western tropical Atlantic (Molinari and Johns, 1994).

Maps of sea height anomalies for a given day are constructed using the altimeter data for a ± 5 day period centered on that day. These maps are interpolated into a regular 1/4° degree grid using a Gaussian interpolator with an e-folding radius of interpolation of 1/4° degree. The sea height anomaly maps are converted into ULT maps using a two-layer reduced gravity model, where the reduced gravity and mean upper layer thickness fields are derived from the 'Levitus 1998' climatological temperature and salinity data (Conkright *et al.*, 1998). This methodology has been validated in several regions including the Agulhas retroflection region (Goni *et al.*, 1997). The rms difference of the fit between XBT-derived and altimeter-derived upper layer thickness estimates for the NBC region during the study period is approximately 15 m. NBC rings and other anticyclonic eddies in the region are identified from the ULT maps as closed ULT contours having length scales (radius of maximum surface velocity) larger than 0.5 degrees. Figure 2 shows a sea height anomaly map and its corresponding Figure 2 altimeter-derived upper layer thickness map, showing the NBC retroflection and a NBC ring near 10°N, 55°W, that was formed during December 1996. Note that since typical length scales of rings and eddies are approximately 100 km (see Table 1), Table 1 their SHA and ULT signatures are ocassionally lost between the altimeter groundtracks. In such cases the piecewise trajectory segments are linearly connected to form a continuous track.

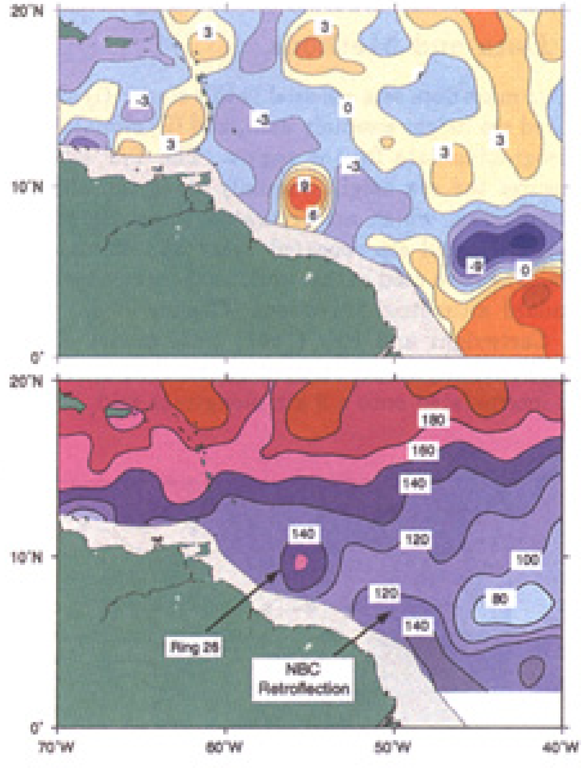

Figure 2. (top) SHA map corresponding to December 15, 1996. The contour intervals are every 3 cm. (bottom) Altimeter-derived ULT map for the same date. Ring number 26 is located at approximately 45°W 10°N. The retroflection, which is clearly identified, will shed ring number 27 by the end of December 1996. The lighter shade off the coast of South America corresponds to water depths smaller than 500 m.

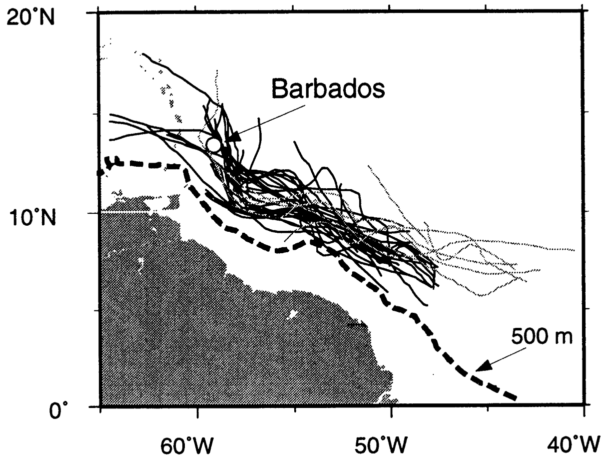

Figure 3. T/P-derived NBC ring, NBC eddy, and eddy trajectories during October 1992-December 1998. Trajectories in black correspond to NBC rings and eddies, while those in grey correspond to NECC eddies. The 500 m isobath is superimposed.

