Impact of North Brazil Current rings on local circulation and coral reef fish recruitment to Barbados, West Indies


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Early observations of the flow environment around the island of Barbados indicated frequent occurrence of strong current reversals associated with surface salinity fronts. Higher resolution spatial and temporal measurements of the flow regime in 1996 and 1997 provided a comprehensive view of the local surface circulation (0-100 m), revealing that external forcing by North Brazil Current (NBC) rings plays a dominant role in the near-field flow variability surrounding the island. NBC ring forcing had comparable effects on the velocity field during both years, indicating that the ring structure was retained while interacting with topography. In the present study, the interaction of NBC rings with coastal flow dynamics and the biological response of the system as measured by recruitment of coral reef fishes is examined. Our observations show that NBC rings can remain quite coherent as they pass the Tobago-Barbados ridge. Further, the flow direction and associated residence time in the vicinity of the island appear to vary depending on the orientation of the rings as they collide with the island. Concurrent biological samples revealed complex responses to the presence of rings in that during some of the events, larval fishes appeared to be rapidly advected away, resulting in a failure of larval settlement, whereas under other conditions larval retention was enhanced and was followed by a settlement pulse. Impingement by a ring did not alter the concentration of water column chlorophyll a (Chl a), but it did influence the depth of the Chl a maximum. Simultaneous changes were observed in the vertical distribution of fish larvae. Larval fish encountering ring waters exhibited reduced growth rates and longer

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larval periods, both potentially reducing survival and, ultimately, recruitment success. Overall, results demonstrate that NBC rings interfere with the island-scale flow dynamics around Barbados and interject considerable variability in the local recruitment signal of coral reef fishes.

1. INTRODUCTION

The upper layer circulation in the northern tropical Atlantic off the coast of South America is characterized by a mean circulation in the NW direction, often referred to as the Guyana Current and fed by the North Brazil Current (NBC). This region is dominated by large anticyclonic rings shed at the retroflexion of the North Equatorial Counter Current (NECC) and the NBC, which then move northwestward along the South American coast [Johns et al., 1990; Didden and Schott, 1993; Richardson et al., 1994; Fratantoni et al., 1995]. These rings entrain water masses from the southern hemisphere and often, in their peripheral waters, water from the Amazon River [Fratantoni and Glickson, 2002]. As the NBC rings translate toward the Lesser Antilles, the major shallow topographic feature they encounter is the Tobago-Barbados Ridge and the island of Barbados, which lies along the eastern flank of the Lesser Antilles (Figure 1). Due to this downstream location of Barbados relative to NBC rings [Goni and Johns, 2001], the surrounding pelagic environment of the island is directly impacted by ring passage. Consequently, examination of the impact of NBC rings and their associated water masses on coral reef fish larvae recruiting to Barbados is critical to understanding the ecology of fish populations of the eastern Caribbean.

Rising from depths greater than 2000 m, the island of Barbados is a feature of approximately 50 x 145 km (measured at the 1000 m isobath), which may present a real obstacle to a passing ring. Analysis of satellite-derived sea height anomaly fields from Topex/Poseidon data indicate that most NBC rings tend to veer from their generally northwestward trajectories to the north as they approach the Tobago-Barbados Ridge [Kelly et al., 2000; Goni and Johns, 2001], causing the rings to pass directly by or around Barbados. Both structure of the ring [Fratantoni et al., 1995; Goni and Johns, 2001] and its orientation to the island may influence the nature of the flow interaction with the island topography. Theoretical treatments of eddy-island interactions suggest that a ring potentially can pass around an island, trapping anticyclonic motion in a Taylor column around the island [McWilliams, 1986; Simmons and Nof, 2000]. Alternatively, or as a direct result of the initial impingement of a ring with a topographic feature, some outer portion of the ring circulation may peel off the ring and flow around the island as vorticity is maintained, with the added potential of splitting into a separate ring [Simmons and Nof, 2000].

Previous observations of the flow around Barbados demonstrated the variable nature of the incident flow interacting with the local topography [Bowman et al., 1994; Cowen and Castro, 1994; Stansfield et al., 1995]. In these studies, strong
current reversals were observed during two years in association with significant low salinity features consistent with the passage of NBC rings in the vicinity of Barbados. However, in one year the resulting flow was anticyclonic, with low salinity passing to the west of the island [Bowman et al., 1994; Cowen and Castro, 1994], whereas in the other year a cyclonic circulation around the island ensued, trapping low salinity water around the south, east and north coastal portions of the island [Stansfield et al., 1995]. Coherent signals of low salinity and strong current reversals were similarly observed in a more recent study [Paris et al., 2002], raising the question regarding the ubiquity of these energetic features and their role in the local coastal dynamics of islands such as Barbados.

