Low-salinity pools at Barbados, West Indies:
Their origin, frequency, and variability

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Abstract. A vertical array of conductivity-temperature recorders moored off the west coast of Barbados, West Indies, from May 1996 to November 1997 revealed a heterogeneous and variable salinity pattern punctuated by five pools of low-salinity water (<34.5 practical salinity units (psu)) entering the region. A typical pool extended to 30-m depth and lasted ~25 days, although one pool extended to 47 m and lasted 94 days. Water samples taken from a pool in May 1997 have radium 228/226 activity ratios of ~1, consistent with previous measurements in Barbados of water that originated in the Amazon River mixing zone. The Amazon water likely was translated to Barbados in rings spawned from the North Brazil Current. Analysis of sea height anomaly and residual derived from the TOPEX/Poseidon satellite supports this conclusion and reveals that, contrary to previous studies, rings are shed throughout the year, mostly during spring. The pools of low-salinity water and their associated velocities dramatically changed the already variable flow in our study area. We believe the complex salinity and flow we observed represented the disorganized remnants of North Brazil Current rings that were at or near the ends of their lives. The changes we observed in the velocity and water structure are interesting in their own right as evidence of the Barbados region as a mixing zone and for their influence on recruitment of larval fishes to the reef along the island’s west coast.

1. Introduction

For decades, long-term salinity records taken near the isolated eastern Caribbean island of Barbados (13°10'N, 59°30'W, Figure 1 inset) have revealed periods when salinity at and near the surface is noticeably lower than is typical for the open ocean [e.g., *Parr*, 1938; *Steven and Brooks*, 1972; *Borstad*, 1982]. These patches of relatively low-salinity water have long been attributed to advection of diluted river water from the Amazon and/or Orinoco Rivers, and it is now established that much of this water is advected from the Amazon mixing zone (0°, 50°W) to Barbados in large, anticyclonic rings shed from the North Brazil Current [*Didden and Schott*, 1993; *Johns et al.*, 1990; *Johns et al.*, 1998]. These rings may have diameters up to 400 km when shed, and they travel northwest along South America at speeds of the order of 10 cm/s [e.g., *Richardson et al.*, 1994; *Fratantoni et al.*, 1995]. The rings translate toward the Caribbean, where

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they disintegrate, having lived about 100 days [*Fratantoni et al*., 1995].

The rings are of interest to physical and biological oceanographers because of their roles in the meridional transport budget across the equator, in transporting heat from equatorial to cooler regions, and, when they reach Caribbean islands, in perturbing the local mean hydrography and circulation. Of particular biological interest is the effect of the rings or their remains on recruitment of larval reef fishes [e.g., *Cowen and Castro*, 1994].

As part of a study of the biological and physical processes involved in retaining larval fish to the reef along Barbados's west coast, we deployed a moored array of conductivity-temperature recorders and an acoustic Doppler current profiler (ADCP) just west of the island from May 1996 to November 1997. This 18-month-long mooring deployment was complemented in May 1996 and May 1997 by two month-long cruises on the R/V *Seward Johnson* west of Barbados during which we measured water column properties and velocity, deployed surface and subsurface drifters, and carried out extensive biological sampling.

This paper has four parts: First, we describe the results of radioactive tracer analysis, which indicate that the low-salinity water we observed in May 1997 came from the Amazon River mixing zone. Second, we examine historical surface salinity data near Barbados to understand long-term trends in salinity values. Third, we describe the salinity field in the top 100 m of the water column as revealed by the 18-month time series and note the velocities associated with marked salinity changes. The flow field will be examined in detail in a future publication. Fourth, we examine sea height anomalies and sea height residuals in the Barbados region as derived from NASA's TOPEX/Poseidon satellite to examine the annual cycle of ring generation and to correlate observed low-salinity water with sea height residuals and to investigate the origin of the warm anticyclonic rings associated with these anomalies and residuals.

