Abstract

Brazil’s equatorial margin, extending from Natal to the French Guiana border, is a region characterized by both extraordinary development opportunities and significant operational hazards. Chief among the hazards are intense and highly variable ocean currents capable of delaying, disrupting, or damaging oil and gas exploration and production efforts. Here we review key aspects of the physical oceanography of the equatorial margin based on a collation of historical and contemporary measurements of wind, waves, and currents supplemented with output from a high-resolution numerical ocean circulation model. We present new observations of near-surface circulation along the northeastern coast of South America including more than 12 years of satellite-tracked drifter trajectories. These observations reveal strong near-surface flows of greater than 0.75 m/s (1.5 kt) in close proximity to all lease areas within the equatorial margin region. Within this oceanographic context we explore the implications of a high-current environment for seismic survey planning, rig selection and relocation, station keeping, drilling, diving, and spill response. Ultimately, we present recommendations for mitigating the impact of strong and variable oceanic currents on offshore field operations. These include thorough pre-activity preparation (such as site-specific ocean current measurements) and an ongoing program of elevated situational awareness utilizing continuous real-time observations of ocean conditions.

1. Introduction and Oceanographic Context

Brazil’s equatorial margin (BEM) consists of five basins along the northeast coast of Brazil between Natal and the French Guiana border: the Foz do Amazonas, Pará-Maranhão, Barreirinhas, Ceará, and Potiguar Basins. The dominant regional surface current in the BEM is the North Brazil Current (NBC) which originates just south of the equator from the bifurcation of the westward-flowing South Equatorial Current (Figure 1; e.g. da Silveira et al, 1994; Johns et al., 1998; Schott et al., 1998; Bourles et al, 1999). The NBC serves as both the western boundary current of the wind-driven equatorial gyre and as a conduit for interhemispheric flow associated with the global-scale meridional overturning circulation (see Frantantoni et al., 2000 for a review). The most persistent and intense surface flows associated with the NBC are generally found adjacent to the continental shelfbreak and seaward of the 200 m isobath, although northwestern coastwise flow along the broad continental shelf can also be significant (e.g. Metcalf and Stalcup, 1967; Metcalf, 1968; Flagg et al., 1986; Csanady, 1985; Richardson and Walsh, 1986; Richardson and Reverdin,1987; da Silveira et al, 1994; Johns et al., 1998; Schott et al., 1995, 1998; Bourles et al, 1999; Frantantoni et al., 2000).

At depths greater than 2500 m, a strong and southeastward Deep Western Boundary Current (Johns et al., 1990; Johns et al., 1993; Johns et al., 1998) flows contrary to the surface currents at speeds near 0.25 m/s. This seasonally persistent flow reaches its maximum intensity – approaching 0.5 m/s – at depths greater than 4000 m. Although the majority of the lease areas in the BEM are contained shoreward of the 3000 m isobath and isolated from the strongest abyssal flows, the existence of significant surface-to-bottom velocity shear should be expected anywhere seaward of the continental shelfbreak within the BEM.

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Brazil’s Equatorial Margin consists of five basins. For convenience, we have grouped these basins into three geographic regions as follows: the Foz do Amazonas Basin (Region I), the Pará-Maranhão and Barreirinhas Basins (Region II), and the Ceará and Potiguar Basins (Region III). Additional features shown include a schematic representation of the North Brazil Current, bathymetric contours at 1000 m intervals, and BEM lease areas.

The low-latitude Atlantic is characterized by a pronounced annual cycle forced by the seasonal migration of the atmospheric intertropical convergence zone (ITCZ), a meridionally-narrow region of deep convection associated with reduced winds and increased rainfall. The strength and character of the NBC changes seasonally in response to this regional wind forcing: The boundary current is narrower and less intense during boreal spring (April-June), but broader, deeper, and more vigorous during boreal autumn (September-December) with flows near the continental shelfbreak exceeding 1.5 m/s (Johns et al., 1998). Wind and waves in the BEM are typical of other trade wind-dominated regions with moderate wind speeds of 5-10 m/s and significant wave heights generally less than 2 m (Figure 2). The BEM is located well to the south of Atlantic hurricane activity. Winds and waves across the 1000+ km extent of the BEM exhibit substantially different seasonal behavior due to the importance of the ITCZ migration. For the purposes of this analysis we have grouped the five BEM basins into three distinct analysis regions (Figure 1). In the far southeastern BEM (Region III) winds are strongest August-October, while in the far northwestern Foz do Amazonas basin (Region I) the same time period is characterized by relatively weak winds and small waves. In general, both locally generated wind waves and remotely-generated trade wind swell are of lesser significance and concern in the BEM than the strong ocean currents described in detail below.

