

Quantifying the Seasonal and Interannual Variability of the Formation and Migration Pattern of North Brazil Current Rings

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Abstract: The complex nature of the North Brazil Current (NBC) has led to various studies regarding its seasonal variations and eddy-shedding regime. Horizon Marine, Inc. has conducted operational analysis of the NBC for the past 8 years, making use of drifting buoys, satellite imagery, and ADCP data. We have validated observations made by previous studies such as references [1-5] during this time period. Energy fluctuations within the NBC Retroflexion can create a closed circulation at the point of inception of the North Equatorial Counter Current (NECC). This closed circulation can spin off as it gains momentum to create a separate anticyclonic eddy, known as an NBC ring. Our observations indicate that the NBC Retroflexion sheds between 5 and 8 NBC rings over the period of 1 year. These rings vary from 100 to 500 km in diameter and 70 to 200 cm s^{-1} in surface intensity. The depth of the coherent velocity structure can vary from 200m to 1000m as described in [1] and [4]. The structure and intensity of each ring varies seasonally as does its migration rate and trajectory. The energy sector offshore Trinidad and Tobago is most strongly impacted by the NBC ring influence on local oceanographic conditions, most critically the vigorous near-surface currents associated with the rings' strong vertically coherent velocity fields. The extent of this influence depends on the NBC ring proximity to the shelf break, the ring swirl velocity, and vertical variation in the ring velocity field. In this study, we quantify characteristic patterns of oceanographic variation imposed by NBC rings observed in our operational datasets. Of central importance is determining the variations in migration patterns of NBC rings with changing seasonality.

I. INTRODUCTION

The complex ocean current system composed of the South Equatorial Current (SEC), North Brazil Current (NBC), and North Equatorial Counter Current (NECC) is the chief source of energy for the Atlantic Equatorial Gyre (Fig. 1). This is a basin scale current system that is driven primarily by the trade winds. The east-west flow of the equatorial gyre consists of the strong westward flow of the SEC found south of the equator and, to the north, the eastward flowing NECC. The thermohaline western boundary current is the NBC which travels northwest parallel to the coast of Brazil from 2°S to 10°N. It separates from the coast near 6°N, turns sharply around to the east, and extends into the NECC. This sharp turn is referred to as the NBC Retroflexion. Typical surface currents within the NBC range from 1 to 3 knots. The NBC currents decrease with depth and extend down to 1000m.

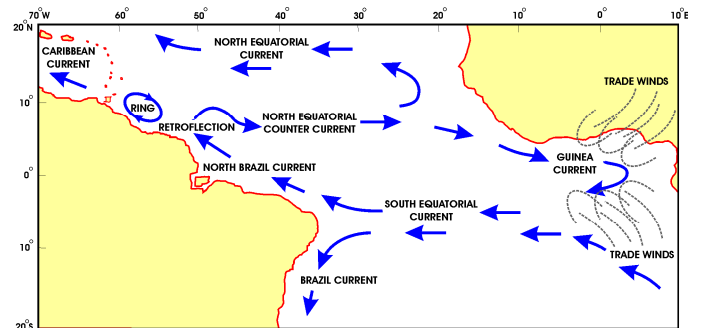


Figure 1. Equatorial Atlantic Circulation System.

Although the NBC is closely related to the Inter-tropical Convergence Zone (ITCZ) and remote wind forcing, the predominant factor influencing the intensity of the NBC is the Atlantic Meridional Overturning Circulation (MOC) [1, 2, 3, and 6]. Maximum transport within the NBC takes place during the months of July and August, and minimum transport occurs between December and February [3] and [6]. Thus, there is minimal flow strength during late spring, acceleration during summer, and maximum strength during late summer and fall. During its weakest season, the NBC is more coastally trapped, increasing into a broader and deeper flow during the fall. The NECC has a significant seasonal signature in which an eastward flow completely ceases and is replaced by a weak westward flow from February to May.