2. Methods

On May 16, 1997, at approximately 13°8'N, 59°44'W, we encountered water of a greenish cast as opposed to the deep ocean blue typical of the region. According to the ship's thermosalinograph, the surface salinity at the time was ~31.5 practical salinity units (psu), whereas it had been ~35.6 psu a few days earlier at approximately the same position. Over the next hour, three surface (~3 m deep) water samples were collected as the ship moved slowly to the northeast, occupying conductivity-temperature-depth (CTD) stations along the way. The samples were analyzed in the laboratory of Willard S. Moore of the University of South Carolina for their ^{228}Ra and ^{226}Ra content using a well-shaped intrinsic germanium (WeGe) detector [*Moore*, 1984]. The ^{228}Ra/^{226}Ra activity ratio may be used as a tracer of river water [*Moore et al.*, 1986]. The technique makes use of the differing chemical behavior and half-lives of the two radium isotopes and is described by *Key et al.* [1985] and *Moore and Todd* [1993].

Briefly, ^{226}Ra, with a half-life of 1620 years, enters the dissolved phase of estuarine water largely by desorption from river-borne sediment particles as the particles encounter the increasing ionic strength of estuarine water. Radium 228 has a much shorter half-life (5.75 years) and is supplied largely from the estuarine sediments. Assuming that the estuarine water is mixed repeatedly with the sediment, ^{228}Ra's shorter half life means that the sediment will supply ^{228}Ra activity to the overlying water repeatedly, while the amount of ^{226}Ra activity changes little. The resulting ^{228}Ra/^{226}Ra activity ratio is unaffected by rain, evaporation, or biological uptake; it is affected only by mixing with water of a lower activity ratio.

To choose a maximum salinity by which low-salinity pools could be characterized, we analyzed historical surface salinity values within a 3° box centered at Barbados for all CTD and bottle casts in the National Oceanographic Data Center (NODC) database, which covers 1921-1983. The overall salinity distribution was decomposed into three significant, normal distributions (Table 1) via a nonlinear regression analysis (Kolmogorov-Smirnov goodness-of-fit test, $p<0.05$). The algorithm cannot discern how many distributions may be contributing to an observed distribution; that information must be supplied to the algorithm as seed values: means, standard deviations, and proportions of the suspected distributions that serve as starting points for the iteration. In our case, when seeded with only two distributions the algorithm could not produce meaningful results. Seeded with three distributions, however, it did produce useful results.

Conductivity and temperature were measured by a vertical array of conductivity-temperature (CT) recorders (Brightwaters Instrument Corp. Model 112, rated sensor accuracy 0.05 mmho/cm, 0.05°C) moored in 290 m of water 2 nautical miles west of Barbados at 13°11.4'N, 59°41.5'W (Figure 1). To measure velocity in the upper water column, an acoustic Doppler current profiler (ADCP) was attached to the mooring between 85 and 105 m depth in an upward looking orientation. The depths of the CT recorders and ADCP varied with each deployment (Table 2). Together the four deployments provided a time series that is approximately 18 months long, with gaps of 24, 27, and 3 days.

Preparation of the mooring data for analysis included corrections for drift of CT recorder clocks, removal of prominent spikes in the conductivity and temperature records, creation of a time series of the depth of each recorder, and calibration of the conductivity and temperature data. During each deployment the shallowest CT recorder also measured pressure. These time series of pressure were used to create a time series of pressure for each lower recorder under the trigonometric assumption that as the entire mooring was pushed over by the current the mooring line remained straight. To determine whether this assumption was reasonable, we compared the depth of the top CT recorder as given by its pressure sensor with the depth of the top recorder calculated from the pitch and roll of the ADCP (not shown). The mean difference between these two measures during the first three deployments, when there was a working pressure sensor on the shallowest CT recorder, was 2.0 m. The standard deviation of the difference was 6.7 m. Based on this reasonably close agreement we decided against using a more complicated method of calculating the depth of each recorder.