Analysis of satellite altimeter data and of temperature-salinity recorders moored off of the west coast of Barbados [Goni and Johns, 2001] revealed that NBC rings may pass Barbados up to 4-5 times per year, more frequently than previously thought [Richardson et al., 1994; Fratantoni et al., 1995]. It has been suggested that as many as 6-7 rings per year may develop in the Western Atlantic, all with the potential to collide with the island environment of the Lesser Antilles [Goni and Johns, 2001, Fratantoni and Glickson, 2002]. This suggests that local coral reef species that spawn year-round and have a mean larval duration of 30 to 50 days have a high likelihood of being exposed to a ring event for at least a portion of their pelagic phase.

Recurring translations of NBC rings from the retroreflection region toward the eastern Caribbean, and collision of rings with the Ridge bathymetry introduce southern hemisphere water masses, including low salinity waters from the Amazon River, into the coastal island environment. These events may have a complex and cumulative effect on the recruitment of coral reef fishes to Barbados. Here we examine the physical and biological interactions among NBC rings, the coastal environment around Barbados, and reef fish larvae. We describe the typical signature of the upper 100 m of the water column prior to and during the passage of a ring in terms of the currents and salinity fields along the coast of Barbados. We also examine how these coastal flow properties may interact strongly with the distribution and survival of larval fishes, ultimately affecting the recruitment of these fishes to coral reef habitats. Specifically, we examine how the larval fish community potentially is impacted by ring passage both in terms of their physical (i.e. vertical) distribution and their daily growth rates. These biological variables directly impact the potential for recruitment by influencing larval retention and survival.

2. METHODS

2.1. Bio-physical Sampling

The bio-physical field experiment consisted of two 30-day cruises on the R/V Seward Johnson during May-June of two consecutive years, 1996-1997, in the vicinity of Barbados (13°10'N, 59°30'W), West Indies. The study area extended 15 km from the west coast of Barbados and 20 km parallel to shore (Figure 1). Hydrographic and biological survey measurements, each conducted over a 24-hr
Figure 1. Study area - (a) Topography of the Lesser Antilles in the vicinity of the island of Barbados. The biophysical survey area (15 x 20 km) is indicated by the white rectangle. Inserts indicated by the white frame in (a) illustrate (b) the biological sampling consisting of larval fish MOCNESS hauls during day (circle) and night (cross) stations and juvenile fish census and collection sites (star), and (c) the physical sampling consisting of CTD stations (letters) along ADCP tracks (dashed line).
period, were repeated every 3 days. During day 1 of each sampling period, a conductivity-temperature-depth (CTD) survey was conducted with a Sea-Bird SBE9 in a grid pattern covering the domain to provide a quasi-synoptic temperature/salinity field. CTD transects ran parallel to shore and on average 21 CTD casts (ca. 2-4 km apart) were made to a maximum depth of 500 m or to within 25 m from the bottom. To maximize sampling resolution, Acoustic Doppler Current Profiler (ADCP) data were continuously recorded along the ship track with short-term maximum error estimates on bottom-tracked velocity of 6 cm s\(^{-1}\) at 400 m. The ADCP data were acquired at a vertical resolution of 4 m and 300 s sampling ensembles. During CTD casts, total chlorophyll \(a\) concentration (mg Chl \(a\) m\(^{-3}\)) was recorded via calibrated fluorometry profiles [Choi et al., 2001].

During day 2 of each survey, 24 vertically discrete ichthyoplankton samples at 20-m intervals from the sea surface to 100 m were taken in a 12-h day/12-h night paired sampling and fixed in 95% Ethanol. Ichthyoplankton samples were collected using a 1 m\(^2\) MOCNESS (Multiple Opening-Closing Net and Environmental Sampling System) fitted with 333 µm mesh nets. Fish larvae later were sorted and identified to species or the lowest taxonomic level possible. This sampling sequence was repeated a total of 8 times (surveys) during the cruise. The entire experiment was repeated during the following year.