Between 5 and 8 times per year, the NBC Retroflexion turns back on itself, forming a region of closed circulation that becomes a ring (also known as an eddy). These rings move northwest along the South American coast towards Barbados and the Windward Islands. The NBC Retroflexion typically forms between 50°W and 54°W as the NBC encounters northward extension of the shelf break at the Demerara Rise downstream of the Amazon River delta. The inception of most NBC rings can thus be traced to this region. As the NBC is their main source of energy, NBC rings maintain their initial momentum, with stronger currents along the southern and southwestern portions of the ring. This energy propels the ring to continue migrating to the northwest parallel to the shelf break. As the ring migrates, it also exhibits clockwise rotation of its structure due to the stronger currents within the southern

portion and relatively weaker currents within the northern portion.

NBC rings propagate at speeds averaging between 8 and 20 km/day, remain intact for up to 150 days, and have diameters ranging from 100 to 500 km. Surface currents within these rings circulate anticyclonically (clockwise) and may at times exceed 3.0 knots. Significant subsurface ring currents can extend as deep as 400m. The NBC rings are similar to eddies found in the Gulf of Mexico because they are usually characterized by an ideal vortex where vorticity is conserved when they are not in proximity to other eddies.

As these rings typically follow the shelf break along the South American coast, they interact with the bathymetry and subsequently behave differently than Gulf of Mexico eddies. Another factor influencing conditions in the region is river outflow. Discharge from the Amazon, Orinoco, and Essequibo River systems can be substantial, influencing the dynamics of the local circulation. The drainage basin of the Orinoco River alone covers some 880,600 square kilometers and, on average, discharges 33,001,200 liters of water per second.

In this study, we will quantify the seasonality associated with the formation, separation, and migration of NBC rings as observed during operational analyses conducted by Horizon Marine, Inc. during an 8-year period (September 2001 to June 2009) of the Eddy Watch™ – Trinidad/Venezuela program. During this period, we deployed our drifting buoys regularly in and around NBC rings as they formed off the coast of Suriname. In addition to velocity measurements from these buoys, we analyzed satellite imagery (GOES SST and MODIS ocean color) to aid with the accurate placement of the fronts. This data was assimilated to create charts of ring location and migration for our clients off the coasts of Trinidad and Tobago. Seasonal and interannual variations have been studied to establish better predictability of this process.

The basic outline of this paper is as follows. In Section I, we enumerate the various datasets that were used for the analysis in this study. Section II describes the methodology that was used to process and analyze the data. In Section III, we discuss the results obtained from the study, and in Section IV, we summarize the interpretations made from the results and discuss the conclusions of this study in Section V.

II. DATA

A total of 213 satellite-tracked surface drifting buoys (Far Horizon Drifters) were air deployed off the coasts of Suriname and Guyana over the 8-year period to study the strength and lateral structure of NBC rings as they form and migrate along the northern coast of South America. The Far Horizon Drifter (FHD) (Fig. 2) is a low-cost, air-deployable drifting buoy that was first deployed in 1985 in the Gulf of Mexico (Fig. 1). The cylindrical buoy hull measures 96.5 cm by 12.4 cm. The parachute has an effective drag area of 1.28 m² and is

connected to the buoy with a 45m nylon tether. The buoy deployment package is designed to be dimensionally compatible with a standard Sonobuoy. Each FHD is equipped with a GPS receiver, allowing for a position retrieval every hour. In addition to Horizon Marine's buoys, NOAA buoys drifting in the region were also used in the analyses.

Satellite imagery obtained from GOES and MODIS Aqua was used to locate strong gradients along the fronts of the rings. The chlorophyll-rich shelf water was used as a tracer as it wraps around these features. Sea surface temperature (SST) measurements made by the PIRATA buoys in the mid Atlantic was also used to observe seasonal trends.

