The Evolution and Demise of North Brazil Current Rings*

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ABSTRACT

Subsurface float and surface drifter observations illustrate the structure, evolution, and eventual demise of 10 North Brazil Current (NBC) rings as they approached and collided with the Lesser Antilles in the western tropical Atlantic Ocean. Upon encountering the shoaling topography east of the Lesser Antilles, most of the rings were deflected abruptly northward and several were observed to completely engulf the island of Barbados. The near-surface and subthermocline layers of two rings were observed to cleave or separate upon encountering shoaling bathymetry between Tobago and Barbados, with the resulting portions each retaining an independent and coherent ringlike vortical circulation. Surface drifters and shallow (250 m) subsurface floats that looped within NBC rings were more likely to enter the Caribbean through the passages of the Lesser Antilles than were deeper (500 or 900 m) floats, indicating that the regional bathymetry preferentially inhibits transport of intermediate-depth ring components. No evidence was found for the wholesale passage of rings through the island chain.

1. Introduction

a. Background

The North Brazil Current (NBC) is an intense western boundary current and the dominant surface circulation feature in the western tropical Atlantic Ocean (Fig. 1). Near 6°–8°N the NBC separates sharply from the South American coastline and curves back on itself (retroflects) to feed the eastward North Equatorial Countercurrent (e.g., Csanady 1985; Ou and DeRuijter 1986; Johns et al. 1990, 1998; Garzoli et al. 2003). The NBC retroflection is present year-round but is most intense in boreal autumn (Garzoli et al. 2004; Lumpkin and Garzoli 2005). The NBC occasionally retroflects so severely as to pinch off large isolated warm-core rings exceeding 450 km in overall diameter. Following separation from the NBC, anticyclonic rings with azimuthal speeds approaching 100 cm s^{-1} move northwestward toward the Caribbean Sea on a course parallel to the South American coastline (Johns et al. 1990; Didden and Schott 1993; Richardson et al. 1994; Fratantoni et al. 1995; Wilson et al. 2002; Fratantoni and Glickson 2002; Goni and Johns 2003). After translating northwestward for three to four months, the rings decompose in the vicinity of the Lesser Antilles.

During their brief lifetime, and especially upon encountering the islands of the eastern Caribbean, the strong and transient velocities associated with NBC rings episodically disrupt regional circulation patterns, impact the distributions of near-surface salinity and icthyoplankton (e.g., Kelly et al. 2000; Cowen and Castro 1994, Borstad 1982; Cowen et al. 2003), and pose a physical threat to expanding deep-water oil and gas exploration on the South American continental slope (e.g., Summerhayes and Rayner 2002). Both the NBC and its rings contribute to the dispersal of fresh, nutrient-rich outflow from the Amazon River and provide a mechanism for transport of this water northwestward toward Tobago and Barbados (e.g., Muller-Karger et al. 1988; Johns et al. 1990; Fratantoni and Glickson 2002). Observations also suggest that the interaction of

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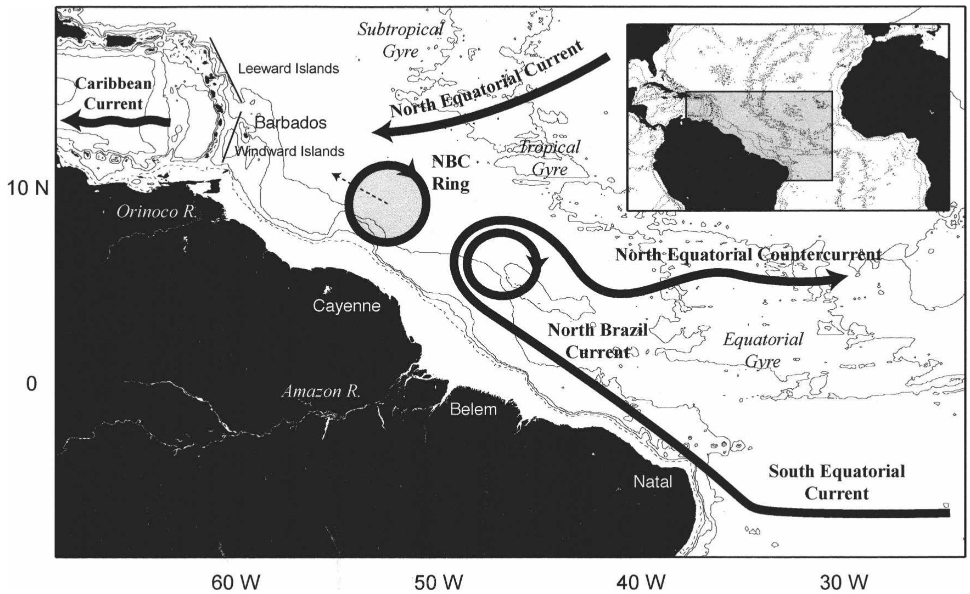


FIG. 1. Schematic depiction of circulation in the western tropical Atlantic Ocean showing the North Brazil Current retroflecting into the NECC near 6°N. The NBC retroflection occasionally collapses upon itself, resulting in the generation of anticyclonic NBC rings that translate northwestward toward the Caribbean and the arc of the Lesser Antilles. The 200- (dashed), 1000-, 2000-, and 4000-m depth contours are shown on this and all figures that follow.

NBC rings with the Lesser Antilles contributes to the generation of energetic anticyclonic eddies observed downstream of the island arc in the eastern Caribbean Sea (Richardson 2005).

In the context of the larger North Atlantic circulation it has been suggested (Johns et al. 2003) that NBC rings are responsible for a preponderance of the 13–15 Sv (Sv $\equiv 10^6$ m^3 s^{-1}) warm-water return flow required to close the Atlantic meridional overturning circulation (MOC) in compensation for the export of North Atlantic Deep Water (e.g., Schmitz and Richardson 1991; Schmitz and McCartney 1993). The remainder of the MOC return flow in this region is transported by shallow coastal currents along the South American shelf and by Ekman transport in the ocean interior (e.g., Candela et al. 1992; Mayer and Weisberg 1993; D. M. Fratantoni 1996, unpublished manuscript; Fratantoni et al. 2000; Halliwell et al. 2003). The water trapped within the core of NBC rings is principally composed of South Atlantic surface, thermocline, and intermediate waters recently advected across the equator by the NBC. As described by Fratantoni and Glickson (2002) and in greater detail below, NBC rings undergo a rapid evolution, driven primarily by interaction with topography and neighboring rings. As a ring evolves, core water is lost or modified through lateral and/or vertical stirring and mixing. To determine the extent to which NBC rings play a role in the intergyre transport of mass and heat in the tropical Atlantic, it is relevant to ask: What is the eventual fate of the core water transported within an NBC ring? Of particular interest to the present study is the downstream fate of relatively fresh Antarctic Intermediate Water (AAIW) trapped within NBC rings. Because such water is colder than the coldest water constituting the Florida Current (Schmitz and Richardson 1991), it must by necessity follow a different path into the North Atlantic subtropical gyre than warmer layers of an NBC ring, which may enter the Caribbean through the passages of the Lesser Antilles (Schmitz and Richardson 1991; Johns et al. 2002).

b. This study

Here we employ a broad set of oceanographic measurements to examine the life history of several NBC rings with particular emphasis on the interaction of rings with their physical environment and the impact of these interactions on the downstream fate of ring core water. The 1998–2001 NBC Rings Experiment was the first coordinated field effort to address the generation mechanisms, physical properties, and downstream evolution of NBC rings. The observational program included four hydrographic and direct-velocity survey cruises (Fleurant et al. 2000a,b,c; Wilson et al. 2002), an array of current meter and inverted echo sounder

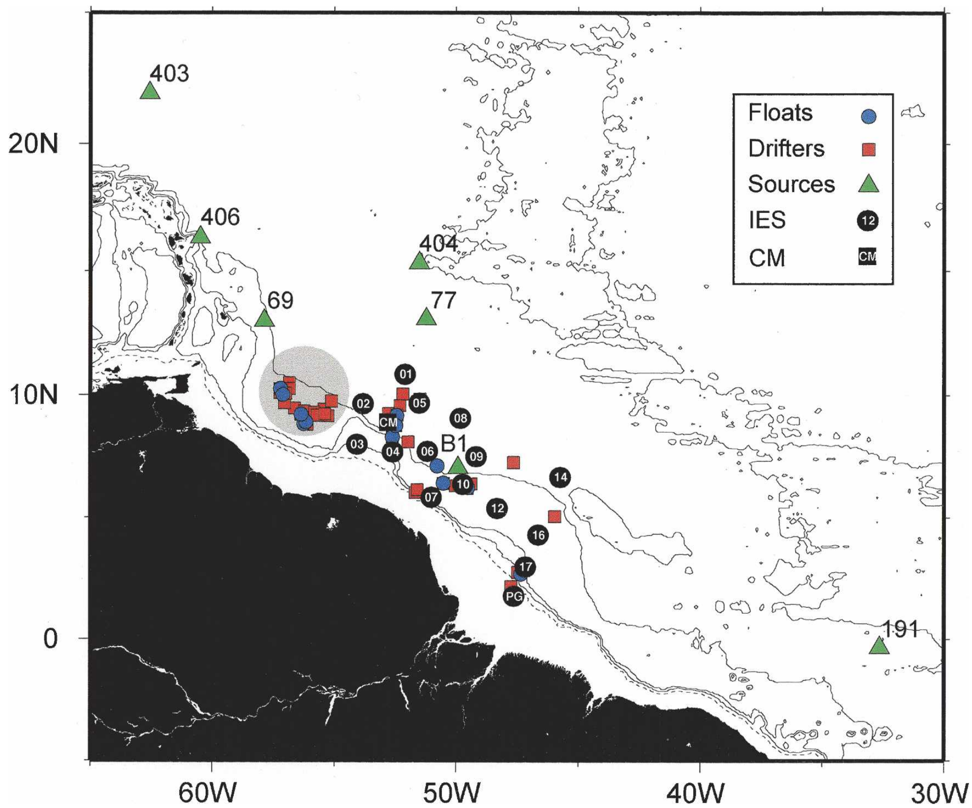


FIG. 2. Instrument deployment locations during the NBC Rings Experiment. RAFOS sound sources 69 and 77 (triangles) along 13°N were installed by WHOI for this experiment. The remaining sources were installed and maintained by scientists from three different countries conducting five different experiments (see Table 1). Also shown are deployment locations of acoustically tracked subsurface RAFOS floats (blue circles) and satellite-tracked surface drifters (red squares). The inverted echo sounder (IES) array and current meter (CM) mooring overlap the typical position of the NBC retroflection. The shaded circle schematically illustrates the location of several NBC rings surveyed by ship and discussed in the text.

moorings (Johns et al. 2003; Garzoli et al. 2004), and satellite observations of sea surface height (Goni and Johns 2001, 2003), sea surface temperature (Ffield 2005), and ocean color (Fratantoni and Glickson 2002).

Of particular relevance to the present investigation are the trajectories of 45 satellite-tracked surface drifters and 28 acoustically tracked subsurface RAFOS floats deployed in and near NBC rings. Unlike the shipboard, moored, and remotely sensed observations noted above, the float measurements described herein have not been reported elsewhere. Furthermore, these measurements include details of subsurface ring structure unattainable via remote sensing and provide a uniquely detailed description of the demise of 10 NBC rings in a region downstream (i.e., to the west) of the primary NBC Rings Experiment study area (Fig. 2). Floats and drifters released within a ring can be thought of as tracers for the fluid dynamically trapped within the ring core. The number of discrete instruments is necessarily small and thus this method does not have the precision associated with, for example, careful water mass analysis or intentionally released anthropogenic tracers (e.g., Watson and Ledwell 2000). It is not appropriate to infer equivalent water-mass volume transports from sparse float and drifter trajectories. Rather, we will use the floats to elucidate the structural evolution of NBC rings and to illustrate a general tendency for differential transport of water at various levels within the ring core.