The pressure sensor on the shallowest CT recorder failed shortly after the beginning of the final deployment, but, fortuitously, the deepest CT recorder during this deployment also contained a pressure sensor; that recorder's pressure data were used to create time series of pressure for the rest of the recorders during that deployment.

The conductivity and temperature data were calibrated against conductivity and temperature taken from CTD casts made at the mooring site at the time the mooring was first deployed in May 1996 and again when it was deployed for the last time in May 1997. The pressure, conductivity, and temperature data then were used to create time series of salinity and density. Because we were interested in low-frequency events, the time series of salinity, temperature, and density were filtered using a fifth-order low-pass Butterworth filter with a 48-hour cutoff period to eliminate the tide and higher-frequency components of the signal.

The ADCP was an RD Instruments BroadBand "Workhorse" Model WB-300 (rated accuracy ±0.2 cm/s) set up in a four-beam Janus configuration with a 20° beam angle. Time per ensemble was 10 min for all deployments. For the first two deployments the bin size was 8 m and pings per ensemble was 45. For the last two deployments, bin size was reduced to 4 m and pings per ensemble was 68. The number of bins for the four deployments was 15, 20, 40, and 40, respectively. Velocities were filtered with a fifth-order low-pass Butterworth filter using a cutoff period of 72 hours. The filter removes tides and any inertial oscillations, which at the latitude of Barbados (13°10'N) have a period of ~53 hours ($T_i = 2\pi/2\Omega\sin\theta$, $\Omega = 7.292 \times 10^{-5}\ s^{-1}$, θ = latitude). To make stickplots clearer, velocities used in this paper were subsampled every 9 hours from the low-pass filtered data.

To put the salinity data from the mooring into a larger context, TOPEX altimetry-derived data from October 1992 to August 1997 in the region of 5°-15°N and 40°-63°W were used to identify anticyclonic rings using the method described by *Goni et al.* [1996]. These rings are characterized by a higher sea height than the water around them. The low sea height anomaly (actual sea height referenced to mean sea height) signature of warm rings in this region makes them difficult to observe and track [*Fratantoni et al.*, 1995]. Altimeter-derived sea height anomaly data from this region reveal a large annual signal. In fact, when the time series of sea height anomaly at each location is described in terms of annual and semiannual harmonics, the annual harmonic exhibits a maximum amplitude value of ~8.5 cm (Figure 2), which is close to the maximum amplitude of a typical warm core ring in the region. During winter the mean sea height reaches a minimum because the water cools. Warm rings embedded in these cooler waters may exhibit very low positive, or even negative, sea height anomalies. Therefore it is necessary to subtract the annual signal from the sea height anomaly values to obtain the sea height residuals, which then may be used to identify and track these rings throughout the year.

From this analysis we created a frequency distribution of the number of rings generated per month (Figure 3), space-time plots of sea height anomaly (Plate 1) and sea height residual (Plate 2) along two satellite groundtracks near Barbados, and a compilation of all ring tracks from November 1992 to November 1997 (Figure 4).

3. Results

The 228Ra/226Ra activity ratios calculated from our samples all were near 1.0 (Table 3), well within previously reported ranges for Amazon origin [*Moore et al*., 1986; *Moore and Todd*, 1993].

The frequency distribution of the 546 surface salinities within the 3° box around Barbados (Figure 5) indicates three possible modes centered at 33, 34.5, and ~35.6 psu. We propose that the first distribution represents a low-salinity source, the third distribution represents an ambient oceanic salinity, and the second distribution represents a mixture of the two. We were interested in those salinities that fell outside of the oceanic salinity distribution. Because the lower limit of this distribution is 34.5 psu, we chose this value as the upper bound of our working definition of a pool.

A first-order feature of the salinity time series is its heterogeneity (Plate 3). We had expected the 18-month time series to show a relatively constant oceanic background salinity occasionally and briefly perturbed by low-salinity pools. Instead, the duration, depth, salinity, and degree of stratification of the low-salinity pools all vary considerably over the 18 months. However, within this heterogeneity it is possible to discern discrete low-salinity events, especially when the velocity is used in concert with the salinity. Using the 34.5-psu cutoff described above, five pools or events may be discerned during the 18-month deployment of the mooring (Table 4).