The ITCZ is a region characterized by weak winds and excessive rainfall. This results from reduced solar heating due to cloud cover accompanied by deep atmospheric convection. Quarterly averaged outgoing longwave radiation (OLR) contour plots were obtained from the NOAA Earth System Research Laboratory (Physical Sciences Division) website to estimate the location of the ITCZ.

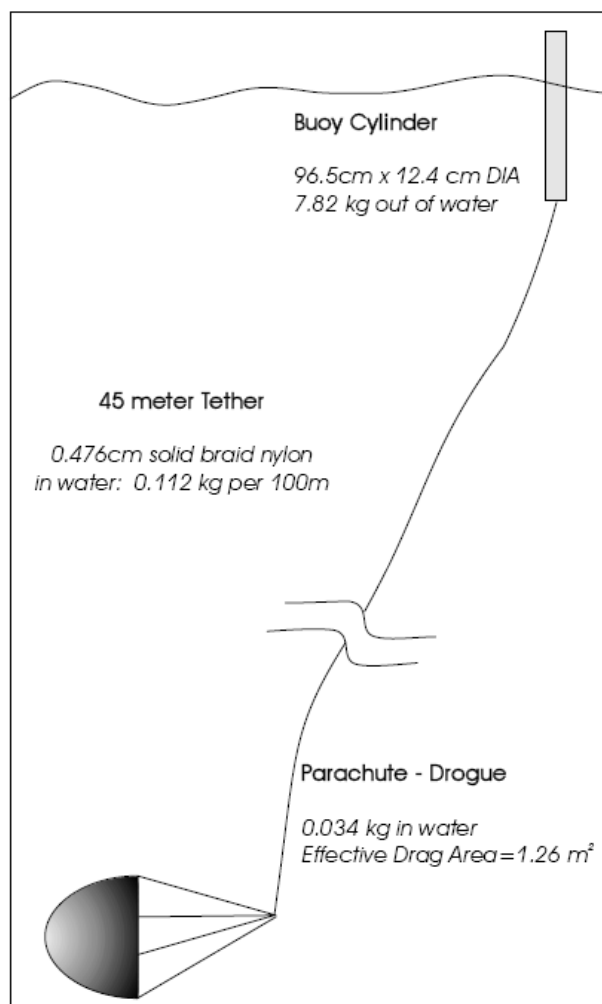


Figure 2. Far Horizon Drifter (FHD) design and dimensions.

III. METHODOLOGY

The Eddy Watch™ program's weekly charts and analyses were used in this study for determining the structure, generation, migration, and disintegration of 44 NBC rings over the past 8 years. This daily analysis is done with the integration of various data sources (buoys, satellite imagery, and model outputs) to determine frontal locations of all mesoscale features. Strong temperature gradients in SST imagery (from the GOES satellite) were used to detect the presence of strong shear at and near the fronts of these anticyclonic eddies. Similarly, gradients in ocean color imagery from NASA's MODIS Aqua satellite assisted in determination of water movement.

The dimensions for each ring (namely the center of circulation, major and minor axes and orientation) were obtained from these charts by fitting perfect ellipses into the structure of the ring. These measurements were then used to calculate average rate of migration, size, and orientation. Annual variations of these parameters were studied. Overall mean and standard deviations of the path traveled by all NBC rings were established. SST measurements made by the GOES satellite were averaged to create monthly means for the time period between February 2005 and July 2009.

IV. RESULTS

We have observed a continuous interaction of almost all rings with the shelf break throughout their lifetimes due to formation over or near the Demerera Rise. The rate of migration during and immediately after separation is fairly

slow for each ring as a result of its interaction with the plateau and weak connections with the NBC. As the ring migrates west of 55°N, it encounters deeper water, resulting in a southward dip of its trajectory and, in most cases, an increase in the rate of migration. The ring's rotation decreases as it aligns itself parallel to the shelf break between the Demerera Rise and the shelf break off the east coast of Trinidad.