The remainder of this article is organized as follows. In section 2, we briefly review the instrumentation, methods, and data processing techniques used to obtain the final-quality float and drifter trajectories. In section 3, we review the trajectories of the floats and drifters with an emphasis on those that looped within NBC rings or other vortexlike features. In section 4, we examine, using shipboard observations, the initial structure of several rings and identify key structural variations relevant to our study of ring evolution. In section 5, we describe the evolution of several well-documented NBC rings, focusing on the role of ring interactions with their environment. In section 6, we use floats and drifters as water mass tags to infer the fate of ring core water. The significant results of this study are discussed in section 7.

2. Data and methods

a. Instrumentation

The 45 surface drifters used in this study are similar in construction to the World Ocean Circulation Experiment (WOCE) and Tropical Ocean and Global Atmosphere Coupled Ocean–Atmosphere Response Experiment (TOGA COARE) Lagrangian drifters described by Sybrandy and Niiler (1991). Each drifter consists of a spherical surface float with radio transmitter, antenna, and batteries connected with a wire tether to a 6.44-m-long, 0.92-m-diameter cylindrical cloth drogue with circular holes in its sides. The drogue is centered at a depth of 15 m below the surface. The ratio of the drag area of the drogue to the drag area of the tether and float is approximately 41:1, which results in the drogue's slip through the water being less than 1 cm s^{-1} in winds of 10 m s^{-1} (Niiler et al. 1995). Additional information about drifter performance and data processing can be found in Glickson et al. (2000).

The 28 RAFOS floats (Rossby et al. 1986) deployed as part of the NBC rings field program were of two types. The electronic components for 22 DLD2 RAFOS floats were acquired from the Seascan Corporation of Falmouth, Massachusetts. The floats were assembled in 2-m-long glass pressure hulls, calibrated for temperature and pressure, and ballasted to be neutrally buoyant on prescribed pressure surfaces. Six additional RAFOS floats of an earlier design were assembled from spare parts and components salvaged from earlier float experiments. All floats recorded temperature, pressure, and the times of arrival of 80-s, 260-Hz sound signals transmitted by an array of eight moored sound sources, two of which were installed by the Woods Hole Oceanographic Institution (WHOI) as part of this experiment (Fig. 2; Table 1). One of two RAFOS sound source moorings located east of Barbados was instrumented with temperature–salinity recorders to evaluate variability associated with NBC rings near the depth of the AAIW salinity minimum. The DLD2 floats listened for acoustic broadcasts every 12 hours while the older floats listened every 24 hours. Only a small subset of sources was heard by a float at any one time.

The RAFOS floats were weighed in air and in water at several different pressures to estimate their density and compressibility. Floats were adjusted to drift at preset depths chosen to represent regionally important water masses (Table 2). Waters of South Atlantic origin lying equatorward of the North Equatorial Countercurrent carry a distinctive temperature, salinity, and dissolved oxygen signature, being relatively fresher and higher in oxygen compared to waters from the North Atlantic on the same density surfaces (Wüst 1964; Emery and Dewar 1982; Schmitz and Richardson 1991). We attempted to target depths on which the contrast between North and South Atlantic water mass properties were particularly distinct. The levels chosen roughly match transport classes chosen by Schmitz and Richardson (1991) in their assessment of the source waters of the Florida Current (Table 2).

The mean depth of the floats over their lifetime was slightly deeper than their target depths (Table 2). This

TABLE 1. Sound sources used for tracking RAFOS floats. Two 260-Hz RAFOS sound sources (69 and 77) were deployed by the WHOI specifically for the NBC Rings Experiment. The remaining sources were installed by colleagues associated with other regional observational programs. These experiments include the Boundary Current Experiment (BOUNCE), the Deep Basin Experiment (DBE), a long-term French effort to explore the tropical Atlantic with acoustically tracked profiling floats, the NBC Rings Experiment (NBC), and the German MOVE experiment. End dates for sources without a confirmed recovery or failure are listed as "none." In all tables, dates are listed as yymmdd, where yy gives the last two digits of the year, mm is month, and dd is day. Here ID is identifier and PI is principal investigator.

Source ID	Expt	PI (institution)	Start date	End date	Lat (°N)	Lon (°W)	Depth (m)
185	BOUNCE	Bower (WHOI)	941019	None	36.687	58.263	1500
B1	French	Ollitrault (IFREMER)	950101	None	7.028	49.925	1000
191	DBE	Hogg/Owens (WHOI)	950212	None	−0.327	32.643	1000
69	NBC	Fratantoni (WHOI)	981108	000622	13.000	57.886	650
77	NBC	Fratantoni (WHOI)	981110	000620	12.996	51.107	700
403	MOVE	Zenk/Send (IFM/Kiel)	000117	None	21.938	62.570	1100
404	MOVE	Zenk/Send (IFM/Kiel)	000129	010103	15.324	51.526	1110
406	MOVE	Zenk/Send (IFM/Kiel)	000204	001230	16.333	60.499	1088

TABLE 2. Target depths and water masses for float and drifter measurements. A total of 45 surface drifters and 28 RAFOS floats were deployed as part of the experiment. Target depths were similar to temperature intervals chosen by Schmitz and Richardson (1991) in a study of the sources of the Florida Current (see rightmost column). The upper level of RAFOS float deployment coincides with the subthermocline North Equatorial Undercurrent (NEUC), which is fed by a combination of Southern Hemisphere water from the NBC and Northern Hemisphere water from the North Equatorial Current (NEC). There is thus a particularly large hemispheric contrast in salinity and oxygen at this level. The two deepest float levels correspond to upper and lower variants of Antarctic Intermediate Water with respective minima in dissolved oxygen and salinity. Below a depth of 1000 m, North Atlantic Deep Water flows southward, counter to the expected direction of ring translation. Temperature, salinity, and pressure shown are the targets used when the floats were prepared. The average pressures actually recorded by the collection of floats at that nominal depth are in parentheses.

Level	Instrument	No. deployed	Pressure (dbar)	Temperature (°C)	Salinity (psu)	Potential density	Significance	Temperature interval (°C)
1	Drifter	45	Surface	28.0	36.2	23.3	Surface water	>24°C
2	RAFOS	11	200 (249)	15.0	35.9	26.5	NEC/NEUC	12°–17°C
3	RAFOS	8	450 (526)	8.0	34.8	27.1	U-AAIW/O_2 min	7°–12°C
4	RAFOS	9	800 (873)	5.2	34.6	27.3	L-AAIW/S min	<7°C

offset, typical of several recent WHOI float experiments, suggests an unknown systematic bias in our ballasting procedure. At the end of their (approximately 18 month) missions, the floats dropped external ballast weights, rose to the surface and transmitted recorded data via Service Argos. Additional information about float performance and data processing can be found in Wooding et al. (2002).

b. Deployment

Four regional survey cruises were conducted as part of this program (Fleurant et al. 2000a,b,c). During each cruise, rapid mapping of the upper-ocean temperature and velocity fields was performed using expendable bathythermographs (XBTs), a 150-kHz shipboard acoustic Doppler current profiler (ADCP), and a wire-lowered hydrographic package including conductivity–temperature–depth (CTD)/O_2 and lowered ADCP (LADCP). Station spacing within rings was approximately 20–50 km. Cast depths were limited to 2000 m to increase survey speed. These rapid surveys provided a coarse determination of the ring center position, overall size and shape, and water mass composition and circulation intensity at several depths. Once the basic geometry of each ring was determined, surface drifters and RAFOS floats were deployed at several radii, generally within 25–50 km of the ring center. Over time, these floats and drifters moved outward from the ring center and circulated at larger radii generally limited by the radius of maximum velocity (typically 125–150 km at the surface). Additional drifters and floats were released outside of rings in order to sample the background circulation field. In several instances, a vertical array consisting of floats at multiple depths was deployed at a single geographic location within a ring. Float and drifter deployment positions are summarized in Fig. 2.

c. Data processing

Surface drifter positions were quality controlled and linearly interpolated at a regular 6-h spacing. Position uncertainty for the drifters is estimated to be around 300 m. A 2-day half-width Gaussian filter was applied to the interpolated trajectories to suppress tidal and inertial variability. Velocities were computed from the filtered position time series using a cubic spline function. Of the 45 drifters deployed, 42 returned useful data.

RAFOS float positions were calculated by least squares triangulation using time of arrival measurements from as many sound sources as were available (usually three) at each 12-hourly interval. A cubic spline was used to interpolate missing values. In most cases, interpolation was limited to gaps under 10 days. A Doppler correction was applied to adjust the times of arrival for the distortion caused by the speed at which the float was traveling. Position time series were then smoothed using a Gaussian-shaped filter. Last, a cubic spline was fitted through the positions and velocity series were calculated along the trajectories. Of the 28 floats deployed, 24 returned data and 21 were successfully tracked.

In general the float trajectories were of good quality with few gaps or discontinuities. We estimate the error in our acoustic tracking to be around 4 km. In a latitudinal band near 13°N east of the Lesser Antilles floats initially heard only the two WHOI sound sources (Fig. 2) and ambiguities arose in the triangulation when floats approached the baseline connecting the two sources. The Meridional Overturning Variability Experiment (MOVE) sound sources (Table 1), installed in early 2000, significantly improved tracking in this region. Several floats drifted into the Caribbean where tracking was impossible because islands and shoaling topography blocked the acoustic signals.

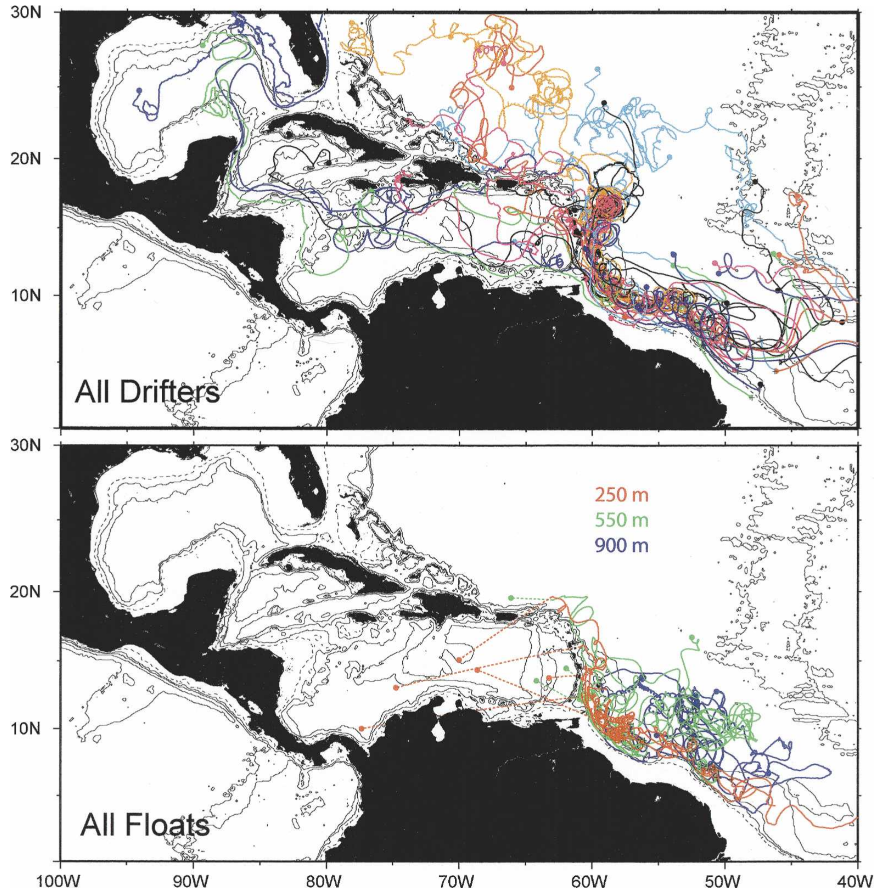


FIG. 3. Trajectories of all (top) surface drifters and (bottom) RAFOS floats deployed during the NBC Rings Experiment. In the top panel colors are randomly assigned. The band of looping trajectories indicative of NBC ring translation closely follows the western boundary and the Antilles island arc northward to around 18°N. Note the large number of looping trajectories that passed close to Barbados (near 13°N, 60°W). The trajectories of several drifters that moved eastward in the NECC are truncated. In the bottom panel colors denote the nominal depth of each RAFOS float: 250 (red), 550 (green), and 900 m (blue). It was not possible to conclusively determine through which passage each RAFOS float entered the Caribbean. The dashed lines connect the last known acoustically tracked position of the float with its surfacing position determined by Argos satellite tracking.