The first pool appeared at the mooring on May 20, 1996, brought by currents flowing to the north at 18-20 cm/s. Surface salinity (3 m deep) from CTD casts (Figure 6) show low-salinity water overspreading the study area from southwest to northeast. This pool was advected away from the mooring via north-flowing currents of ~25 cm/s by June 2, shortly after which currents of unknown direction arrived and pushed the mooring over so that the top CT recorder was nearly 80 m below the surface.

The second pool was more pronounced. It appeared on July 9, 1996, accompanied by currents of ~15 cm/s to the north. By the second half of July, north-flowing currents near 25 cm/s were recorded and surface salinity approached 33 psu. Water <35 psu extended to 47 m. Toward the end of September a low-salinity lens of ~33.5 psu appeared at 30 m. It was gone by October 1, when the stratification decreased abruptly and the pool shallowed. Currents at the time were to the south at ~ 10 cm/s, then immediately reversed coincident with the rapid shallowing of the pool. This shallow phase lasted until October 10, 1996, when all water of salinity <34.5 psu left the mooring site.

The third pool, which arrived on February 19, 1997, followed a pattern similar to that of the first: influx of low-salinity water followed by currents (>20 cm/s) strong enough to push the top CT recorder to a depth of almost 60 m. In the case of the third pool the salinity at 10 m was between 32.5 and 33 psu by March 1, then fluctuated slightly until the second week of March, when an apparently north-flowing current tilted the mooring enough to stop the ADCP from recording.

What we call the fourth and fifth events were part of a larger, long-term residence of water of salinity <35 psu that began in mid-May 1997 and was still in place when the top CT recorder failed on September 1, 1997. The fourth pool lasted just over 2 weeks starting May 15, 1997. Just before the <34.5-psu water arrived, the current was flowing to the south at ~15 cm/s, but in this case the current did not seem to be correlated with the arrival of low-salinity water. For example, during the middle 2 weeks of April 1997, a similar period of southward flowing water is seen without a low-salinity pool. The fifth pool arrived on July 9, 1997 accompanied by southward flowing currents of 20 cm/s, which then reversed as the lowest-salinity water of the event, 33.5 - 34 psu, passed the mooring. Like pool two, this pool had water of salinity <34.5 psu extending to more than 30 m, but unlike pool two, the salinity of the water at 10 m was slightly lower. Pools two and five, the two deepest pools, shared another feature: the time of deepest extent of low-salinity water was accompanied by relatively strong north-flowing currents. They differed in that pool five was preceded by a period of south-flowing currents, while pool two was not.

Analysis of TOPEX/Poseidon-derived upper layer thickness maps (not shown) reveals that rings are formed in the region of study at all times of year, but slightly more often in spring (Figure 3). Plate 1 shows two space-time diagrams of sea height anomaly for one ascending (track A) and one descending (track B) TOPEX groundtrack in the vicinity of Barbados between April 1996 and November 1997. The annual cycle is prominent in these diagrams, where the winter (summer) months are characterized by lower (higher) sea height anomalies. The circles in Plates 1 and 2 are placed at the times when low-salinity events occurred and at the along-track latitude corresponding to Barbados. The map shows the TOPEX groundtracks in the region where the two selected groundtracks, A and B, are highlighted. Two groundtracks that run closer to Barbados were not chosen because the data may be contaminated by tidal errors as the groundtracks pass through shallow regions. Plate 2 shows the space-time diagrams of sea height residual for the same altimeter groundtracks. Warm and anticyclonic features usually are characterized by positive values of sea height residual. Because of the different altimeter sampling dates for the two groundtracks, the sea height residuals are not exactly the same at the latitude where these two groundtracks cross. The advantage of using sea height residual is revealed by examining the third pool, which occurred during winter 1997; it cannot be identified on sea height anomaly diagrams (Plate 1), but can be clearly identified on the sea height residual diagram (Plate 2).