Fig. 3 shows the weekly progression of a typical ring over a 3-month period during the NBC seasonal peak export in boreal fall and winter. The ring's outer extents are color coded to illustrate the progression. Dotted fronts indicate a lower level of confidence in the placement due to poor satellite imagery and/or lack of buoy coverage at the time. The line joins the centers of all positions to depict the trajectory followed by the ring. In this figure, the NBC Retroflexion exhibits a progressive westward movement followed by a surge that culminates in a ring formation and separation. Upon encountering the islands of Trinidad and Tobago, the ring changes its course of migration to move northward. At the same time, the interaction of the ring's vertical structure with the shallower bathymetry of the region results in a loss of momentum and energy, deteriorating the ring's structure until it is no longer able to sustain a distinct closed circulation. North of the island of Tobago, most rings disintegrate completely to form a flow that diffuses through the Windward Islands into the Caribbean Sea. This process has been observed in satellite imagery and buoy trajectories over the course of the Eddy Watch™ program (Fig. 4).

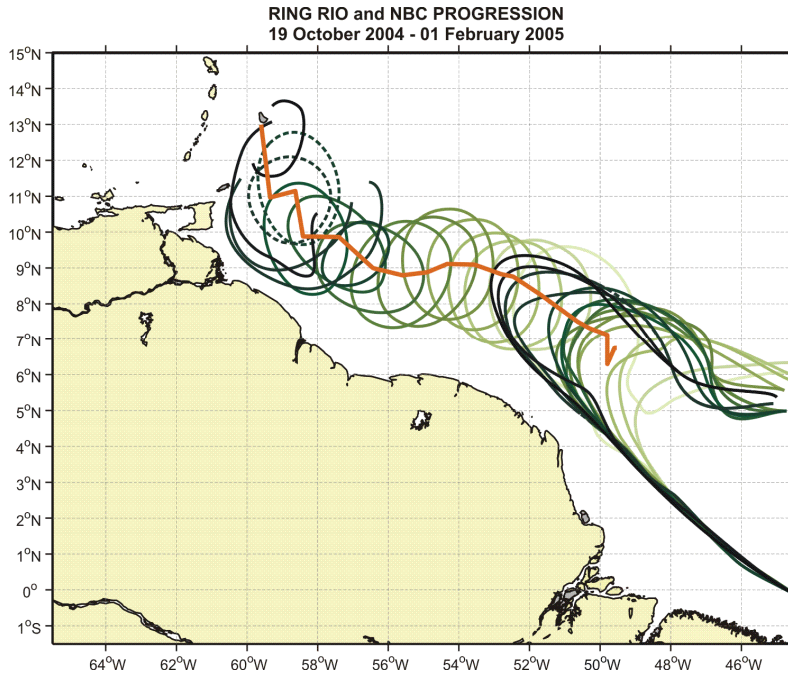


Figure 3. Example NBC Ring progression to the northwest parallel to the northern coast of South America shown as elliptical fits to ring fronts and the center of circulation. The rings are color coded from light green to black with the lighter shades corresponding to the beginning of the sample period and the darker colors to the later weeks. The orange line represents the mean trajectory followed by the ring centers over time.