Note that neither the isobaric floats nor the surface drifters are truly Lagrangian and thus do not exactly follow water parcels, particularly in regions of strong vertical motion. To the extent that we are investigating here only the first-order aspects of the horizontal circulation, we do not believe the approximately Lagrangian nature of the measured trajectories has any significant impact on our interpretation. A more detailed study of, for example, ageostrophic secondary circulations associated with flow near topography (e.g., Fratantoni et al. 2001) or interior transport pathways involving shallow overturning cells (e.g., Halliwell et al. 2003) would benefit from application of truly Lagrangian instrumentation (e.g., D'Asaro et al. 1996; D'Asaro 2003).

3. Summary of float and drifter observations

a. Overview of trajectories

Figure 3 summarizes the trajectories of all floats and drifters used during the experiment. Thirty drifters were purposefully launched in rings. Many of these became trapped within the ring's azimuthal circulation and circulated (looped) for various amounts of time as the ring translated northwestward (Table 3). Additional drifters looped as they were entrained into the periphery of translating rings. The longest trajectories in NBC rings were drifter 18753 in R7 (14 loops; 7 months) and Float 33 in R2 (35 loops; 14.4 months). Figure 3 shows a large concentration of looping drifters in a band, approximately 300 km wide, parallel to the

TABLE 3. Floats (F) and drifters that executed at least one convincing anticyclonic loop within an NBC ring. The time period during which each instrument looped and the number of loops completed are indicated.

Ring	ID	Depth (m)	Start date	End date	Loops
R1	F29	275	981208	990310	14
R1	F32	620	981209	990113	1
R2	9636	SFC	981206	990303	5
R2	9638	SFC	981206	990113	2
R2	9639	SFC	981206	990220	6
R2	F35	540	981206	981219	1
R2	F33	320	981206	990719	35
R2	F30	555	981206	990105	1
R2	F34	600	990410	990420	1
R2	F46	840	990701	990730	1
R2	F31	540	990213	990317	2
R3	9632	SFC	990221	990501	7
R3	9635	SFC	990221	990421	6
R3	12201	SFC	990221	990421	6
R3	15989	SFC	990221	990522	10
R3	16006	SFC	990221	990426	6
R3	9634	SFC	990401	990428	1
R3	F34	600	990305	990315	1
R4	12232	SFC	990221	990512	4
R5	24555	SFC	990910	991013	2
R5	18751	SFC	991108	991214	3
R6	9167	SFC	000218	000401	2
R6	9898	SFC	000218	000331	3
R6	18802	SFC	000218	000402	3
R6	18810	SFC	000221	000423	5
R6	18811	SFC	000221	000407	3
R6	18815	SFC	000221	000505	7
R6	18834	SFC	000315	000704	9
R6	F193	510	000220	000508	7
R6	F156	220	000221	000327	7
R6	F34	600	000222	000407	2
R7	18752	SFC	000402	000810	12
R7	18753	SFC	000331	001022	14
R7	18810	SFC	000520	000908	7
R7	F22	SFC	000701	000930	5
R8	17540	SFC	000422	000630	5
R8	18832	SFC	000605	000630	1
R9	19082	SFC	010208	010320	3
R10	23061	SFC	010202	010620	8

continental slope of northeastern South America and the arc of the Lesser Antilles. This band defines the NBC ring translation corridor and is comparable to that identified using satellite altimetry (Didden and Schott 1993; Goni and Johns 2001, 2003).

The band of looping drifters approximates the 300-km diameter within which particles are trapped within an NBC ring. These values are consistent with independent estimates of the typical surface radius of maximum velocity (125–150 km) (e.g., Fratantoni and Glickson 2002; Wilson et al. 2002; Johns et al. 2003) and with results from the present experiment (see below). There is no evidence in Fig. 3 that this band extends into the eastern Caribbean: The Lesser Antilles clearly divert the initially northwestward translation of NBC rings to a more northward course parallel to the island arc.

Using the same band of drifter trajectories as an indicator of ring motion, we can identify the region north of Barbados between 14° and 18°N as the northern limit of NBC ring translation. The persistent yet near-stationary circulation of NBC rings in this area of very low background circulation results in a local maximum in eddy kinetic energy, as previously illustrated by Fratantoni (2001) using a larger collection of surface drifters. A few drifters transited the entire length of the Caribbean and entered the Gulf of Mexico. Only one drifter (9635 in R3) followed the Gulf of Mexico Loop Current through the Straits of Florida and into the Gulf Stream. Approximately 10 drifters traveled eastward in the North Equatorial Countercurrent (NECC) or northward along the Mid-Atlantic Ridge near 45°W.

The trajectories of 21 RAFOS floats, including 20 launched in NBC rings, are shown in the lower panel in Fig. 3. For simplicity, we refer to the floats by one of three nominal depth classes: a thermocline layer near 250 m, a middepth layer near 550 m, and a deep layer near 900 m (Table 2). The pattern of ring translation illustrated by the float trajectories is less clear than that shown by the drifters because most floats did not circulate in rings for very long. Overall, five of the eleven 250-m floats penetrated the Lesser Antilles, as indicated by the dashed lines in Fig. 3. Ten of the 250-m floats exhibited a general movement toward the northwest, while one drifted eastward in the North Equatorial Undercurrent near 4°N to approximately 32°W (not shown in full in Fig. 3). Two of the eight 550-m floats entered the Caribbean through the Windward Islands, and a third drifted northwestward around the Lesser Antilles and surfaced north of Puerto Rico.

Based on the previous work of Richardson et al. (1994), we expected to measure long looping trajectories with our 900-m floats. In fact, with the exception of an energetic subsurface cyclone discussed below, none of the 900-m floats looped very long in rings and few made significant northwestward progress along the South American coast. In an earlier float experiment in this region, two Sound Fixing and Ranging (SOFAR) floats at a nominal depth of 800 m looped and translated northwestward along the boundary within NBC rings, and one of these floats was inferred to have entered the Caribbean and drift northward through the Gulf of Mexico into the Gulf Stream (Richardson et al. 1994). The present experiment did not yield any trajectories approaching that length. Several of our 900-m floats were advected anticyclonically when in the vicinity of a ring, confirming that the ring's azimuthal velocity does extend to this depth, though perhaps not at an amplitude sufficient for a float to remain trapped. For a ring moving at constant velocity, particles are trapped only when the azimuthal velocity is greater than the ring translation velocity (Flierl 1981). When a ring moves erratically, the azimuthal velocity needs to be significantly greater than the mean translation velocity. Northward transport in the NBC upstream of the retroflection is minimal at 800 m, and below this depth the southward transport of the Deep Western Boundary Current increases to greater than 20 cm s^{-1} by 1400 m (Johns et al. 1998). Thus our 900-m floats (originally targeted for 800 m) may have found themselves in a depth interval of weak and variable velocity in the shear layer between northward and southward flow.

b. *Observed NBC rings*

A summary of NBC ring characteristics inferred from the looping floats and drifters is shown in Table 4. Maximum azimuthal speeds observed at the surface were around 90 cm s^{-1} and loop diameters generally ranged from 200–300 km, with a mean of 249 km and a standard deviation of 51 km. Surface drifters in rings looped with periods of 9–14 days. The subsurface portions of rings tended to be smaller in diameter (around 90 km) with reduced azimuthal velocity (40 cm s^{-1}) and a somewhat shorter rotation period (6 days). The average tracked lifetime of the 9 rings observed with drifters was 3.3 months (standard deviation 1.3 months). The actual ring lifetime is somewhat greater as the drifters were not deployed at the moment of formation and may have ceased looping prior to complete ring demise. The lifetime estimates are therefore best viewed as a lower bound. Rings R2, R3, and R6 were observed with several simultaneously looping drifters and floats and thus the characteristics and downstream evolution of these rings are the best documented. Trajectories of floats and drifters in these and several other rings are summarized in Fig. 4. Ring R1 was unusual in that several surface drifters failed to remain trapped within the azimuthal circulation while a single RAFOS float at 270 m completed 14 loops. Shipboard surveys of this ring reveal a thermocline-intensified velocity structure with little or no surface expression (Fratantoni et al. 1999; Wilson et al. 2002; Johns et al. 2003). Rings of this type constitute a substantial new discovery resulting from the NBC Rings Experiment and will be discussed in greater detail below.

Approximate paths of translation followed by individual rings were drawn subjectively through the looping trajectories and are shown in Fig. 5. In general the rings followed a fairly narrow path with the center of circulation located roughly 200 km offshore of the 200-m depth contour. The pathways of ring translation, particularly near Barbados and the Lesser Antilles, are defined more clearly in the present float and drifter data than in the altimetric representation of Goni and Johns (2003) because of the considerably coarser spa-

TABLE 4. NBC ring characteristics inferred from floats and drifters. Rings were tracked with surface drifters except for the thermocline-intensified R1 (see text) and the cleaved subsurface remnants of R2 and R6. Those rings tracked with subsurface floats are indicated by an asterisk. The number of loops was estimated visually using trajectories and velocity time series. Diameter of loops, rotation period, and azimuthal speed are estimated maximum values for each ring. Rings are numbered chronologically starting with rings R1–R3 observed on the first two regional survey cruises. Since not all rings that existed during the dates discussed here (December 1998–June 2001) were tracked with floats or drifters, this list is a subset of the total number of rings present. Float 33 in R2* entered the Tobago Trough in August 2000 and looped there for 7 months. This float could not be tracked in the trough because signals from only one sound source could be heard. Continued looping was inferred by the periodic variation in float distance from the source. Mean and standard deviations include surface drifter measurements only.

Ring	Dates tracked	Months	Loops	Period (days)	Diameter (km)	Speed (cm s^{-1})
R1*	981208–990313	3.2	14	6	95	45
R2	981206–990303	2.9	6	12	310	95
R2*	981206–990719	14.4	35	6	85	35
R3	990217–990522	3.1	10	9	190	65
R4	990302–990512	2.3	4	12	240	60
R5	990910–991214	3.1	3	13	230	50
R6	000216–000704	4.5	9	9	190	75
R6*	000220–000508	2.5	7	10	180	30
R7	000331–000912	5.4	14	9	210	80
R8	000422–000630	2.3	4	14	330	90
R9	010208–010320	1.3	3	11	250	90
R10	010202–010620	4.5	8	14	290	75
	Mean	3.3	7	11	249	75
	Std dev	1.3	4	2	51	15

tial and temporal resolution of the latter. For example, the inferred drifter-tracked ring trajectories pass over or slightly west of Barbados while the altimetry-tracked ones lie mainly east of that island. As shown below, no drifter in an NBC ring circulated northward to the east of Barbados—this implies that the center of rotation must have passed to the west of Barbados.

The tracked paths of R2, R4, R5, and R8 terminate east of Tobago and Trinidad where the drifters ceased looping. North of Barbados ring translation slowed markedly and several rings became quasi stationary between 14° and 18°N. We infer that R7 merged with R6 in this vicinity in May 2000. The two drifters that had been separately looping in each ring began to circulate coherently around the same center during May 2000 as R7 moved northward along the Antilles arc and overtook R6. Drifters subsequently looped continuously in this region for at least five months in the combined ring. Dynamic height distributions (e.g., Reid 1994) and numerically derived streamfunction maps (e.g., Fratantoni et al. 2000; Johns et al. 2002) indicate that, in this latitude band, the generally northwestward flow of South Atlantic surface water into the Caribbean (Johns et al. 2002) transitions to the generally southwestward flow of the North Equatorial Current. We speculate that the southward component of the large-scale geostrophic flow in this region is sufficiently contrary to the direction of ring translation to halt northward ring movement.