Figure 1: The average annual cycle of (a) wind speed (2004-2012) and (b) significant wave height (2009-2012) computed from daily model output in three composite analysis domains: Region I: the Foz do Amazonas basin (black), Region II: the Pará-Maranhão and Barreirinhas basins (red), and Region III: the Ceará and Potiguar basins (blue). Wind data was extracted from the U.S. Navy NOGAPS global atmospheric model. Wave data was extracted from the U.S. Navy WaveWatch III global wave model. Output from both models is archived and available via the U.S. Global Ocean Data Assimilation Experiment (GODAE) website: http://www.usgodae.org.
In addition to seasonal changes driven by the winds, the NBC also exhibits substantial mesoscale variability. In the BEM, 25-40 and 60-90 -day oscillations of the NBC were noted by Johns et al. (1998) with the shorter periods associated with shallower, surface-trapped motions. The 60-90 –day oscillations were linked by Johns et al. (1998) to anticyclonic eddies propagating through the BEM with a likely origin in the interior equatorial Atlantic.

Farther to the northwest, a portion of the NBC separates sharply from the coast near 6°-8°N and curves back on itself (retrofects) to feed the eastward North Equatorial Countercurrent. The NBC occasionally retroflects so severely as to pinch off large anticyclonic current rings exceeding 450 km in overall diameter and with azimuthal speeds exceeding 1 m/s (Johns et al., 1990; Didden and Schott, 1993; Richardson et al., 1994; Fratantoni et al., 1995; Fratantoni and Glickson, 2002; Wilson et al., 2002; Fratantoni et al., 2006; Castelao and Johns, 2011). During their brief lifetime, and especially upon encountering the islands of the southeastern Caribbean, the strong and occasionally deep-reaching velocities associated with NBC rings pose a physical threat to expanding deep-water oil and gas exploration on the South American continental slope. 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 northeastward toward the Guyanas, Trinidad and Tobago, and the southeastern Caribbean Sea (Johns et al., 2003; Fratantoni et al., 2006). While not a specific hazard to operations within Brazil’s equatorial margin, NBC rings could serve as a significant aggregation and long-distance transport mechanism for pollutants released in the BEM.

In the remainder of this article we introduce a new regional surface velocity dataset derived from satellite-tracked surface drifter trajectories. This collection of ocean current measurements spans more than a decade and provides insight into the patterns and intensity of surface circulation in the BEM. A high-resolution numerical ocean model is then used to further explore the structure and variability of flow in this region. Finally, we consider strategies for enhanced ocean observation, simulation, and prediction that may help to mitigate the risk for oil and gas operations in the energetic equatorial margin.

2. Data Sources

2.1 Satellite-Tracked Surface Drifters

Over the last 25 years, satellite-tracked surface drifters have emerged as an efficient means to explore upper-ocean circulation patterns. The number of drifter observations in the North Atlantic has increased substantially in recent years through national and international efforts to produce a high-resolution depiction of the basin-scale circulation and its variability (e.g. Fratantoni, 2001; Lumpkin and Garzoli, 2005).

The Global Drifter Program (GDP) is part of the U.S. National Oceanic and Atmospheric Administration (NOAA) Global Ocean Observing System (GOOS) and a scientific project of the World Meteorological Organization (WMO) Data Buoy Cooperation Panel (DBCP). The GDP is comprised of a persistent array of about 1,200 drifting buoys that provide operational, near-real time surface velocity, sea surface temperature (SST) and sea level pressure observations for global numerical weather forecasting, research, and in-situ calibration/verification of satellite observations (e.g., Lumpkin and Garzoli, 2005). The World Ocean Circulation Experiment (WOCE) Surface Velocity Program (SVP) buoy is a surface float of 30 cm diameter containing batteries, a transmitter, and a thermistor to measure sea surface temperature. An attached holey-sock drogue is centered at 15 m beneath the surface to measure mixed layer currents in the upper ocean. For this study we identified 180 GDP surface drifters that obtained position/velocity measurements within our analysis domain (details below in Section 3). These data were acquired from the public archives of the Global Drifter Data Assembly Center at the National Oceanographic and Atmospheric Administration’s Atlantic Oceanographic and Meteorological Laboratory (AOML) in Miami, Florida.