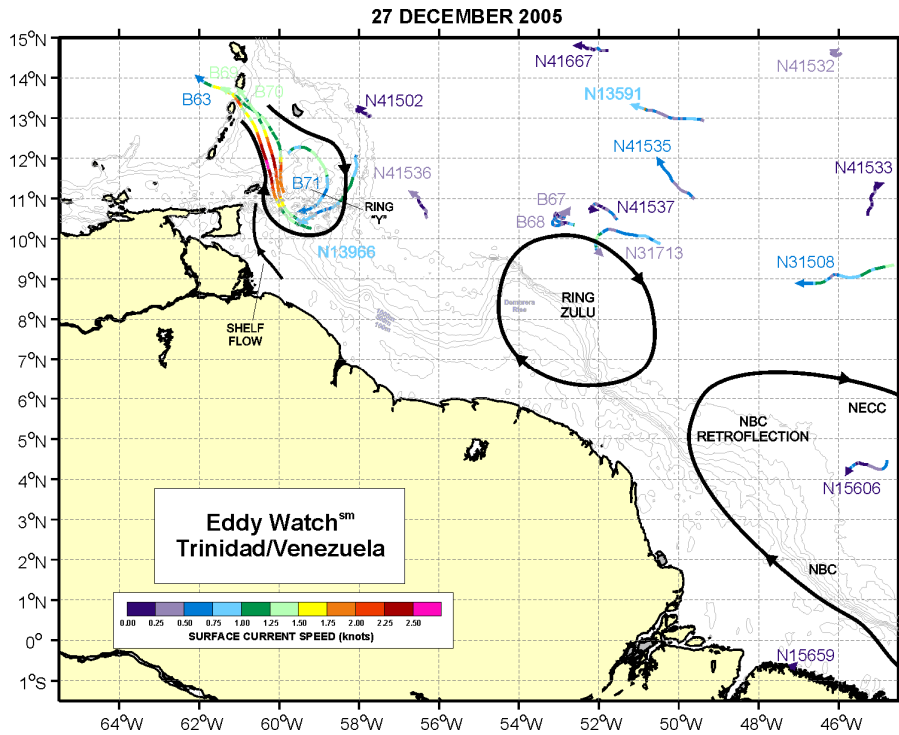


Figure 4. Example Eddy Watch™ chart illustrating the collapse of an NBC ring east of the Windward Islands. Buoy trajectories suggest the filtering of water mass and energy into the Caribbean Sea.

The migration paths followed by the 44 NBC rings have been illustrated in Fig. 5. As denoted, the average rate of migration along the entire path is approximately 14.83 km/day or 17.16 cm/s. The rate of migration through individual longitude intervals has been described in the figure and in Table 1. Interannual variation in the rate of migration is provided in Table 2. Higher rates of migration are observed to the west of the Demerara Rise and lower rates during the period of continued interaction with the NBC.

Table 1. Rate of Migration of the NBC Rings.

Longitudes	Slowest (km/day)	Average (km/day)	Fastest (km/day)
52°W to 54°W	4.95	14.39	73.49
54°W to 56°W	4.63	15.54	41.28
56°W to 58°W	3.09	17.87	68.76
58°W to 60°W	5.33	17.83	53.54

Dimensions of NBC rings appear to generally decrease as the ring migrates, with sharper gradients immediately after inception and immediately before collapse. The change in major axis lengths for all 44 rings over the course of their lifetimes is illustrated in Fig. 6, with the starting point representing the first formation of a closed circulation within the NBC Retroflexion (which differs for each ring). The colored lines in the plot represent each of the rings observed over the past 8 years with the thick black line representing the mean of all rings. The increase in size of the ring, as observed in the mean, only illustrates the variations in ring dimensions

while it remains connected to the NBC. Immediately following separation, rings tend to exhibit a decrease in size for the initial 100 to 200 km of its migration. As the ring continues to migrate, it maintains its size until it encounters the islands of Trinidad, Tobago, Barbados, and the Windward Islands. With continued interaction with the bathymetry, these rings lose their structure and surface signature. Variation in ring size by geographical location, interannual variability, and interseasonal variability is provided in Table 3.