### 2.2. Flow Field Calculations

To understand the dynamic of coastal currents during the impingement of a NBC ring at Barbados, we generated a series of horizontal flow fields for each survey using independent observations of velocities (e.g., dynamic height and currents) via a multivariate spatial objective analysis [Gomis et al., 2001]. Dynamic heights were computed in reference to 200 m for each CTD survey and the ADCP data were filtered using standard statistical analyses. The ADCP and CTD data were analyzed from the surface to 100 m on 5 horizontal planes (every 20 m) and returned velocities in a 12 x 12 mesh (2 km x 1 km) determined by the density of observed data. The maximum depth for the flow field output matched the depth limit of ichthyoplankton sampling, which also approximated the depth of the inshore CTD line. Since the ADCP measures the total current, it includes ageostrophic flows such as wind-driven current, near-inertial motion, and tides. Tides in Barbados are semi-diurnal, with ca. 10 cm s\(^{-1}\) amplitude [estimated from the ADCP mooring; Kelly et al., 2000], and were not explicitly removed from the total current. The objective analysis procedure reduced measurement errors by removing noise from scattered sampling and predicted homogeneous maps of the total horizontal current in the coastal waters of Barbados [Paris et al., 2002].

In order to investigate the potential ring effect on the transport of locally spawned fish larvae, we used the horizontal current maps and measured water residence time in the sampling box as well as before and during ring impact for each year. This procedure allowed us to evaluate the role of the rings in limiting or enhancing larval dispersal. Water residence times were calculated using a Lagrangian particle-tracking scheme in which sub-grid scale turbulence was added to the deterministic
current [Dutkiewicz et al., 1993]. A total of 15,000 tracers was released on a regular mesh of 30 locations across the 12 x12 km grid in each of the five 20-m horizontal layers. Releases at those fixed depths were initiated during survey 1 and repeated daily until the end of the sampling experiment. Note that residence times may have been underestimated since tracers cannot be tracked for more than the length of the experiment. The horizontal distribution of water residence time was calculated for each layer and for a selected time period (before and during ring impact).

2.3. Biological Measurements

For the biological component of this study, we focused our efforts on a single species of coral reef fish, the bluehead wrasse (*Thalassoma bifasciatum*), due to its common occurrence within our ichthyoplankton samples and previous experience with the recruitment dynamics of the species [e.g., Sponaugle and Cowen, 1997; Searcy and Sponaugle, 2000, 2001; Victor, 1982]. The vertical distribution of the larvae was examined with respect to the vertical structure of the flow field and chlorophyll a (Chl a) profiles, to provide a measure of both potential impacts on retention within the vicinity of the island and a possible food related response of the larvae to a changing physical environment.

To examine how NBC rings might influence settlement dynamics, we measured the timing and strength of *T. bifasciatum* recruitment. Newly settled *T. bifasciatum* were regularly surveyed every two weeks and collected by two divers from 30 randomly placed 1 x 5 m transects at three sites along the west coast of Barbados (Figure 1b), providing an estimate of the relative size of recruitment events (i.e. density of recruits). A portion of each bi-weekly sample was aged to determine the specific timing of settlement. Age was determined using the daily increment analysis of otoliths (ear bones). The otoliths of most reef fishes consist of a series of increments deposited on a daily basis, resulting in a continuous record of age and day-specific relative growth rates [e.g., Searcy and Sponaugle, 2001]. The daily nature of increment deposition has been validated previously for *T. bifasciatum* [Victor, 1982]. The combination of the density estimates obtained from the transect data and the sample-specific age data from the fish otoliths provided a daily recruitment record for *T. bifasciatum* from March 1996-October 1997.

A changing food (prey) environment may directly impact the growth and ultimately survival of fish larvae. Slow-growing larvae may experience longer development times that can translate into greater mortality risks (i.e. longer time exposed to high mortality rates associated with planktonic existence, as well as due to smaller size). Therefore, to examine the potential influence of NBC rings on the growth and pelagic duration of fish larvae present in the water column before and during the passage of the rings, the otoliths of newly settled *T. bifasciatum* were examined for relative growth. Fish otoliths not only provide an estimate of age and larval duration, but the width between consecutive increments provides a measure of relative larval growth rates. To examine the influence of rings on larval growth, the mean otolith increment widths (or relative growth trajectories) were compared during the larval period for fishes
Table 1. Schedule of bio-physical surveys for the 1996 and 1997 Barbados cruises and of observations of low salinity intrusions. CT, conductivity-temperature; ADCP, acoustic Doppler current profiler; MOCNESS, multiple opening-closing net and environmental sensing system.