Along the coast of South America between 50° and 58°W the mean translational velocity of rings R2, R3, R4, R5, R8, and R10 was 17 ± 2 cm s^{-1}, in general agreement with previous remote and in situ measurements (Fratantoni and Glickson 2002, Garzoli et al. 2003; Goni and Johns 2003). As the rings passed Barbados, the drifters looping within them accelerated northward through the 140-km gap between Barbados and St. Vincent with typical speeds of 100 cm s^{-1}. The actual ring translation speed during this period is difficult to estimate from both drifters and remote observations because of the distortion in ring shape and azimuthal velocity imposed by the proximity of the islands. Upon reaching the Lesser Antilles R3, R6, R7, R9, and R10 all turned northward (Fig. 5) and passed very close to Barbados. One drifter in R6 looped completely around Barbados in a northward-oriented elliptical trajectory with major and minor axes of 100 and 50 km and came within 5–10 km of the island's west coast. A second drifter in the same ring grounded on the east coast after a partial loop to the north of the island. We infer from these trajectories and the spatial extent of a typical NBC ring that Barbados must have been completely enveloped during these encounters. North of Barbados the rings slowed and became quasi stationary with little mean velocity, R3, R6, and R7 being the best examples (Fig. 4). These observations illustrate the potential importance of NBC rings to the variability of the coastal circulation surrounding Barbados and highlight their potential as a mechanism for redistributing marine populations (e.g., Cowen et al. 2003).

RAFOS source mooring S1 consisted of both an acoustic source (69 in Fig. 2) and a vertical array of 10 temperature sensors and five conductivity sensors (see Glickson and Fratantoni 2001). Time series from this mooring provides evidence of substantial temperature–salinity variation east of Barbados associated with passage of a NBC ring. Figure 6 shows that water properties to the east of Barbados and at depths as great as 1000 m change dramatically during ring encounters with salinity and temperature excursions approaching 0.2 ppt and 1°C near a depth of 800 m. This tendency for intermittent freshening and cooling east of Barbados coincident with ring passage confirms that a quantity of Antarctic Intermediate Water (identified as a local salinity minimum near 800 m) is present within translating NBC rings at this latitude. Transport of intermediate water within NBC rings was first suggested by the SOFAR float trajectories of Richardson et al. (1994).

c. *Observed cyclonic eddies*

Three cyclonic eddies (Table 5) were observed in addition to the anticyclonic rings spawned by the NBC retroflection.[1] Two cyclones (C2 and C3) were observed with surface drifters in a region north of Barbados. As described above, the azimuthal flow in several rings was observed to accelerate as a ring moved northward along the island chain and its western limb occupied the constriction between Barbados and St. Vincent. In the case of R3, we posit that the accelerated flow and enhanced cyclonic shear on the western side of the resulting jet led to the formation of a small (70 km) cyclonic vortex (C2: see Table 5 and Fig. 4). The azimuthal velocity of this feature was near 25 cm s^{-1} and its rotation period was 6 days or roughly 3 times the local inertial period (2.2 days). Vortex C2 drifted slowly northward parallel to the island chain to 17°N over a period of 1.6 months.

A particularly long-lived cyclonic eddy (C1) was identified using floats deployed near R3 during a Feb-

[1] In the spirit of Fuglister (1972) and Olson (1986) we reserve the term "ring" to describe a vortex pinched off from a convoluted ocean current and refer to other vortices generically as "eddies."

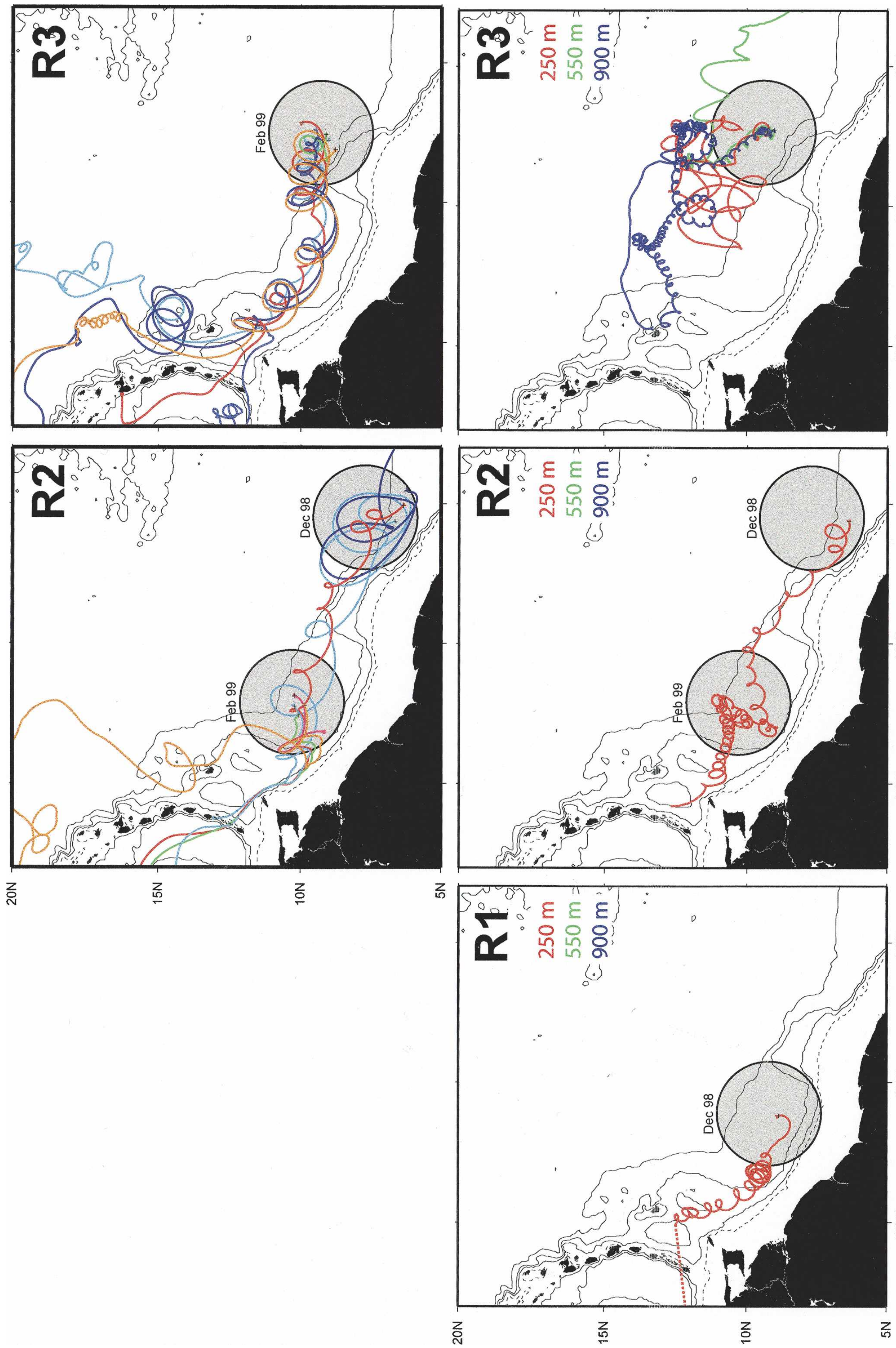


FIG. 4.

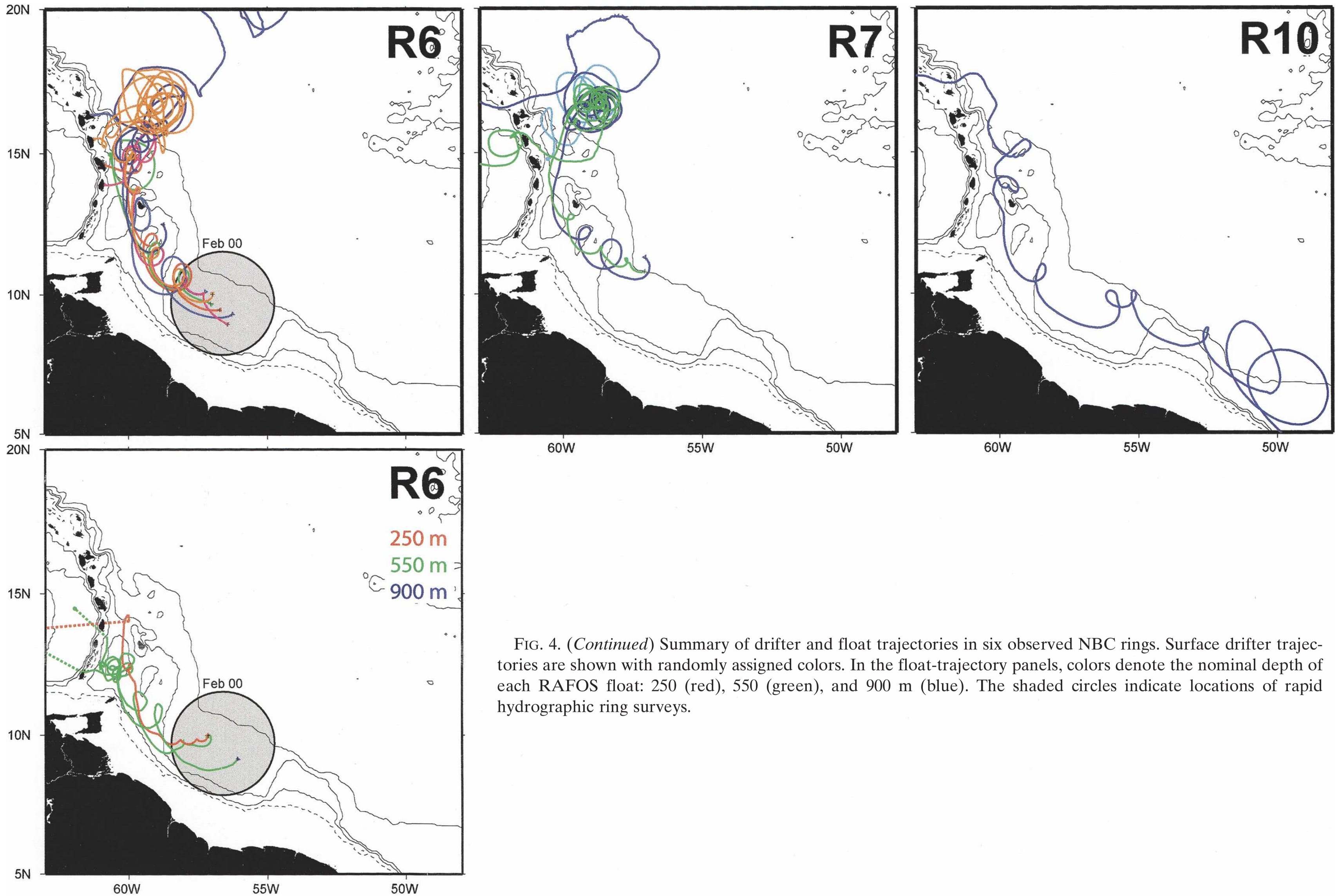


FIG. 4. (*Continued*) Summary of drifter and float trajectories in six observed NBC rings. Surface drifter trajectories are shown with randomly assigned colors. In the float-trajectory panels, colors denote the nominal depth of each RAFOS float: 250 (red), 550 (green), and 900 m (blue). The shaded circles indicate locations of rapid hydrographic ring surveys.