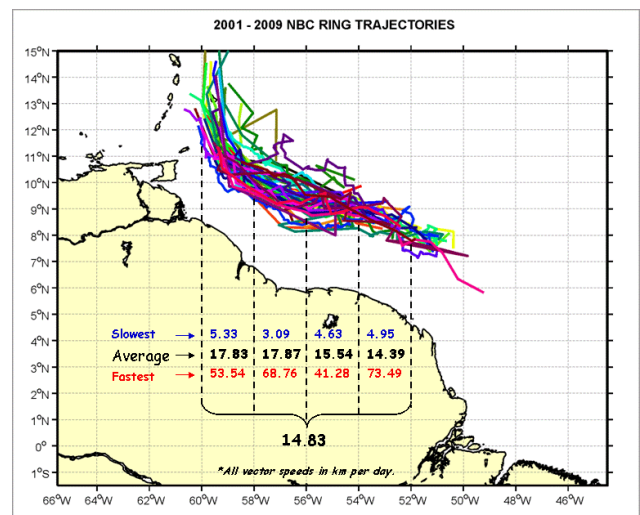


Figure 5. Trajectories of all 44 NBC rings tracked in this study and the average in the rate of migration at 2° longitude intervals.

Table 2. Interannual variation in the rate of migration of all rings.

Annually Averaged Rate of Migration (km/day)	
2001 (September – December)	10.70
2002	14.41
2003	15.67
2004	14.26
2005	10.84
2006	15.43
2007	14.77
2008	9.74
2009 (January – July)	8.52

Table 3. Ring size by geographical location, interannual variability, and interseasonal variability.

Longitudinally Averaged Ring Size (km)	
Total Path	182.19
52°W to 54°W	205.86
54°W to 56°W	191.02
56°W to 58°W	195.53
58°W to 60°W	195.22
Annually Averaged Ring Size (km)	
2001 (September – December)	153.22
2002	183.29
2003	180.68
2004	180.71
2005	183.14
2006	208.78
2007	176.71
2008	173.61
2009 (January – July)	187.43
Seasonally Averaged Ring Size (km) (2001 – 2009)	
January – March	205.89
April – June	190.12
July – September	186.16
October – December	201.34

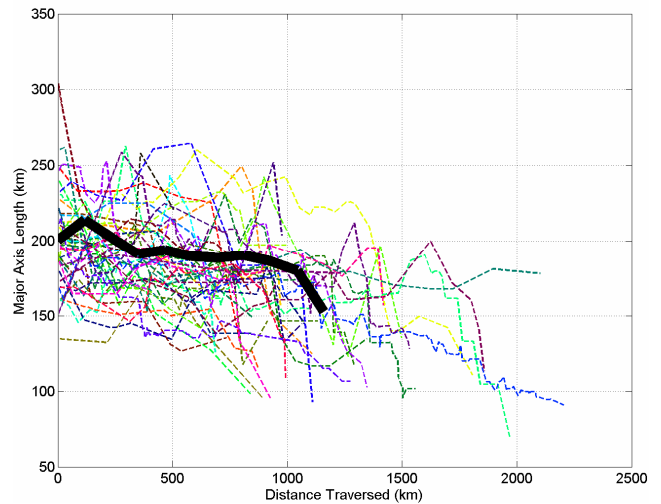


Figure 6. Variation in ring size by distance traversed with '0' indicating the point of inception of the ring within the NBC Retroflection. The black line indicates the average of all 44 rings by size and distance traversed.

Over the study period, seasonality associated with the formation of NBC rings is evident but inconsistent between successive years. Once a ring separates from the NBC and migrates northwestward, another ring forms as soon as the NBC Retroflection develops the necessary momentum and a defined closed circulation. Over the last two years of the time period (2008 and 2009), a distinct gap in the formation of rings was observed in the region during late spring and early summer. This period of low activity is directly associated with the seasonality of the NECC. As mentioned by [1, 2, 3, and 6] and corroborated in our continued observations, the eastward flowing Atlantic current dissipates completely and is not present during spring and early summer. Fig. 7 illustrates the percentage of time a ring was present during various times of the year within the longitudinal interval 52°-54°W. The figure depicts the general decrease in ring activity during late spring and early summer and increased activity in the second half of the year.