In addition to drifter trajectories available in the public domain from governmental organizations, Horizon Marine, Inc. maintains its own proprietary network of surface drifters in support of industry-focused regional ocean observing systems located around the world, including the BEM. The Far Horizon Drifter (FHD) is a satellite-tracked drifting spar buoy (Figure 3). Each FHD obtains hourly GPS positions and transmits this data via low-earth-orbit satellite (Iridium or Globalstar) to a shore station where the information is processed and archived. The FHD drifters have been shown to behave similarly to the 15 m drogued WOCE SVP drifters (e.g. Poulain et al., 2002; Perez-Brunius et al., 2013). In particular, the drift of FHD and SVP buoys exhibit similar correlation with wind and with geostrophic currents derived from altimetry. Over the past 31 years, Horizon Marine, Inc. has deployed over 4,700 FHD buoys in strategic locations worldwide in support of operational forecasting programs. For this study we identified 430 FHD buoys that obtained position/velocity measurements within our BEM analysis domain.
A median filter was used to identify outliers in the GPS position records of both GDP and FHD drifters. A 2-day Gaussian filter was applied to the final trajectories to suppress tidal and inertial fluctuations, and velocities were computed from the filtered position time series using a cubic spline function at each hourly interpolated position.

2.2 Numerical Ocean Model

The HYbrid Coordinate Ocean Model (HYCOM; e.g. Halliwell et al., 1998) is a primitive equation ocean general circulation model with a hybrid vertical coordinate. In the open ocean HYCOM uses isopycnal (constant-density) coordinates but transitions smoothly to sigma (terrain-following) coordinates in shallow regions and to z (constant-depth) coordinates in very shallow water and the surface mixed layer. Ongoing HYCOM research has been funded under the U.S. National Oceanographic Partnership Program (NOPP) and the U.S. Office of Naval Research (ONR). Horizon Marine, Inc. uses the public domain HYCOM output as one component of several regional ocean observing and forecasting systems. The HYCOM model assimilates a variety of remotely-sensed surface fields (SST, SSH) and in-situ observations (Argo float profiles, XBT transects). In general, we find agreement between the assimilating HYCOM model and in-situ observations to be reasonably good, especially for large oceanographic features (rings, eddies, boundary currents) which are substantially resolved by satellite altimetry – a key assimilated quantity in the HYCOM and other global models. Due to the low-latitude location of the BEM, the efficacy of satellite altimetry (and thus the performance of HYCOM) for prediction of ocean surface currents is likely to be degraded compared to mid-latitude locations. For this study we acquired public domain fields of 1/12-degree global HYCOM model output from http://hycom.org for the period 2007-2013.

3. Extreme Ocean Currents in the BEM: Observations and Models

3.1 Direct velocity observations using satellite-tracked surface drifters

A composite illustration of all FHD and GDP drifter trajectories identified in the BEM is presented below in Figure 4. Note particularly the fast (1 m/s and greater) trajectory segments parallel to the coast and near the continental shelfbreak. Lease areas in all five basins are affected by the northwestward flow of the NBC with the far northwestern Foz do Amazonas Basin the most heavily impacted. Flow over the continental shelf (generally in water depths of 200 m or less) remains northwestward but at substantially lower velocity than in the offshore environment.

The range of currents experienced in the BEM may be more easily quantified by examining the distribution of all hourly surface current measurements within the three analysis domains defined above (see Figure 5). In Region I, both the mean and mode are near 100 cm/s, suggesting that the surface current in the Foz do Amazonas Basin is
consistently strong. In Regions II and III the mean speed is reduced due to the inclusion of slower drifter measurements on the comparatively broader continental shelves in these areas. Nevertheless, speeds of greater than 100 cm/s are not unusual in either region. Surface current speeds greater than 200 cm/s (nearly 4 kts) are uncommon but have been measured in all three domains within the BEM.