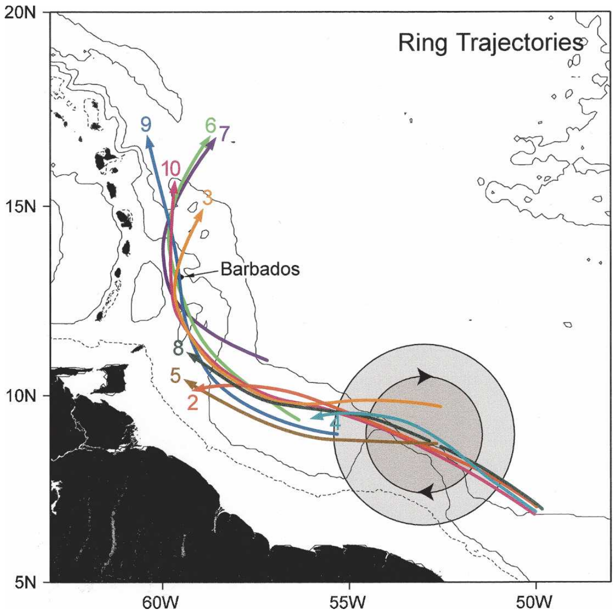


FIG. 5. Trajectories of nine NBC rings inferred from looping surface drifters. The centers of five rings passed northward over or close to Barbados. Drifters in four rings stopped looping before reaching Barbados.

ruary 1999 survey near 53°W. Surface drifters launched in R3 looped anticyclonically in the shallow surface-intensified circulation and remained with the ring as it translated westward (Fig. 4). In contrast, RAFOS floats launched in R3 (22, 23, and 36) looped *cyclonically* at depths of 530 m, 907 m, and 843 m, respectively. The subsurface cyclone was the longest continuously tracked feature of this experiment with a total of 80 loops over 10.5 months recorded by float 36 (Fig. 7). Eddy C1 was not obvious in the shipboard LADCP or moored current meter data although it could be identified in hindsight using the float trajectories as a guide. This eddy was relatively small (35-km diameter) with a moderate 25–30 cm s^{-1} azimuthal velocity and a 4-day rotation period (Fig. 8), slightly longer that the local inertial period (3.5 days). Note that irrespective of the rotation period, the sense of rotation (cyclonic) is opposite to that of an inertial oscillation in the Northern Hemisphere. The cyclonic eddy translated erratically northwestward at a mean velocity of 3.2 cm s^{-1} on a path distinct from that followed by the anticyclonic near-surface component of R3 (Fig. 4). The general motion of the remaining 900-m floats in this region was to the east (Wooding et al. 2002), suggesting that the northwestward-moving C1 was not advected by a background flow. Float 36 stopped looping when the cyclone encountered the shoaling bathymetry east of Barbados.

4. Ring structure

Before considering the evolution of NBC rings it is useful to review their hydrographic and velocity structure shortly following formation. Ring-to-ring differences in the structure of NBC rings were briefly described by Fratantoni et al. (1995) in an analysis of moored velocity and temperature observations collected by Johns et al. (1990). That dataset lacked the detail necessary to fully describe these structural differences. More recently, detailed in situ observations of three NBC rings surveyed near 57°W (identified as R1, R2, and R6 here) revealed significant ring-to-ring variability in both azimuthal velocity structure (Fratantoni et al. 1999; Wilson et al. 2002) and water mass composition (Johns et al. 2003). These surveys were located about 1.5 typical ring diameters west of the ring formation region, coincident with the maximum westward extent of the NBC retroflection near 52°W. At least two distinct structural variants can be identified: a surface-intensified ring with maximum azimuthal velocity located at or near the surface and a thermocline-intensified ring with maximum velocity at or below the main thermocline. In addition, a vertically coherent "barotropic" circulation extending to depths greater than 2000 m was observed in several rings, and at least two rings observed with shipboard and moored current meter measurements had little or no surface velocity expression (see Wilson et al. 2002; Johns et al. 2003).

In Fig. 9 we have used in situ observations of azimuthal velocity (from shipboard LADCP measurements) to highlight these structural differences. Ring R1 is a thermocline-intensified ring with maximum azimuthal velocity located near 150 m and minimal surface expression. Ring R2 is surface intensified and had a deep-reaching barotropic velocity structure with velocity of 20 cm s^{-1} at 1000 m. Ring R6 exhibited strong circulation at both surface and thermocline levels and could be reasonably described as a superposition of the structure expressed by R1 and R2. Radial hydrographic and velocity sections (Fig. 10) indicate that the relative absence of surface circulation in R1 is accompanied by the upward doming of isotherms in the upper thermocline. This is consistent with a geostrophically compensated lenslike vortex with maximum velocity in the thermocline.

At the surface, only R1 exhibits a pool of relatively fresh water (inferred to be of Amazon origin) capping the entire ring core. In contrast, R2 and R6 (with vigorous surface circulations) exhibit near-surface bands or streamers of relatively fresh water constrained to lie just beyond the radius of maximum azimuthal velocity (Fig. 10). At greater depths all three rings exhibit a

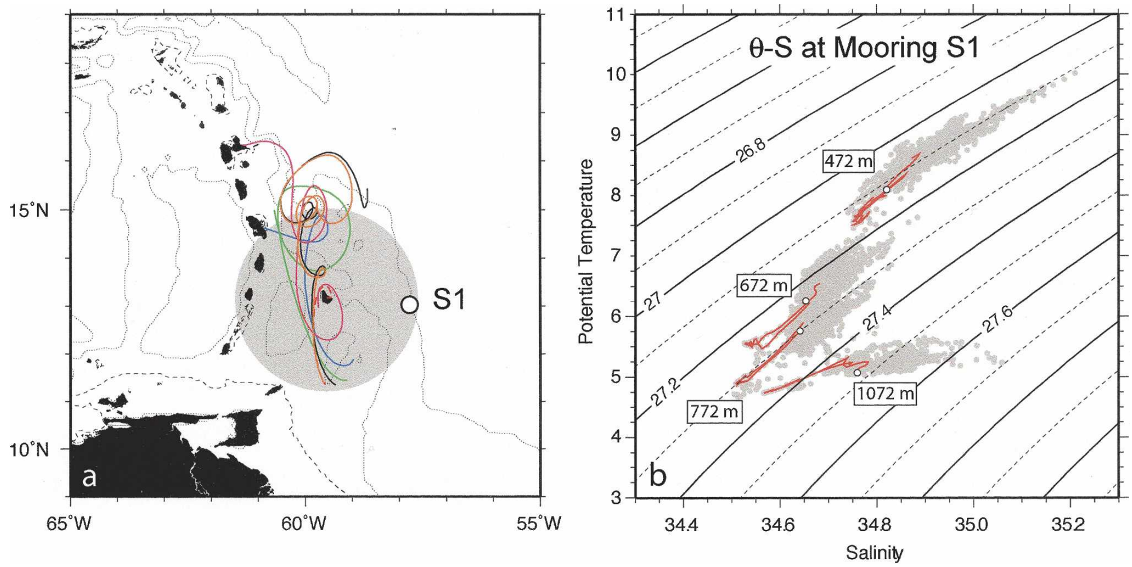


FIG. 6. Evidence of substantial temperature–salinity variation east of Barbados associated with passage of NBC ring R6. (a) Drifter trajectories in R6 as the ring enveloped Barbados during the period 22 Mar–19 Apr 2000. The location of sound source mooring S1 is indicated. The shaded circle indicates the relative scale of a 400-km diameter ring. The actual ring geometry would likely be elongated parallel to the island arc. (b) Composite potential temperature–salinity diagram constructed from the 16-month mooring time series at source mooring S1 (gray dots). Potential temperature–salinity values corresponding to the approach of R6 are shown in red with an open circle indicating the first day of the event. Depth (m) of each moored measurement is indicated. Note the tendency toward cooler and fresher conditions at all depths as the ring passes near Barbados.

hydrographically distinct core volume bounded by a vigorous circulation and significant lateral gradients in salinity and dissolved oxygen. Near 100-m depth the salinity gradient is accentuated by a band of North Atlantic subtropical underwater (salinity maximum water) (e.g., Worthington 1976). Relatively low-salinity South Atlantic thermocline water is trapped within the ring core but is flanked by relatively high-salinity North Atlantic water. The anomalous tracer properties within the ring cores indicate that all three observed NBC rings transport, to varying degree, South Atlantic surface, thermocline, and intermediate waters into the subtropical North Atlantic. These transports are carefully quantified and discussed in detail by Johns et al. (2003).

Garzoli et al. (2004) investigated the relationship between NBC transport and ring generation using an array of inverted echo sounder moorings (see Fig. 2) and found ring formation was linked to maxima in upstream NBC transport. Observations of NBC ring structure synthesized from the NBC Rings Experiment current meter mooring near 9°N, 53°W confirm the structural differences noted and prompted Johns et al. (2003) to propose a seasonal dependence related to the upstream structure of the NBC. These observations also revealed structural variants similar to those mentioned above including four subsurface-intensified rings with little or no surface signal. Johns et al. found no seasonal variation in the formation rate of rings although they did find a seasonal dependence of ring structure related to the upstream structure of the NBC. Specifically, deeper

TABLE 5. Characteristics of three observed cyclonic eddies. The number of loops was estimated visually using trajectories and velocity time series. Diameter of loops, azimuthal speed, and rotation period are estimated maximum values for each ring. Eddy C1 was tracked with subsurface floats for nearly 11 months. This long-lived deep cyclone is described in the text and illustrated in Figs. 7 and 8. Eddies C2 and C3 were observed with surface drifters north of Barbados and appear to be associated with the demise of R3 (see Fig. 4).

Eddy	Dates tracked	Months	Loops	Period (days)	Diameter (km)	Speed (cm s^{-1})
C1	990219–000105	10.5	80	4	35	30
C2	990427–990615	1.6	9	6	70	20
C3	990614–990721	1.2	4	8	100	40

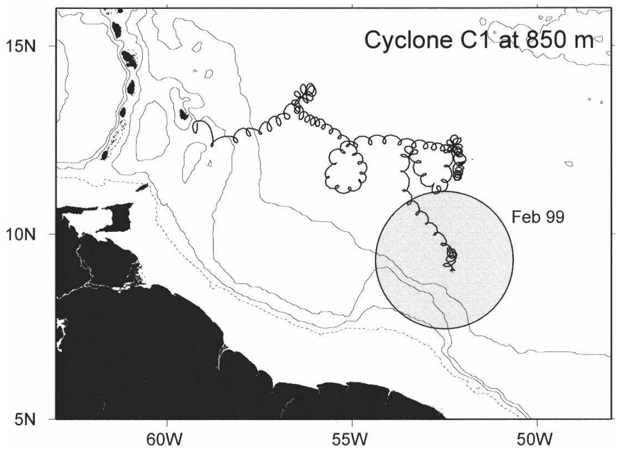


FIG. 7. Trajectory of RAFOS float 36 looping at 843 m within an intermediate-depth cyclonic eddy. The float was launched during a hydrographic survey of R3 in February 1999. The float completed 80 cyclonic loops over 10.5 months as it drifted northwestward toward Barbados.

surface-intensified rings tended to occur in fall and early winter when the NBC was in its declining phase from the summer transport maximum but while the NBC retroflection was still clearly established; shallower surface-intensified rings tended to occur in spring and summer. The float and drifter observations described here can provide no new information about the formation mechanisms that result in the variety of observed ring structures. However, as we describe below, the process of ring formation is just the first of several complex phenomena that determine the evolving structure of NBC rings and the eventual downstream fate of the water isolated within them.

5. NBC ring evolution and interactions

a. Ring cleavage

The float and drifter trajectories indicate that, regardless of its initial vertical configuration, an NBC ring's vertical structure evolves significantly during its brief lifetime. One of the most interesting and unexpected results of this experiment is the observation that the surface and subsurface portions of NBC rings may separate from one another with each portion retaining a coherent, independent, and ringlike vortical circulation. We will use the term *cleave*[2] to describe this phenomenon. Two instances of cleaving, apparently prompted by ring encounters with abrupt bathymetry, are illustrated by the observed evolution of R2 and R6.

[2] To split or separate, especially along a natural line of division (*American Heritage Dictionary of the English Language*, 4th ed., s.v. "cleave").