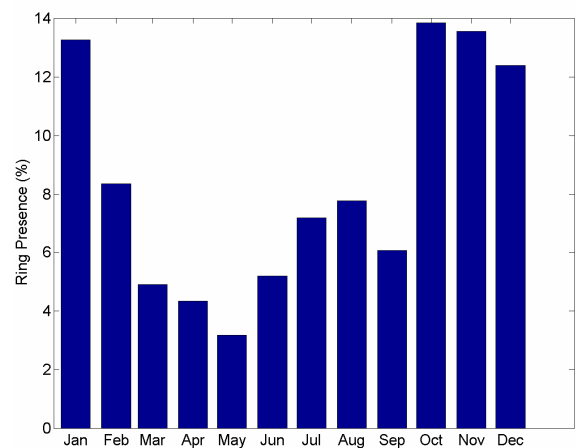


Figure 7. Multi-year average of ring occurrence per month between 52°W and 54°W.

In our observations, the formation and migration of NBC rings even during the late spring and early summer has been documented. This lack of seasonal influence is observed in a biannual pattern. Alternate years do exhibit a distinct gap in ring formation during the late spring and early summer. The rings that do form in this season tend to have shorter life spans. The year 2009 was an exception to this.

The predominant anomalies that are apparent in the study were observed in the ring formation pattern during the years 2005 and 2007. These two years appear to have the maximum number of rings following a relatively steady cycle of formation and migration with little seasonal variation. Rings were observed forming during the late spring and early summer seasons as well. Fig. 8 illustrates the occurrence of ring formation during 2006 and 2007 for comparison. The reduced seasonal influence during 2007 is apparent. This indicates that thermal conditions may override remote wind forcing and heat flux into the atmosphere.

V. CONCLUSION

In this study, 44 NBC rings were researched to determine seasonal trends and find interannual variations (if any) in the formation and migration patterns of these rings. An NBC ring is formed when sufficient kinetic energy develops within the NBC Retroflection as the NBC turns back on itself to flow eastward into the NECC. A closed circulation forms within this region which eventually pinches off to form an anticyclonic eddy. By conservation of momentum, these rings continue to migrate along the northwestern coast of South America towards the Caribbean Islands. On average, a typical NBC ring migrates at a rate of 17.16 cm/s in the west-northwestward direction following separation from the NBC. As rings form near or over the Demerara Rise, the influence of the shelf break remains throughout the life span of most rings. A few rings have been observed to separate completely from the shelf break to follow a more northwestward path. Such rings are likely to maintain a relatively higher rate of migration.

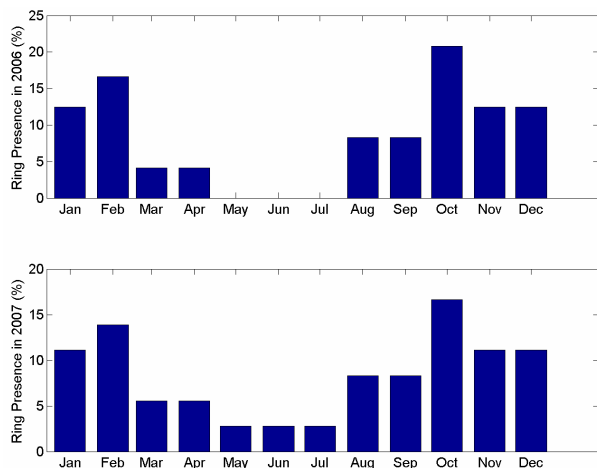


Figure 8. Ring activity in 2006 (upper panel) and 2007 (lower panel).