The space-time diagrams of sea height residual constructed along two TOPEX groundtracks from April 1996 until

November 1997 (Plate 2) exhibit definite periods of time at the latitude of Barbados when the sea height residual is positive. These positive values are associated with warm features formed at or traveling through the altimeter groundtracks.

The sea height anomaly field is transformed into the upper layer thickness field using a methodology proposed by Goni et al. [1997], in which the upper layer extends from the sea surface to the depth of the 20°C isotherm. This field is then used to identify and track warm rings in the region. The tracks of each warm ring detected by the altimeter from November 1992 until December 1997 are shown in Figure 4. The tracks of four warm rings associated with the low-salinity pools observed during our study period are indicated by thick lines, with the numbers corresponding to each of the low-salinity pools in Table 4. Gaps in the TOPEX data during June and August 1997 made it difficult to track the fifth event back in time.

We can summarize our results as follows: First, the low-salinity water we observed likely came from the Amazon River mixing zone. Second, the salinity field in our study area west of Barbados was very heterogeneous over the 18 months we studied. Third, within this heterogeneity we identified five events that we labeled low-salinity pools. Fourth, the residence times of the pools were longer and more variable than we had anticipated: four of the five pools lasted between 14 and 33 days; the remaining one lasted 94 days. Fifth, the currents associated with the pools were variable, coming from the north or south. Finally, an abrupt change in current direction need not bring low-salinity water, but low-salinity water usually is accompanied by an abrupt change in current direction.

4. Discussion

Previous investigators [e.g., *Borstad*, 1982] have established that surface salinity at Barbados is lowest in July and August and highest in December, January, and February. Our results are consistent with this pattern, although we found low-salinity water as early as February and as late as October (Plate 3). The source of this low-salinity water has been the object of much study, with both the Amazon and Orinoco Rivers proposed as major sources. Recently, the ^{228}Ra/^{226}Ra activity ratio has been used to trace the progress of Amazon and Orinoco water in the western Atlantic and Caribbean [*Moore et al.*, 1986; *Moore and Todd,* 1993]. *Moore et al.* [1986] found ^{228}Ra/^{226}Ra activity ratios of ~2 near the mouth of the Amazon, surrounded by Atlantic Ocean water with a ratio of ~0.2. By the time this water reaches Barbados the activity ratio has fallen, typically to values between 0.5 and 1.3 [*Moore et al.*, 1986; W.S. Moore, personal communication, 1998]. The ^{228}Ra/^{226}Ra activity ratios in water samples we took at Barbados in May 1997 (Table 3) are all within this range. The activity ratios we measured are too low to have stemmed from Orinoco water. *Moore and Todd* [1993] measured activity ratios of 2.8-5.5 near the Orinoco estuary in April 1998. Because the Orinoco estuary is so much closer to Barbados than is the Amazon, the activity ratio of Orinoco water would not have time to decay to a value as low as 1 during its advection to Barbados.

Another possible source of low-salinity water is fresh water from coastal aquifers under Barbados. Island aquifers cannot be ruled out as a significant source of fresh water without further study, but appear unlikely because the ^{226}Ra activities in our samples were similar to those of ocean water, not to the higher values that would be expected were aquifers the source [W.S. Moore, personal communication, 1998]. Further, the location of the low-salinity water progressed from offshore to onshore, supporting a nonlocal origin. Combinations of these three sources cannot be ruled out, but it is probable that if this is the case in our samples, Amazon-derived water predominates over water from other low-salinity sources for the reasons stated.

We do not know the source(s) of low-salinity water encountered at all other times during our two cruises and the 18 months the mooring was deployed, but the radium results and the information provided by drifters [e.g., *Nittrouer*, 1991; *Richardson et al*., 1994], our results from TOPEX data and other remote sensing investigations [e.g., *Muller-Karger et al*., 1988] and numerical models [e.g., *Fratantoni et al.*, 1995] strongly suggest that most of the low-salinity water seen near Barbados is Amazon mixing zone water.