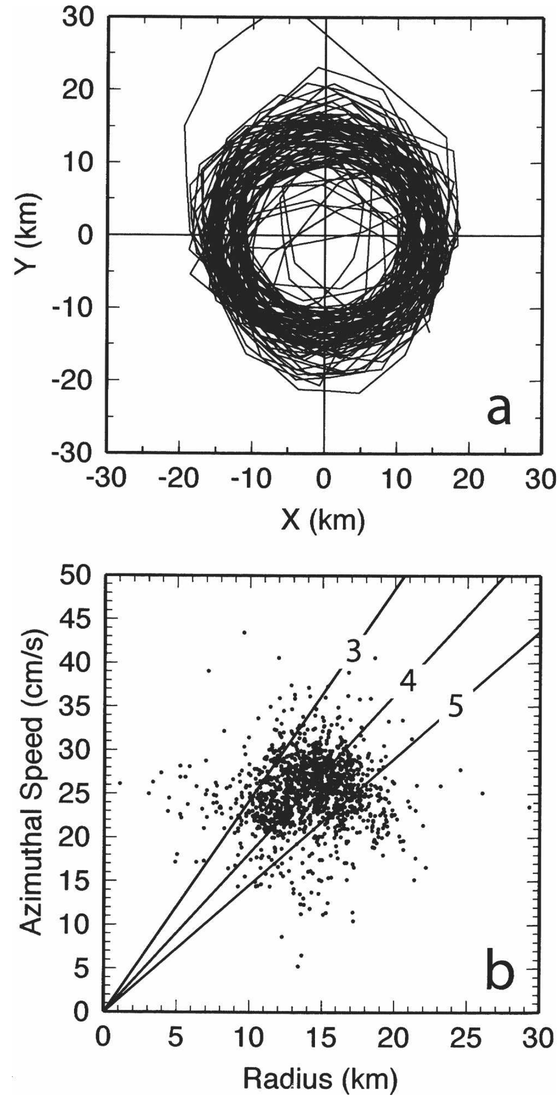


FIG. 8. (a) Residual rotational component of RAFOS float 36 looping at 843 m within an intermediate-depth cyclonic eddy. Axes are in kilometers relative to the eddy center after the low-frequency translational component was removed by application of a low-pass Gaussian-shaped filter. A total of 80 cyclonic loops were recorded by this float. (b) Scatterplot of azimuthal speed (defined as rms velocity about the low-passed velocity) vs radial distance from the eddy center. Straight lines indicate slopes corresponding to a solid-body rotation period of 3, 4, and 5 days. The local inertial period at 8°N is 3.5 days.

Between December 1998 and February 1999, the surface-intensified, strongly barotropic ring R2 (Fig. 10) translated westward at 15 cm s^{-1} as a vertically coherent unit as illustrated by simultaneously looping drifters and a RAFOS float (Figs. 4 and 11). Upon encountering the western boundary southeast of Tobago near 58°W in late February, all five surface drifters looping in R2 ceased looping, suggesting destruction of the surface vortex. A subsurface remnant of R2, illustrated by

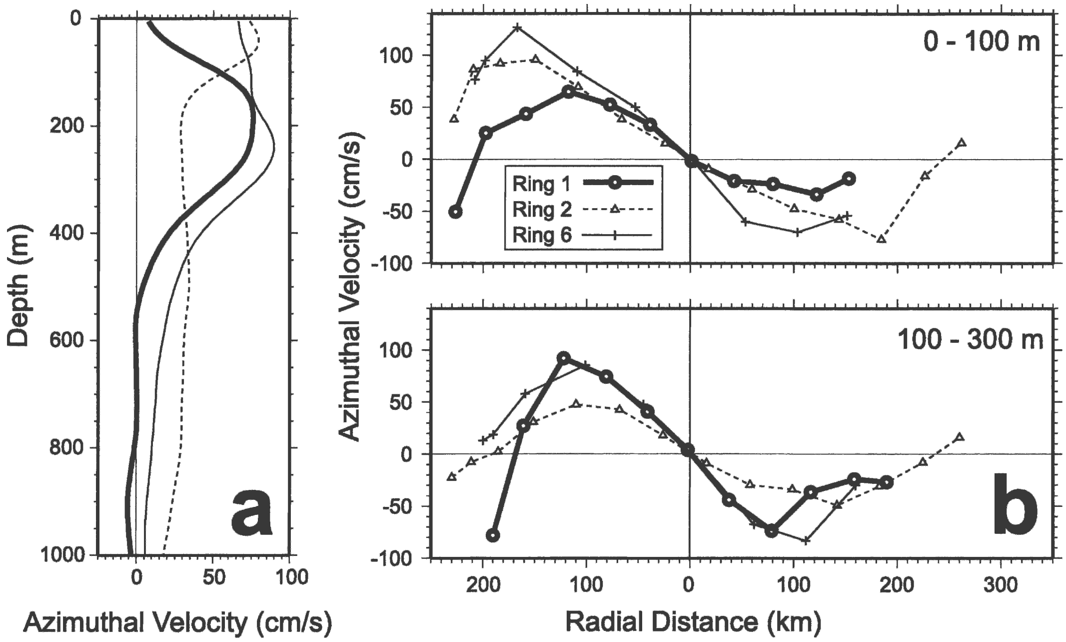


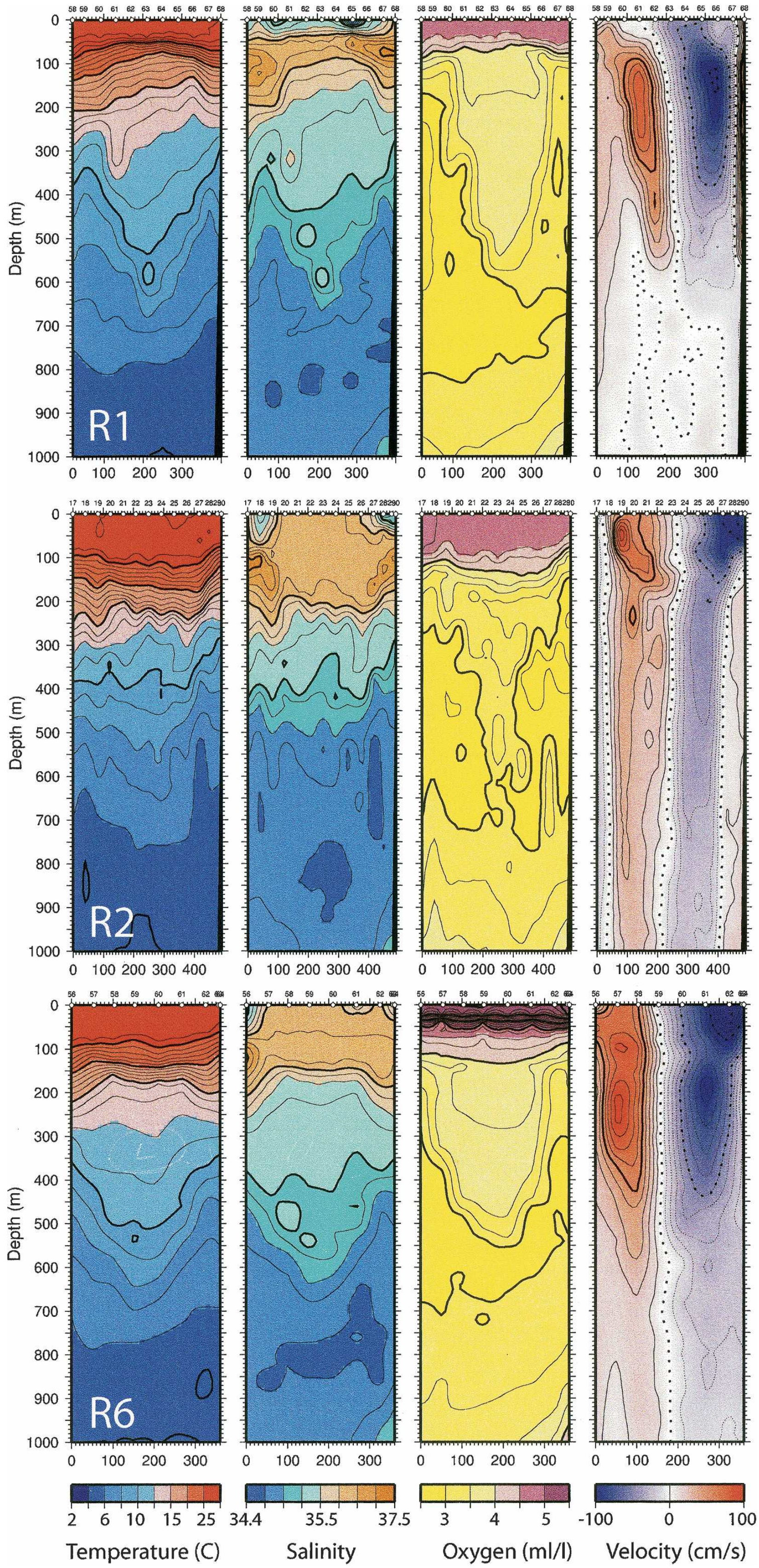
FIG. 9. (a) Vertical profiles of LADCP velocity from R1, R2, and R6 obtained from shipboard surveys when each ring was located near 57°W. Profiles were taken from comparable positions on the offshore limb of each ring. (b) Radial profiles of LADCP velocity across the diameter of rings R1, R2, and R6 averaged into two depth bins: 0–100 and 100–300 m. The right-hand side of the plot corresponds to the offshore limb of each ring (i.e., the edge of the continental shelf is near 200–225 km on the left-hand side of the plot).

float 33 at 300 m, nevertheless continued looping with approximately the same diameter and rotation period for an additional 5 months (see dashed circles near 58°W in panels 7–12 in Fig. 11). This remnant remained in the center of the busy ring translation corridor and was subsequently overtaken by at least two other rings. We observed that the larger and more intense surface-intensified rings translated relatively quickly and were able to overtake the smaller and slower subsurface vortices. In this particular case, the subsurface remnant of R2 was overtaken by both R3 and R4, being deflected more than 100 km offshore by the former and perhaps causing the destruction of the latter. As shown in panel 11 in Fig. 11, drifters in R4 ceased looping shortly after the two rings collided. These drifters moved swiftly northwestward toward the Lesser Antilles, while the subsurface remnant of R2 continued looping in the Tobago Basin for about 7 months.

In a manner and location similar to that of R2's cleavage, two middepth (550 m) floats looping in R6 ceased translation but continued looping in the Tobago Basin while the surface and thermocline portions of that ring moved northward past Barbados (Fig. 4). As with R2, proximity of the ring to the shoaling bathymetry near Tobago appears responsible for the cleavage. Float 156 at 220 m attempted to follow the thermocline portion of the ring northward between Barbados and St. Vincent. Acoustic tracking was lost at this point and the float later surfaced in the eastern Caribbean near 63°W. Float 193 at 500 m remained trapped within the Tobago Basin and looped there for two months. Based on these trajectories, we infer that the cleavage of R6 into a translating surface/thermocline ring and a stalled middepth/deep remnant must therefore have occurred somewhere in the vertical interval between 220 and 500 m.

In both of these cases, float trajectories indicate that the vertical level separating the surface and subsurface vortices is somewhat deeper than 200 m and, in the case of R2, shallower than 300 m. To investigate why rings may cleave at this level, we examined more detailed subsurface measurements of ring structure and velocity. The momentum balance in an NBC ring has been shown to be approximately geostrophic with the addition of a small centripetal acceleration due to the ring's curvature (Didden and Schott 1993; Fratantoni et al. 1995). We therefore expect the simplest, dynamically consistent configuration of an NBC ring to be a surface-trapped, baroclinic vortex with depressed isopycnal surfaces in the core that flatten significantly at depths below the velocity maximum.

Somewhat fortuitously for this investigation, rings R2 and R6 were surveyed with shipboard CTD and LADCP measurements near 57°W in February 1999


R1
R2
R6
Depth (m)
2 6 10 15 25
Temperature (C)
34.4 35.5 37.5
Salinity
3 4 5
Oxygen (ml/l)
-100 0 100
Velocity (cm/s)

and February 2000, respectively (Fig. 10). In both R2 and R6, we note the suggestion of subsurface velocity maxima near 250 m, a significant reduction in azimuthal velocity below 300–400 m, and a fairly substantial (10–30 cm s^{-1}) barotropic circulation extending to a depth of at least 1000 m. While neither R2 nor R6 exhibits a significant depression in the main thermocline (as might be expected in first-mode baroclinic eddy), a water mass boundary (see the oxygen and salinity panels in Fig. 10) is evident in R6 at a level coincident with the 10°C isotherm near 450–500-m depth. In fact, the lower thermocline (near 15°C) in R6 is actually bowed upward in a manner suggestive of a compensated, isolated anticyclonic lens. This structure is reflected in a relative maximum in azimuthal velocity near 250 m. Based on the hydrographic and velocity structure of R6 it therefore seems reasonable to hypothesize a natural division between the surface-intensified upper region and the deep-reaching circulation at a depth near 500 m. This is consistent with our earlier inference about the cleavage depth based on the relatively low vertical-resolution float measurements. A similar statement could be made for R2 at a level near 250–300 m, although the hydrographic delineation is less distinct.