The basic seasonal cycle that was observed corroborates the observations made by [1-6] and indicates the maximum transport of water mass across the Atlantic Ocean occurs during the period June to August and minimum transport occurs during the period December to February. Thus, the NBC is only beginning to exhibit an increase in transport and intensity during spring and early summer. The southward migration of the ITCZ, remote wind forcing by the trade winds off the west coast of Africa, and the circulation patterns of the Atlantic gyres influence this seasonality. Due to its reduced intensity (during April-June), the NBC becomes coastally trapped and flows continuously along the northern coast of the South American continent. The NECC ceases its eastward flow during the late spring and early summer and is replaced by a weak westward flow that does not influence the formation or migration of NBC rings. Thus, a lack of kinetic energy either prevents the NBC Retroflection from forming altogether or allows for only a weak Retroflection. Previous studies indicate that no NBC rings typically form during this time of the year and a relatively moderate flow is observed all along the northern coast of the South American continent and into the Caribbean Sea.

The cause of the biannual cycle observed in this study remains unclear. The year 2009 did not follow this cycle. Although a weakened NECC was observed during the late spring and early summer period, a ring was observed forming and migrating to the northwest. The only factor that appears to have influenced this anomaly in early 2009 appears to be the relatively southern location of the ITCZ at the time. Further investigation into this process will be conducted to conclusively determine the factors causing it.

During the second half of the year, the NECC regroups and accelerates, forming a distinct eastward flow across the Atlantic Ocean. The NBC also intensifies as the ITCZ migrates northward. Greater stratification of the water column due to increased SST also contributes to this process. More kinetic energy is available within the NBC Retroflection, facilitating the development of a closed circulation and subsequent formation of an NBC ring.

Rings were observed to have longer life spans during the second half of the year. This phenomenon can be explained by the availability of more kinetic energy to sustain the closed circulation of these eddies as they migrate to the west-northwest.

The years 2005 and 2007 exhibited a relatively large number of rings forming with minimal seasonal influence. Both these years had relatively warmer SST conditions during the first quarter and no distinct anomalies in the location of the ITCZ. Distinct rings developed during the late spring season as well, indicating that the dominant factors influencing the weakening of the NBC and NECC (namely the trade winds and ITCZ fluctuations) were overpowered by some other forcing.

The migration paths of all rings were observed to follow a route parallel to the coastline. The variations in the general trajectory from ring to ring do not appear to follow any seasonal trend and are heavily dependent on the availability of kinetic energy at the time of ring formation and separation.

The years 2005 and 2008 indicate the presence of interannual fluctuation in the average rate of migration of the rings. During these years, rings observed a relatively slow rate of migration. Further study will be conducted to determine the causal process for the same.

Ring dimensions have been observed to follow a regular pattern, having the largest major axis during formation and immediately following separation from the NBC. As the ring migrates, the structure compacts. Irrespective of ring dimensions, on average, all rings follow more or less the same trajectory to the west-northwest from their point of inception to their ultimate collapse. There is little seasonal or interannual variation in ring dimension. Interaction with the bathymetry along its path results in a continuous loss of energy within the feature. This effect is most pronounced when the ring approaches the islands of Trinidad and Tobago. Thereafter, rings lose substantial energy and lack the ability to maintain a closed circulation. NBC rings lose their structure and deteriorate as they continue to impact the subsea land masses. North of the island of Tobago, rings tend to disintegrate and form a northward flow that eventually filtrates through the Windward Islands into the Caribbean Sea. The average ring size during 2006 appears to be larger than other years.

The ITCZ, as observed from the OLR contour plots, appears to maintain a regular cycle throughout the study period with little to no anomalous variations. The ITCZ and remote forcing by trade winds are not dominant factors influencing circulation, ring formation, or migration in this region.

This study lacked data through the vertical structure of NBC rings. This is an important concept to grasp due to the significant variations in vertical structures of rings irrespective of lateral structure dimensions. Also, during times of uniform heating of the sea surface, rings have been known to have little to no surface signature. Thus, rings may be present just below the surface and were not observed during the period of this study. This may explain the gap in ring formation during the second half of 2002. Such rings tend to surface during the course of their migration and may be wrongly considered to have a large rate of migration from their point of inception. Further investigation in this regard would be the primary point of focus in the future.

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