3. Results

A total of 40 warm rings and eddies were identified during the October 1992 to December 1998 study period. Of these features, 24 were clearly identified as NBC rings that pinched off from the NBC retroflection, while 10 more originated in the same general location but during periods when the NBC retroflection was not obviously present. We refer to these latter features as "NBC eddies". Six additional anticyclonic eddies were

Table 1. Ring (R) and NBC eddy (N) parameters. For each ring and eddy, this table shows the date when it is first identified, the translation velocity (km/day), the time (months) the ring or eddy remained in the region of study, the sea height residue ($\eta_o(cm)$), h_0 (m), and the length scale L (m). The light shade correspond to a ring or eddy that crossed the Windward Islands passages into the Caribbean Sea.

R,N	date	v	t	ηo	h'	L
R-1	Oct 1992	12	4	8	23	107
R-2	Dec 1992	21	4	8	25	131
R-3	Feb 1993	15	3	9	22	95
N-4	Jun 1993	16	3	8	24	71
R-5	Jul 1993	17	3	9	37	95
R-6	Aug 1993	9	2	8	32	71
R-7	Dec 1993	10	5	8	28	119
N-8	Feb 1994	10	4	9	42	131
R-9	Jul 1994	11	4	9	49	60
R-10	Sep 1994	10	3	8	43	119
R-11	Nov 1994	12	5	9	41	83
R-12	Jan 1995	14	4	8	26	107
N-13	Mar 1995	15	5	7	29	155
R-14	Jun 1995	8	6	7	40	119
R-15	Jan 1996	14	5	7	39	107
R-16	Jan 1996	21	4	8	30	83
R-17	Feb 1996	8	6	7	24	95
N-18	Apr 1996	20	3	6	15	95
R-19	Aug 1996	10	5	8	22	71
R-20	Oct 1996	13	4	8	31	83
R-21	Dec 1996	17	3	8	32	107
R-22	Jan 1997	18	3	7	25	95
N-23	Mar 1997	15	3	8	30	48
N-24	Apr 1997	13	3	7	27	119
N-25	May 1997	12	2	7	15	100
R-26	Jun 1997	12	5	8	40	71
R-27	Oct 1997	10	4	8	38	107
R-28	Dec 1997	9	4	6	32	83
R-29	Mar 1998	20	4	8	38	119
N-30	Apr 1998	30	2	5	11	95
N-31	May 1998	10	2	8	48	48
N-32	Jun 1998	12	5	8	50	55
R-33	Sep 1998	14	3	8	38	83
R-34	Nov 1998	15	3	7	25	71
mean	5.3 (R+N)/yr	14	3.8	8	31	95
std dev	1.6	5	1	1	10	25

identified in the region that appeared to be generated farther east along the latitude of the NECC. Trajectories of each of the rings and eddies are shown in Figure 3. Most of Figure 3 these features are first detected between 6° and 8°N, having trajectories in the NW direction, and over regions deeper than 3000 m. In general, once the rings and eddies reach 58°W, they turn suddenly to the north traveling just east of Barbados. Due to the large size of the rings this means that they must interact strongly with the topography around Barbados. Five NBC rings and one NBC eddy crossed through the Windward Islands into the Caribbean Sea through waters of the Lesser Antilles passages, which are shallower than 1000 m. The 500 m isobath superimposed on the ring trajectories (Figure 3) reveals that their trajectories are offshore the 500 m isobath, in agreement with Didden and Schott (1993). This suggests that many of the observed NBC rings have vertical structures that extend to at least 500 m or perhaps deeper (Fratantoni *et al.*, 1995).