<table>
<thead>
<tr>
<th>Survey No.-Year</th>
<th>CT/ADCP</th>
<th>MOCNESS</th>
<th>Minimum Salinity (psu) at 10 m</th>
<th>Vertical Extent (m) of water &lt; 34.5</th>
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that had encountered a ring for at least 7 days during the first half of their larval period (i.e. during day 1-20), and those that encountered a ring during days 21-40, to those that encountered no ring at any time during their larval period. Presence or absence of a ring was determined from the CT sensor timeseries of Kelly et al. [2000]. A ring was considered to be present when salinities were less than 34.5 psu.

3. RESULTS

3.1. Surface Salinity and Transport

During the experiments of both years, near-surface salinity was higher during the first four surveys than the latter four, and surface salinity was initially higher in 1997 compared to 1996 (Table 1). During both years, a strong salinity front appeared in survey 5, separating salty coastal water from fresher and slightly warmer oceanic waters. This offshore front moved rapidly onshore over
Figure 2. Salinity and current fields in the upper 100 m along the western shore of Barbados during (a) May-June 1996 and (b) April-May 1997. Low salinity water (< 34.5 psu) penetrates the domain at the southern boundary and persists throughout the entire domain for the rest of the surveys. Maximum velocity = 50 cm s⁻¹.
the entire domain, resulting in waters of lower salinity for the remaining 3 surveys (Figure 2). In 1996, the low salinity front was coupled to warmer sea surface temperatures. However, in 1997, while the change in salinity from survey 4 to survey 5 was larger (surface salinity decreased by 2 psu), warm waters near the surface lagged by 2 surveys [Choi et al., 2001]. The vertical extent of the low salinity (< 34.5 psu) water was similar between years, reaching to as deep as 35 m (Table 1).

Horizontal currents in the upper 100 m indicated complex and contrasting flow patterns during 1996 (Figure 2a) and 1997 (Figure 2b) in response to the observed intrusion of low salinity water. Although in 1997 the flow during surveys 1 to 4 had a stronger eastward component, overall the pre-intrusion flow in both years was initially northward then, preceding the low salinity intrusion, reversing southward. During both years, as the low salinity lens penetrated the sampling domain, the flow reversed again (northward). In 1996, the flow associated with the low-salinity intrusion remained northward or northeastward (Figure 2a), whereas in 1997, the low-salinity flow was initially northward then eventually turned southward (Figure 2b).

Differences in the residence time of water before and during the low salinity events were associated with the changing salinity and flow field. During 1996, residence time prior to ring passage (May 8-18, 1996) ranged from 0-13 days at 50 m (Figure 3a). Once the NBC ring was present in the vicinity of Barbados, residence time increased over most of the domain to approximately 6-13 days (Figure 3b). An increase in larval abundance coincided with the increase in residence time (Figure 4a). In comparison, during 1997, residence time at 50 m was always higher than in 1996 (Figure 3a), but decreased in the southern part of the sampling domain with ring collision (i.e. May 13-22, 1997; Figure 3b). This decrease coincided with a decrease in larval densities in 1997 (Figure 4b). Change of water residence time with the ring events and associated incident flow, combined with changes in larval fish vertical distributions, results in differences in larval transport (flux).

3.2. Chlorophyll a and larval fish vertical distribution

Chlorophyll a (Chl a) content varied within and between years. Chl a concentration was typically higher in 1996 than in 1997 during all surveys, with a maximum of 2 mg m$^{-3}$ and 0.5 mg m$^{-3}$, respectively (Figure 5). In 1996, the intrusion of low salinity water brought no appreciable change in the depth of the Chl a maximum, which varied between 40-80 m (Figure 5a). However, in 1997, where the change in salinity between pre- and post- intrusion was greater, there was a concomitant shallowing (and broadening) of the Chl a maximum layer from approximately 100 m to 40-60 m (Figure 5b). The shallower nature of the Chl a maximum in 1997 may be explained in part by the presence of a second (and shallower) peak in concentration just below the low salinity water (see Figure 5b).