The data from the mooring, historical NODC salinity analysis, and satellite observations point to the region around Barbados, and around our mooring in particular, as an energetic mixing zone highly variable in salinity, in currents, and in invasion of remotely generated mesoscale events, a result in concert with previous findings [e.g., *Bowman et al.*, 1994]. Our results lead us to conclude that the low-salinity pools we observed during our 18-month-long time series were Amazon water carried in remnants of North Brazil Current retroflection eddies as these remnants advected past our mooring. At least two factors likely act to weaken or destroy these rings before they reach our study site.

First, given the 1440-km distance from the retroflection region to Barbados and the 17-cm/s average translational speed of the rings followed in this study, a ring would require ~100 days to travel from the retroflection region at 8°N, 50°W to Barbados. *Fratantoni et al.* [1995] have shown that many rings disintegrate after 100-120 days after being shed at the North Brazil Current retroflection. Since this lifetime is approximately the same as the travel time from the retroflection region to Barbados, it would seem that some of the rings that led to the low-salinity water we observed might have lost their original spatial structure by the time they reached our study area. Further, these rings may slow as they approach the Caribbean [*Fratantoni et al.*, 1995], so the travel time could be longer than 100 days, and a ring may not follow the shortest path from the retroflection to its impinging on Barbados. The space-time plots of sea height residual from TOPEX (Plate 2) support these conclusions: there appears to be a highly variable procession of events over time at any particular latitude. Further, the satellite data (Figure 3) also reveal that rings may be formed in the region at any time of year, not only from July to January as had previously been thought based on more limited observations.

The second contributor to the disorganized salinity field we observed may stem from a more local cause: the effect of the Tobago-Barbados ridge, which leads southwest from Barbados and reduces water depths to ~1000 m. As *Richardson et al*. [1994] point out, this shallowing of the water, combined with the narrow width (~220 km) of the gap between Tobago and Barbados, could be enough to distort any large-scale rotation or even break it down into a variety of smaller-scale vortices.

Our results may be compared with those of Stansfield et al. [1995], who placed two current meters at 5 m and 50 m on a mooring just south of Barbados from April 28 to May 19, 1990. The 22-day record from the lower current meter [*Stansfield et al.*, 1995, Figure 2] showed weak, variable currents during the first half of the deployment. Halfway through the deployment the current turned sharply to the southeast with magnitudes >100 cm/s. The magnitude gradually diminished to 50 cm/s over the remainder of the observations. During that time a pool of water of salinity between 33.1 and 33.7 psu and <50 m thick was observed south of the island. This clean transition from a weak, nondescript flow to such a strong directional flow, accompanied by the presence of low-salinity water, was interpreted as the passage of a North Brazil Current retroflection eddy. Our record from the west of the island showed similar transitions. Further, we saw a more complicated picture: pools may arrive accompanied by currents from either the north and south.

An understanding of the highly variable salinity distribution and its accompanying currents is important for physical oceanographers interested in mixing processes, especially such processes influenced by bottom topography, and for biologists studying larval recruitment patterns to island reefs. One of the goals of our interdisciplinary study is to assess the extent to which remotely forced, disruptive events such as a low-salinity pool affect the ability of larval fish to recruit to the reef along Barbados's west coast. Therefore there is a need to understand the interaction of these anticyclonic rings with the topography of the eastern Caribbean, especially with respect to flows that may be trapped by islands.

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Table 1. Nonlinear Regression of 546 Surface Salinities From NODC CTD and Bottle Casts Made From 1921 to 1983 in a 3° Box Centered at Barbados

Distribution	Mean	Standard Deviation	Proportion
1	33.47	0.95	0.13
2	34.80	0.57	0.48
3	35.72	0.32	0.39

NODC, National Oceanographic Data Center; CTD, conductivity-temperature-depth.