The observed persistence of anticyclonic circulation in the remnant middepth ring layers is puzzling. In the case of R6, the horizontal temperature and salinity gradients at depths below 450 m are consistent with that required to support a deep geostrophically balanced vortex. However, it seems unlikely that the relatively flat deep stratification of R2, as depicted in Fig. 10, could provide sufficient potential energy to maintain the vigorous circulation in the cleaved subsurface segment for 7 additional months. One possibility is that, at the time of the February 1999 survey near 57°W, R2 was interacting with the subsurface-intensified R1 (see Fig. 11) in such a way that the subsurface density structure was temporarily distorted, perhaps by internal waves generated during the interaction.

b. Ring–ring and ring–NBC interactions

In addition to the profound examples of ring interactions leading to cleavage, described above, the close proximity of various rings and cleaved remnants observed during this experiment lead us to believe that ring–ring interactions are commonplace in the region. An illustrative example is March 1999, a period in which four rings and a cyclonic eddy were observed to coexist (Fig. 12). During this period, R1 entered the Tobago Basin, the cleaved subsurface remnant of R2 was forced offshore by the clockwise circulation of westward-translating R3, a subsurface cyclone (described above) translated away from R3, and R4 formed near 50°W. These observations were made possible by the many drifters and floats deployed on the February 1999 cruise. Because of the limited scope of our measurements and the discrete nature of float sampling, there could well have been many additional vortices that we failed to observe both at this time and during the remainder of the experiment. Ring–ring interactions, while prevalent, are episodic and perhaps even chaotic (e.g., Konstantinov 1994). Given the extreme sensitivity of vortex interactions to the location, geometry, and intensity of the individual rings, we anticipate that simulation and/or prediction of this mode of ring evolution will be particularly difficult.

Several observations suggest that the NBC can occasionally extend farther up the coast than its usual retroflection latitude, resulting in interaction with preexisting rings. Wilson et al. (2002) mention that the NBC retroflection extended unusually far northward to near 10°N before separation of R2. Similarly, the February 2000 survey cruise documented the extreme extension of the NBC retroflection to a position near 10°N, 57°W and encompassing the previously separated R6. By mid-March of that year, the NBC had retracted to the southeast leaving behind both R6 (near 12°N, 59°W) and the newly formed R7 (near 10°N, 55°W). A combination of detailed observations including in situ velocity and water mass measurements and remotely sensed color and altimetry fields enabled us to distinguish the capture and release of R6 by the NBC. It is difficult, particularly when relying on remotely sensed observations alone, to determine the point in time and space at which an NBC ring truly separates from its parent current.

c. Ring–topography interactions

In contrast to the interactions described above, the response of NBC rings to the regional topography ap-

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FIG. 10. Tracer and LADCP velocity sections across three NBC rings when each ring was located near 57°W. The horizontal axis is distance measured across the ring diameter in kilometers. Note that the horizontal scale is slightly different for each ring. For each ring, shown are (left) potential temperature, (second from left) salinity, (third from left) dissolved oxygen, and (right) azimuthal velocity. The velocity contour interval is 10 cm s^{-1}.

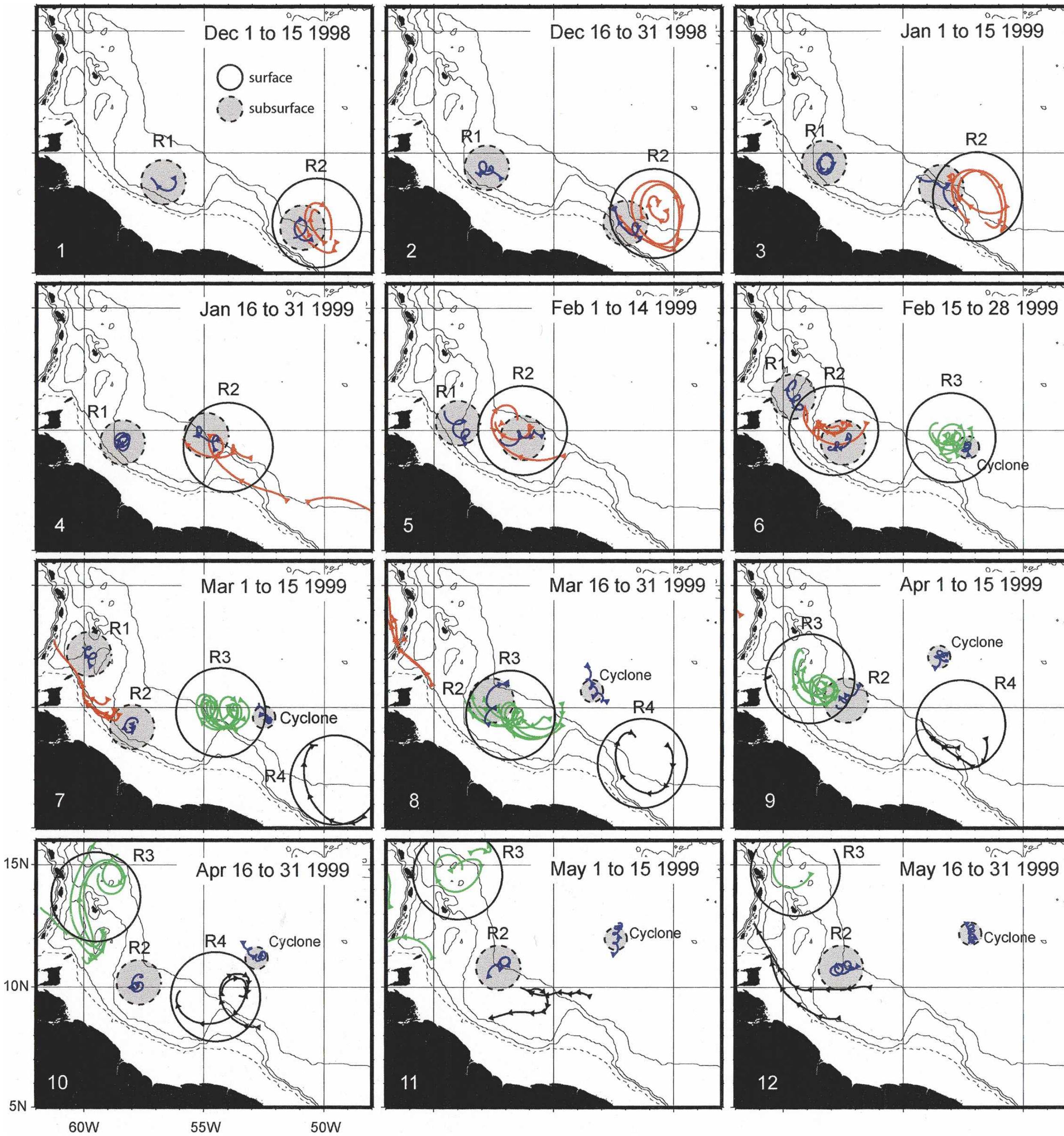

FIG. 11. Time series illustrating the evolution of R1–R4 and a subsurface cyclone during December 1998–May 1999. Looping surface drifter (red, green, and black) and float trajectories (blue) illustrate the circulation. Circles indicate schematically the size of the vortices and where they were located at the midpoint of each 2-week period. Open circles represent surface features observed with surface drifters. Shaded and dashed circles represent subsurface features measured with RAFOS floats. Subsurface floats shown are RAFOS float 29 at 270 m in R1, float 33 at 320 m in R2, and float 36 at 850 m in the cyclone.

pears to be fairly repeatable. NBC rings encounter and respond to topography for most, if not all, of their lives. Continuous interaction is implied by their translation pathways (Fig. 5), which closely follow the edge of the continental shelf and the arc of the Lesser Antilles. For rings that survive long enough to reach the island arc, the Lesser Antilles constitute a major barrier to westward ring translation (Fig. 13). However, we observe that rings do not approach the island chain in a frontal collision (as in the model of Simmons and Nof 2002)

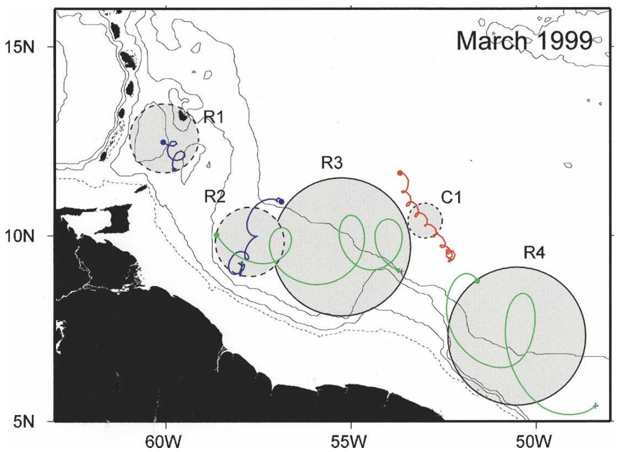

FIG. 12. Float and drifter trajectories illustrating rings (green), subsurface ring fragments (blue), and the long-lived subsurface cyclone C1 (red) during March 1999. The spatial proximity of these many intense vortices and their observed interactions (see text) suggests that ring–ring interaction plays an important role in the downstream evolution of NBC rings.

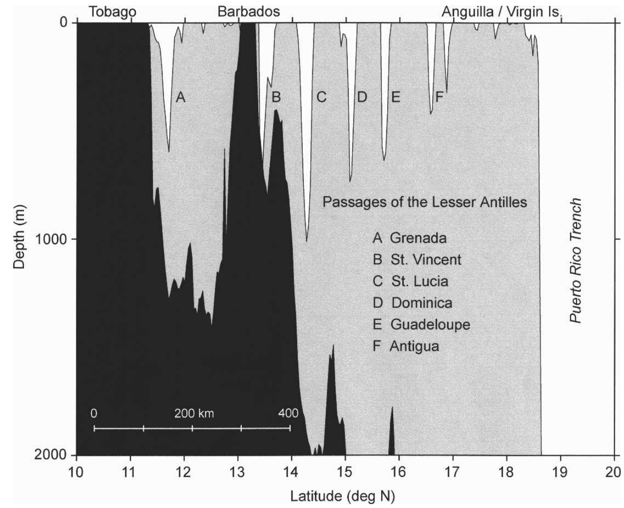

FIG. 13. Profile of the seafloor looking westward toward the Caribbean islands. South America and Tobago are on the left and the Atlantic Ocean is on the right. White areas show passages through the islands and the northern extent of the Lesser Antilles island arc. From south to north the major passages into the Caribbean are Grenada, St. Vincent, St. Lucia, Dominica, Guadeloupe, and Antigua (split in two by the island of Montserrat). Gray areas show depths over the Barbados Ridge (11.4°–13.0°N), which is located east of the main island arc between Tobago (near 11.3°N) and Barbados (near 13.2°N). The island arc is a major barrier to NBC rings translating westward toward the Caribbean. Rings are typically 450 km (4°) in diameter or 10 times as large as the passages and can exceed 2000 m in vertical extent as indicated by shipboard surveys. Depth profiles were created by plotting the shallowest depth at each latitude using ETOPO2 data (Smith and Sandwell 1997) in north–south strips between 59° and 63.5°W (gray) and between 58.0° and 60.5°W (black).

but rather move parallel to the island chain, scraping their western limb against the corrugated boundary. We expect that topographic waves are generated as the strong azimuthal velocities associated with a ring impinge on the sloping bathymetry and that such waves are the dominant mechanism by which the rings lose energy (e.g., LaCasce 1998).