The vertical distribution of larval T. bifasciatum was generally coincident, though slightly shallower, with the depth of the Chl a maximum. In 1996, T.
Figure 3. Maximum residence time (RT) on the western shore of Barbados during the 1996 and 1997 experiments at the mean depth of center of mass for *Thalassoma bifasciatum* (40-60 m) (a) before and (b) after low salinity intrusions.

Figure 4. Temporal distribution of standard catch of larval bluehead wrasse, *Thalassoma bifasciatum*, during the (a) 1996 and (b) 1997 experiments.
Figure 5. Vertical profile of Chl α (-), salinity (-) and mean depth of center of mass for larval *T. bifasciatum* (circle) for each 3-d survey during (a) 1996 and (b) 1997. A total of 17-24 CTD casts and MOCNESS hauls was made during each survey; thin lines and vertical bars represent 1 standard deviation around the mean Chl α or mean salinity, and mean depth of center of mass, respectively.
Figure 6. Relationship between Chl $a$ maximum and the vertical distribution of larval bluehead wrasse (*Thalassoma bifasciatum*), based on 1 month of data in the vicinity of Barbados in April-May, 1997. The linear regression indicates that 69% of the variation in depth of the center of mass of the larvae is correlated with the depth of Chl $a$ maximum. Error bars on the center of mass for each survey correspond to spatial variability in the estimates (24 stations per survey).

*bifasciatum* larvae typically occurred between 20-60 m, and showed little change in depth during the course of the study. However, in 1997, larvae were shallower after the low salinity intrusion. Despite the typical patchy nature of ichthyoplankton, larval vertical distribution was well correlated with the depth of the Chl $a$ maximum ($r^2 = 0.69$, Figure 6).

3.3. Fish settlement intensity

Settlement of bluehead wrasse was typically highly variable in time, though lunar periodicity was present (Figure 7). There was no clear pattern between settlement intensity and the presence of a ring; in several cases there appeared to be a strong reduction in (or complete absence of) settlement immediately following a ring, whereas in at least one case (i.e. Sept-Oct 1996), settlement was very high near the end of a rather long duration low salinity (ring) episode.

3.4. Otolith growth and larval duration

Variation in growth rates as measured by increment width indicated that larvae co-occurring with a ring experienced slower growth. When larvae experienced low salinity ring water for at least 7 days during the first or second
Figure 7. Raw settlement records for *Thalassoma bifasciatum* settling to Barbados over a twenty month time period. The timing of settlement was obtained from individual otolith records of fish settling to nearshore reefs along the west coast of the island; relative sizes of events were obtained from biweekly census of new recruits. Black circles indicate new moons; shaded areas represent low salinity (< 34.5 psu) intrusions.

portion of their larval period, their daily otolith growth during or following this period was lower than that of larvae that did not encounter a ring (Figure 8). The importance of exposure of larvae to the presence of a ring is further indicated with respect to timing of exposure and total larval duration (Figure 9). Larvae with the shortest larval durations were those that grew rapidly, thus most of these were larvae that never encountered a ring. Slower growing larvae that experienced a ring generally had longer pelagic larval durations.

4. DISCUSSION

*Simmons and Nof* [2000] describe ring/island interactions by simulating the collision of a wall into a lens. Using their modeled criteria, the ratio of the length (L) of Barbados to the radii ($R_1$) of typical NBC rings ($L/R_1 \sim 0.49-0.97$) may be smaller than the critical value required for splitting ($1.19R_1$) but not so small that an interaction is prohibited ($0.15R_1$). Additional factors involved in the splitting process are (1) the distance between the center of the ring and the initial contact point with the wall inferring a weak or strong collision, (2) the
Figure 8. Mean otolith increment widths for *T. bifasciatum* recruits encountering a ring during the first portion of their larval period (day 1-20; thin black line) and those that encountered a ring during the last half of their larval period (day 21-40; thick black line), as compared to those that did not encounter a ring during their larval period (gray line). Otolith increment widths are a proxy for larval growth rates. Standard deviations are omitted for clarity.

Figure 9. Proportion of all aged *T. bifasciatum* exhibiting a range of pelagic larval durations (PLDs). Fish with the shortest PLDs were those that never encountered a ring in their larval period (gray). Fish with the longest PLDs were those that encountered a ring early in their larval period (cross hatch). Fish encountering a ring in the second half of their larval period had intermediate PLDs (black).
ring thickness, (3) its translation speed, and (4) swirl speed or intensity [Simmons and Nof, 2000]. In the absence of splitting the ring, a collision may result in deformation of ring geometry and/or trapping of part of the low salinity rim around the island. Within this context, it is worthwhile to compare results from observations and theory.