Observed parameters for all of the NBC rings and NBC eddies that were identified are shown in Table 1, while Figure 4 summarizes the ring Figure 4 and eddy statistics. Rings were observed to pinch off the NBC retroflection from June to March, with the highest frequency of formation in December and January (Figure 4a). The number of rings shed in each of the 6 full years of the study ranged from two (in 1995) to six (in 1996), suggesting a strong interannual variability (Figure 4b). On average about 4 NBC rings and 1.5 NBC eddies were shed each year. Considering the total number of rings and eddies formed, Figure 4b suggests a trend of relatively low formation rates leading up to a minimum in 1995, and higher formation rates after 1996. The NBC eddies were formed anywhere between February to June, depending on the phase of onset and decay of the NBC retroflection in different years, and fill out a nearly uniform seasonal distribution when added to the ring generation frequency (Figure 4a). Most of the rings could be identified for approximately four months in the region of study. The mean translation speed of the rings as obtained from the ULT maps is 14±5 km×day^{-1}, with a range of from 8 to 30 km day^{-1}. Based on the uncertainties in ring location the error of these estimates is of approximately 3 km day^{-1}. These values agree with previously reported modeled and observed mean velocities of 10-15 km/day (Didden and Schott, 1993; Fratantoni *et al.*, 1995).

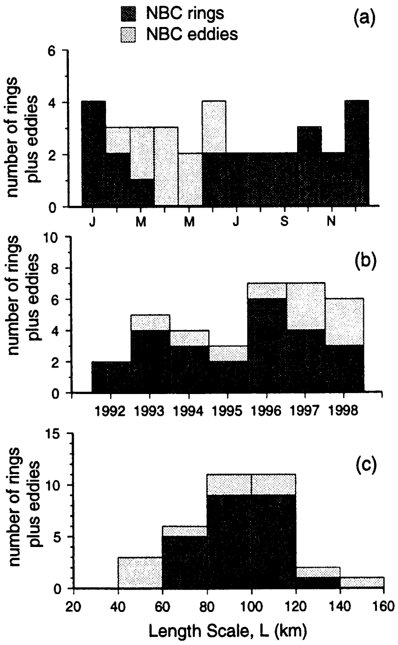

Figure 4. (a) Months in which rings and eddies are formed, (b) number of rings and eddies observed during each year, and (c) length scale (in km) of the rings and eddies.

The length scale, L, and thickness anomaly, h_o, of the NBC rings and eddies are estimated following the methodology used by Goni *et al.* (1997). The T/P alongtrack ULT anomalies are fit to a Gaussian profile

$$h_1(r) - h_\infty = h_o e^{-r^2/2L^2}, \qquad (1)$$

where r is the alongtrack distance measured from the center of the ring, h_1 is the alongtrack ULT, h_∞ is a reference value for the ULT outside the ring, and L is the Gaussian length scale, which within the two layer model corresponds to the radius of maximum velocity. These parameters are estimated just downstream of the ring formation region along groundtracks a301 and a304 (Figure 1). The sea height amplitude (η_o) of the ring is directly related to h_o through the reduced gravity model. The parameter h_∞ is computed from the ULT profiles north of the rings where altimeter estimates are less likely to have errors related to shallow water effects, such as tides. The mean value of L is 95 km and the standard deviation is 25 km (Table 1), with most of the NBC rings and eddies having length scales between 80 and 120 km. The mean values of L, η_0 and h_0 may be slightly underestimated because the altimeter groundtracks seldom pass directly through the ring geometric center.

The most important result of this study is the increased number of NBC rings and eddies that appear to be formed annually compared to that inferred from earlier studies. Under the typical assumptions of a trapped ring water mass volume equivalent to ~1 Sv per ring (Johns *et al*, 1990), and for an average of 5.3 rings and eddies per year, these features may account for more than 1/3 of the total interhemispheric exchange in the Atlantic meridional overturning cell (Schmitz and Mc Cartney, 1993). Since altimetry, by itself, cannot directly determine the vertical structure of rings or eddies, further in-situ observations of these features are needed to determine the volumes of South Atlantic waters trapped and transported by them. Preliminary results from a field program supported by this study indicate that NBC rings can have widely varying vertical structures, and that some rings may be subsurface intensified with very weak surface signatures, making them difficult to detect from altimetry data. Thus, a combination of in-situ and remote sensing approaches will be necessary to fully quantify their role in the MOC.

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