As compared with the glancing blows borne by the Lesser Antilles, NBC rings appear to collide head-on with Barbados. Interestingly, collision with this isolated island does not seem to pose a substantial impediment to ring motion. At a depth of 200 m, the island of Barbados appears to the ring as an obstacle approximately 30 km wide. With a core diameter at least 8 times the width of this obstacle (and a total extent perhaps 2 times that size), a ring is able to maintain its vortical circulation as it envelops the island. A similar problem, that of Mediterranean Water eddies (meddies) colliding with an isolated seamount, has been studied in the laboratory by Cenedese (2002) for both advected and self-propagating vortices. Cenedese found that for ratios of seamount diameter to vortex diameter of less than 0.2 (the regime corresponding to NBC Ring–Barbados interaction), the vortex moved past the topographic obstacle with minimal disturbance. Based on Cenedese's theory, we expect that such disturbance would be greater at depths where the vortex diameter is smaller and the diameter of the subsurface topography might be larger. For example, although it initially translated away from the boundary, the long-lived but relatively small subsurface cyclone C1 eventually collided with Barbados at which time the lone float trapped within this vortex stopped looping, indicating significant disruption or destruction of the feature (Fig. 7). Using the width of Barbados at 1000-m depth, the ratio of obstacle diameter (40 km) to vortex diameter (60 km) is near 0.6 and the theory correctly predicts a substantial disruption as a result of the collision.

Cenedese et al. (2005) have recently extended their laboratory studies to explore the interaction of mesoscale rings with a pair of islands. One possible outcome of such an interaction is the generation of a counterrotating vortex pair, or dipole. Theory and laboratory experiments appropriately scaled to simulate NBC rings and the islands of Barbados and St. Vincent resulted in dipole formation comparable to that observed following the demise of R3, including the generation of a dipole consisting of a weak anticyclone and the cyclonic eddy C2 (Fig. 4; see upper R3 panel near 17°N).

6. The fate of NBC ring core water

The ultimate fates of the 10 NBC rings observed during this program, including the cleaved subsurface remnants of R2 and R6, are summarized in Table 6. Drifters stopped looping in rings R2, R4, R5, and R8 before they reached the Antilles island arc. The thermocline-trapped R1 and the subsurface remnants of R2 and R6 all translated westward south of Barbados over the 1200-m Barbados Ridge and into the Tobago Basin. The remaining five rings (observed with surface drifters only) moved northward along the Antilles arc. Most of the surface drifters in rings that reached this stage eventually entered the Caribbean or grounded on the islands. While drifters in the eastern Caribbean do exhibit looping and meandering (e.g., Richardson 2005), we find no evidence that an NBC ring can enter the Caribbean Sea intact—that is, as a coherent vortex containing the same core properties as the incident ring).

The drifter trajectories do clearly illustrate a net transport of near-surface water through the island chain and into the eastern Caribbean (Table 7). This is not surprising, as flow through the Caribbean Passages is generally westward at the surface (e.g., Schmitz and Richardson 1991; Wilson and Johns 1997; Johns et al. 1999, 2002). Eighteen surface drifters that had been looping in NBC rings entered the Caribbean through various passages or expired on the islands either by grounding or by being picked up and taken ashore by boat (Fig. 14). These previously looping drifters entered the Caribbean at various latitudes, implying that surface water was lost from rings both upon their first encounter with shoaling topography and also later as rings stalled north of Barbados. Eight of the looping drifters entered the Caribbean south of Martinique, including five through relatively shallow (15 m) passages in the Grenadine Islands. Six previously looping drifters moved northward around the Lesser Antilles and entered the subtropical gyre circulation.

TABLE 6. Summary of the eventual fate of each NBC ring identified in this study based on float (F) and drifter observations.

Ring	Circumstances of ring demise
R1*	F29 at 270 m entered Tobago Trough and terminated near 12.5°N, 60.0°W
R2	Collided with boundary near Tobago, drifters entered Caribbean
R2*	F33 at 300 m looped for 7 months in Tobago Trough near 12.5°N, 60.5°W
R3	Passed northward near Barbados, stalled near 15°N, 59°W
R4	Collided with R2* near 10°N, 56°W, drifters stopped looping
R5	Drifters stopped looping near Tobago, 10.5°N, 59.0°W
R6	Passed northward near Barbados, stalled near 16°N, 59°W
R6*	F193 at 500 m stalled in Tobago Trough near 12.5°N, 60.5°W
R7	Passed northward near Barbados, merged with R6, stalled near 17°N, 59°W
R8	Drifters stopped looping east of Tobago near 11°N, 59°W
R9	Passed northward near Barbados, drifters stopped looping near 17°N, 60°W
R10	Passed northward near Barbados, drifters stopped looping near 15°N, 60°W

TABLE 7. Summary of the drifters and RAFOS floats that looped in rings and their eventual fate. Five of seven surface drifters entering the Caribbean through the Windward Islands passages (south of Martinique) did so through shallow (15 m) passages in the Grenadines. We have assumed here that drifters that went aground on the islands (or were prematurely recovered in close proximity to an island passage) would have eventually entered the eastern Caribbean.

	Surface drifters	250-m floats	550-m floats	900-m floats
Looped in rings	25	7	6	4
Entered Caribbean	18	5	2	0
Did not enter Caribbean	7	2	4	4

Only two of the six 550-m floats that looped in rings entered the Caribbean. The float observations confirm that, while most of the surface and thermocline water associated with NBC rings enters the eastern Caribbean, very little intermediate-depth water does so. These deeper constituents may enter the subtropical gyre circulation via another route (e.g., northwestward outside the Caribbean arc) although only one of the 550-m floats and none of our 900-m floats suggested such a pathway. The net displacement of all 550-m float trajectories yields an average northward velocity of 1.7 cm s^{-1} at this depth (Wooding et al. 2002). In contrast, the net motion of all 900-m floats is to the east. As mentioned earlier, the 900-m floats (originally intended for 800 m) may have equilibrated too deeply to accurately define pathways relevant to the AAIW. The analysis of new observations from profiling floats (e.g., Schmid et al. 2003) and, in particular, the German MOVE program (e.g., Lankhorst et al. 2004) should help to resolve intermediate-depth transport pathways in this region.

7. Discussion and conclusions

Float and drifter trajectories obtained during the NBC Rings Experiment illustrate the translation, structure, and eventual demise of 10 NBC rings. Using an array of in situ and remote observations, we have identified substantial ring-to-ring variability in velocity, water mass structure, temporal evolution, and the mecha-

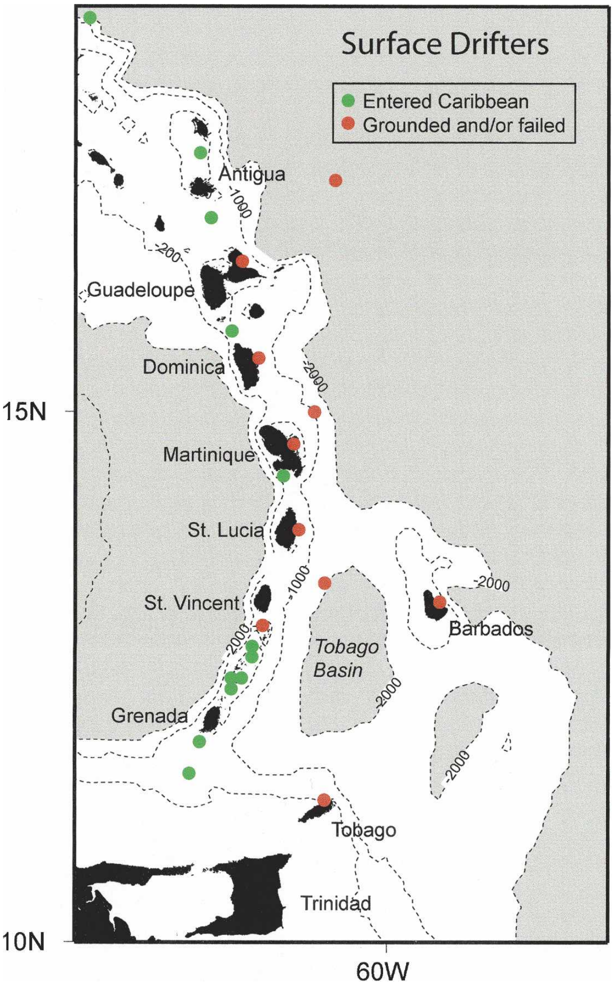

FIG. 14. Locations where surface drifters that had been looping in NBC rings passed into the Caribbean (green dots) or grounded on the islands and/or stopped transmitting (red dots). Some drifters that appeared to ground on the islands might have been picked up and taken ashore by fisherman.

nism of their eventual demise and demonstrated that ring structure and intensity are radically modified through ring–ring and ring–topography interactions.

The influence of topography on both the translation and vertical structure of NBC rings was found to be significant, with the islands of the Lesser Antilles constituting an insurmountable barrier to ring translation. All available in situ and most remote observations indicate that most NBC rings turn northward upon reaching the shoaling topography east of the Lesser Antilles and pass very near the island of Barbados. While some numerical simulations and satellite altimeter observations suggest that some NBC rings somehow pass intact through the narrow passages of the Lesser Antilles (e.g., Murphy et al. 1999; Carton and Chao 1999; Goni and Johns 2003), available in situ observations indicate that the rings themselves are destroyed east of the island arc and only filaments of ring core fluid (e.g., as identified by Lagrangian drifters) are able to enter the eastern Caribbean. We find that NBC rings rarely encounter the Lesser Antilles in a frontal collision. Rather, most rings were observed to turn northward as they reached the island arc. In at least two cases, a northward-translating ring completely engulfed the island of Barbados for a period of several days. Significant fluctuations in potential temperature and salinity were observed at intermediate depths in the vicinity of Barbados as a ring approached. The close approach of looping drifters and floats to coral reef–fringed Barbados indicates that NBC rings may be fundamental to the dispersal of biota in the region as reported by Cowen et al. (2003).

The near-surface and subthermocline portions of at least two rings were observed to cleave upon encountering shoaling bathymetry between Tobago and Barbados. The cleaved portions each retained their ringlike circulation but translated in different directions and at different rates. This cleavage occurred at depths from 250 to 550 m, between the thermocline and intermediate layers of a ring. Recent numerical simulations of the tropical Atlantic (Jochum and Malanotte-Rizzoli 2003; Garraffo et al. 2003) also find evidence of vertically layered vortices in the region. For example, Jochum and Malanotte-Rizzoli (2003) concluded that two different kinds of anticyclones are generated along their simulated western boundary: intermediate anticyclones formed by instabilities when an intermediate western boundary current crosses the equator (see Edwards and Pedlosky 1998) and NBC rings formed when Rossby waves generated from instabilities of the North Equatorial Countercurrent are reflected from the western boundary. In their simulations, a deep-reaching ring can occur when an NBC ring merges with an intermediate anticyclone. Using a very high resolution (1/2°) simulation of the Atlantic, Garraffo et al. (2003) found a strong seasonality to the vertical structure of NBC rings and concluded that rings with a substantial vertical extent can occur when surface- and subsurface-intensified rings merge. The simulated rings often interact and merge with each other and, as we observed, tend to stall and coalesce to the north of Barbados. As depicted by the float and drifter observations, the surface layers of simulated rings can move independently from subsurface layers with the deep portions translating more slowly than the surface portions.

NBC rings constitute the largest source of episodic oceanic variability in the region east of the Lesser Antilles. An important question of societal relevance is whether the impact of NBC rings on the circulation and water properties of the eastern Caribbean is predictable. Although idealized studies of vortex propagation (e.g., Flierl 1977; Nof 1981, 1983; Cushman-Roisin et al. 1990) and vortex–topography interaction (e.g., Shi and Nof 1993; Sutyrin 2001; Jacob et al. 2002; Cenedese 2002; Adduce and Cenedese 2004) have described several relevant dynamical processes in isolation, the observations described herein reveal the overwhelming richness (specifically ring–ring and ring–topography interactions and vertical cleavage) that must be faithfully reproduced by a predictive numerical ocean model. As shown previously by Fratantoni and Glickson (2002), progressive deformation of NBC ring geometry occurs rapidly relative to the rate of northwestward ring translation. Hence, accurate prediction of high-velocity events at a particular location (an island, drill ship, etc.) depends on detailed knowledge of both the ring's translation and deformation histories. The implication is that simple feature-based models that assume a static geometry and constant translation rate may have limited predictive skill. Though few in number, the Lagrangian observations presented here provide the clearest description to date of the changing structure and composition of NBC rings as they evolve and interact with their environment. Future investigations in this region will need to be carefully designed to resolve and quantify the complex structure of these features and their interactions.

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