Among the various rings that passed in the vicinity of Barbados during 1996-1997, at least two passed during the 30-day cruises (1 ring per cruise; Figure 10a). TOPEX/Poseidon-derived sea height data suggest that the center of rings that have turned N-NW can pass Barbados on either side of the island, but mostly to the east [Kelly et al., 2000; Goni and Johns, 2001]. When the core of a ring passes farther to the east of the island, the western side of the island should experience predominantly northward or northeastward flow since it lies within the western edge of the anticyclonic circulation (Figure 10b). In this scenario, the northward dominance of the flow could persist as the ring passes east of the island of Barbados, which may never see the oligotrophic core. However, when a ring passes more to the west of the island, its influence on the local circulation may be more complex, rapidly changing from more eastward dominated flow to northward and northwestward as the island intercepts the northern, then southern rim of the anticyclonic circulation (Figure 10c). In this latter scenario, the ring trajectory would veer to the north after impact with the island topography. Furthermore, the island may experience the oligotrophic core. Our observations are consistent with the predictions of these two scenarios as having occurred during 1996 and 1997, respectively. The eastern component of the northern wall of the anticyclonic ring was apparent in May 1997 when the angle of the impact was not as direct as in May 1996. Current reversals to the south occurred in both years before the arrival of the low salinity waters, indicating a consistent disruption of the background flow by the moving anticyclone (i.e. entraining local water mass in its periphery as the ring approaches the island).

The importance of the interaction of these rings on the local, island scale flow is twofold. First, the salinity field that is introduced around the island appears to directly affect the baroclinic flow field, leading to strong, sheered flows as well as barotropic instabilities. Second, the direction of the flow is highly variable during the various stages of a passing ring, as well as among different ring events due to variable ring core orientation with respect to Barbados. Knowledge of the impact of these rings and the frequency of their occurrence lends insight into the highly variable nature of the flow observed around Barbados [Bowman et al., 1994; Cowen and Castro, 1994; Stansfield et al., 1995; Paris et al., 2002]. Combined, these ring-topography interactions influence the residence time of water, which has a direct impact on the distribution of larval fishes in the vicinity of the island. Because larval fishes move vertically during their larval development (ontogeny), they can encounter unique layers of water. Under some conditions, residence time within waters near the island appear to be enhanced (i.e. during 1996 at 50 m), whereas during other times there was increased flushing. These different scenarios should result in opposite impacts on the success of a cohort of larvae to successfully recruit to the island. This may be
Figure 10. (a) NBC ring and eddy trajectories from TOPEX/Poseidon-derived sea surface anomaly signals detected from October 1992 to December 1998 [modified from Goni and Johns, this volume]. Red and green lines correspond to 2 rings (observed in the field from the CTD surveys of May 1996 and 1997) of the six NBC rings observed from ADCP moored in the vicinity of Barbados from January 1996 to November 1997 [McWilliams, 1986]. Inserts show conceptual configurations of NBC ring of May (b) 1996 and (c) 1997 impinging on the island of Barbados. The shaded area corresponds to low salinity water originating from the Amazon and entrained around the ring core. As the rings translate N/NW, the island of Barbados may not always ‘see’ the oligotrophic core. At impact, the island experiences (b) mostly northern velocities from the western edge the ring, and (c) northeastern velocities from the northern edge of the ring. Hypothetical ring position before, at initial, and during full impact is represented by dotted, dashed, and solid lines, respectively; gray arrow depicts direction of ring translation as it collides with the island; bathymetry is superimposed with contour lines every 1000 m.
apparent in the highly variable recruitment record. Based on field observations of these two rings it is not possible to determine whether ring passage farther to the east will always be less favorable in terms of retention as compared to more westerly passage. During 1990, a ring apparently collided with Barbados. While the exact orientation of the major axis of the ring relative to the island in 1990 is not available based on altimetry, current data suggest the core passed slightly to the east of the island [Bowman et al., 1994; Cowen and Castro, 1994]. During this event, all reef fish larvae were swept away from the western side of the island as well (with a concomitant failure in recruitment of a suite of reef fishes to the island – see Figure 11). This added observation indicates that the factors contributing to retention on the western side of the island are more complex than simply whether the core of a ring passes to the left or right of the island.