Table 2. Mooring Deployment Information

Deployment	Start Date	End Date	CT Recorder Depths, m	ADCP Depth, m
1	May 10, 1996	July 29, 1996	13, 25, 45, 65, 85, 125	105
2	Aug. 23, 1996	Nov. 13, 1996	10, 25, 45, 80, 100	85
3	Dec. 11, 1996	April 28, 1997	10, 25, 65, 80, 100, 120	85
4	May 2, 1997	Nov. 3, 1997	10, 40, 70, 100, 140	90

CT, conductivity-temperature; ADCP, acoustic Doppler current profiler

Table 3. Activities of ^{228}Ra, ^{226}Ra and Their Ratios for Water Samples. Salinities are those measured by the ship's thermosalinograph at the time each sample was collected.

Sample	Sample Volume, kg	Salinity, psu	^{228}Ra Activity, dpm/100 kg	^{226}Ra Activity, dpm/100 kg	^{228}Ra/^{226}Ra Activity Ratio
1	80.64	31.52	7.77	6.54	1.19
2	78.90	31.50	8.12	7.67	1.06
3	61.48	31.48	9.96	9.17	1.09

Table 4. Summary of Low-Salinity Pools Observed at Barbados, West Indies, Between May 1996 and November 1997

Pool	Date Water ≤34.5 psu First Observed	Date Water ≤34.5 psu Last Observed	Duration, days	Minimum Salinity at 10 m, psu	Deepest Extent of 34.5 psu, m
1	May 20, 1996	June 2, 1996	14	33.55	31
2	July 9, 1996	Oct. 10, 1996	94	32.90	47
3	Feb. 19, 1997	March 20, 1997[a]	30	32.84	23
4	May 15, 1997	June 1, 1997	18	33.77	22
5	July 9, 1997	Aug. 10, 1997	33	33.75	36

[a] Water <34.5 psu was present when mooring tilted too far to record salinity at 10 m.

Figure 1. Barbados, West Indies, and location of mooring used in this study. Inset shows the western tropical Atlantic Ocean and the mouths of the Amazon and Orinoco Rivers.

Figure 2. Map of the region of study depicting the amplitude of the annual component of the TOPEX-derived sea height anomaly. The largest values correspond to the North Brazil Current retroflection region. The amplitude of this signal off Barbados is ~7 cm.

Figure 3. Number of rings found from October 1992 to August 1997 in the region 5°-15°N and 40°-63°W from TOPEX/Poseidon altimetry.

Plate 1. Space-time time diagrams of the sea height anomaly corresponding to two TOPEX groundtracks, A and B, highlighted in the map at the top between April 1996 and November 1997. The alternation of low (blues and purples) and high (yellows and reds) values in the diagrams corresponds to the seasonal cooling and heating of the waters in the region. The white circles are placed at the times when each of the low-salinity pools was observed off Barbados.

Plate 2. Space-time diagrams of the sea height residual corresponding to the TOPEX groundtracks A and B. The white circles, as Plate 1, denote the times when the low-salinity pools occurred at Barbados. Higher sea height residual values are associated with warm anticyclonic features.

Figure 4. Tracks of the TOPEX-derived warm core ring tracks originated in the North Brazil Current retroflection region between November 1992 and November 1997. The four highlighted tracks and their numbers correspond to rings associated with the low-salinity pools off Barbados. The complete track of the ring corresponding to pool five could not be successfully followed due to gaps in the TOPEX data.

Figure 5. Distribution of 547 surface salinity measurements from National Oceanographic Data Center contuctivity-temperature-depth (CTD) and bottle casts with theoretical distributions superimposed.

Plate 3. Time series of salinity from 10 to 110 m from May 1996 to November 1997 and velocity at 34 m over the same period. Areas masked in white extending down from the surface are times during which salinity is unknown because the mooring was tilted by the current or because an instrument failed.

Figure 6. Salinity at 3 m during three sampling days in May 1996. Crosses mark locations of CTD casts.

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