Several recent time series analyses of recruitment data at Barbados demonstrate clear lunar cyclic patterns [Sponaugle and Cowen, 1996, 1997; Reyns and Sponaugle, 1999]. However, there is an element of stochasticity apparent in these records. Our observations of recruitment to the island corroborate the potential role of rings to interject considerable variability in retention success of larvae around the island in that substantial variability exists in the intensity of settlement events. While a background of lunar cyclic pulsing is present, there are episodes of failure and enhancement associated with ring passage. Data analyzed here show that the passage of a ring did not create a clear increase in Chl $\alpha$ concentration. However, there appeared to be a Chl $\alpha$ maximum associated with the base of the low salinity lens (at approximately 40 m). Whether this relatively shallow signal is evident with the passage of a ring depends on water column conditions prior to the passage of a ring. During 1996, pre-ring conditions were characterized by lower salinity near the surface and a shallower Chl $\alpha$ maximum than in 1997. The possibility that the 1996 conditions represent the remnants of a previous eddy cannot be confirmed because the mooring was initially deployed at the onset of the 1996 cruise. It is worth noting that the initial observation that an event was occurring within the sampling domain during 1997 came from the observation of a color change (slightly greener water) observed from the ship, whereas no such visual signal was obvious in 1996.

The change in the vertical distribution of larvae with ring passage in 1997 corresponded to an observed change in depth of the Chl $\alpha$ maximum. There are two possible explanations for this observation, though supporting evidence is largely lacking at this point. First, the larvae may be responding to the depth of their preferred food source (micro-zooplankton), which may be directly tracking the highest concentration of primary producers. Data are not available on the zooplankton depth or concentration to confirm or refute this. Larval growth data cannot be used to examine this since reduced larval growth may occur in response to factors other than food (e.g. temperature, salinity). Light level may explain the associated change in depth of the fish larvae with the Chl $\alpha$ maximum. If the fish prefer a particular light level, they may move vertically in response to changes in water clarity (as well as diel light levels). Notably, in
Figure 11. Raw settlement records for eight species of Labridae (wrasses) settling to Barbados during the spring recruitment period of 1990. The timing of settlement was obtained from otolith records of new recruits collected biweekly from the reef (Sponaugle and Cowen, 1997). Arrow denotes timing of intrusion of low salinity, anticyclonic flow colliding with the island; black circles indicate the new moons.

1997 the larvae were as much as 30-40 m above the Chl $\alpha$ maximum when the latter was located in deeper water, but only 10-20 m when the Chl $\alpha$ maximum was shallower in association with the ring. This observation would be consistent with seeking higher light levels in shallow water in the presence of increased production-related turbidity. The second possible cause for change in larval depth could be a change in buoyancy associated with a changing vertical density profile. However, if larvae track a particular isopycnal, the response would be opposite to that observed.

The lower otolith growth rates and longer larval durations of larvae associated with ring water masses would likely convey reduced survival rates, since larval mortality is often size structured (larger fish are better able to evade predators [Leggett and Dublois, 1994]; shorter time in plankton means less time exposed to high planktonic predation rates [Houde, 1997]). Further, recent evidence suggests that higher growth rates in the plankton stage confer increased post-settlement survival potential [Searcy and Sponaugle, 2000, 2001]. Thus, conditions encountered by larval fish during ring passage likely reduce recruitment chances.
Overall, the regular passage of NBC rings in the vicinity of Barbados seems to have conflicting impacts on larval fish around Barbados, depending both on species-specific behavior and ring type. The physical retention of larvae may be enhanced (concentration at fronts with flows bringing larvae closer to shore), or decreased as a result of flushing/advection away from the island. Ring orientation relative to the island influences water residence time, but greater detail of this interaction is needed. The trophic environment associated with a ring remains unknown and even if enhanced, is not sufficient to counter reduced growth due to factors such as salinity. Generally decreased larval growth and lengthened pelagic larval periods would reduce survival and hence have a negative impact on settlement intensity [Searcy and Sponaugle, 2001; Victor, 1982]. In combination with the variable flow (retention) environment introduced by ring orientation and the ring’s associated salinity field, the overall impact of rings on recruitment of coral reef fishes to the island appears to be that of increasing overall variability.

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