To further examine the spatial variability of surface flow in the BEM, the quality-controlled drifter velocity measurements were grouped into spatial bins to construct a spatially gridded velocity field. In any such analysis there is an inevitable trade-off between spatial resolution, areal coverage, and statistical reliability of the box-averaged quantities (e.g. Fratantoni, 2001; Lumpkin and Garzoli, 2005). The fields presented here are based on velocity observations grouped into 1/3° x 1/3° boxes, a size chosen to provide a reasonable depiction of major ocean circulation features (particularly the NBC) while ensuring that most boxes contain sufficient data to form statistically reliable mean values. Only boxes containing a minimum of 10 independent velocity measurements were retained. Measurements in a given box were judged to be independent if (a) they resulted from different drifters, or (b) they resulted from the same drifter but that drifter remained in the box for more than one Lagrangian integral timescale, taken here to be 10 days. This value is comparable to previous estimates computed by Freeland et al. (1975) and used by Richardson (1984), and agrees with more recent values computed by Brügge (1995) and Fratantoni (2001).

Figure 4: Composite plot of all drifter trajectories (FHD and GDP) used in construction of the gridded fields below. Colors correspond to maximum hourly drifter speed measurements based upon GPS position records. Note the rapid NBC flow parallel to the coast in the BEM and the offshore retroflection of the NBC northwest of the Foz do Amazonas basin.

Figure 5: Histogram of surface drifter-derived hourly surface current speeds in the three analysis subdomains defined above in Figure 1. The histograms represent the measurements of 58, 32, and 39 individual drifters, respectively. Bar height reflects measurement frequency within each region.
The spatial distribution of the gridded velocity observations is shown in Figure 6a. As shown (note log scale) there are typically hundreds to thousands of individual velocity observations per grid cell in the BEM lease areas implying reasonable statistical confidence in the resulting mean field in these areas. The data distribution is likely biased by the historically enhanced deployment of drifters in the boundary current relative to the ocean interior. Given our proximate focus on the BEM lease areas near the shelfbreak we do not find this bias problematic -- though the reader should note the reduced statistical confidence in areas where few data exist such as between the NBC and the eastward North Equatorial Countercurrent.

A multi-year mean gridded velocity field derived from our surface drifter collection is shown in Figure 6b. Here the consistent northwestward, shelfbreak-following flow of the NBC is evident with a strong 90+ cm/s core of roughly 75 km width. As noted above, flow over the continental shelf is much weaker but generally northwestward. This depiction of this narrow feature in our mean gridded representation indicates (as previously reported by others, e.g. Johns et al., 1998) that the NBC is a robust feature of the regional circulation and persists at a consistent cross-shore position through all seasons. However, the eddy variability of the NBC as illustrated in Figure 6c suggests that the core of the boundary current exhibits substantial variability (as reported by Johns et al., 1998) at least as far north as the equator. Given the propensity of the boundary current to follow the steep topography of the continental shelfbreak, we surmise (with support from the moored observations of Johns et al., 1998) that this variability manifests primarily as pulsations in the intensity of the northwestward flow.

Figure 6: Results of quasi-Eulerian averaging (spatial binning) of a collection of satellite-tracked surface drifter trajectory data in the BEM on a 1/3-degree resolution rectangular grid. (a) The number of observations per 1/3-degree grid cell. Note the logarithmic color scale. (b) Long-term mean circulation pattern is indicated by vectors with speed indicated by the background color. Note particularly the narrow and intense NBC which passes through all five BEM basins parallel to the continental shelfbreak. (c) Eddy kinetic energy (EKE). BEM lease blocks and basin boundaries are shown.

As a means to estimate the likely surface current environment in any particular offshore location in the BEM, the relationship between the long-term mean ocean current speed and the water depth is presented below in Figure 7. While there is substantial scatter in these observations, note the near-shore maximum current speed in the Foz do Amazons Basin (region I; near the 500 m isobath). In contrast, the strongest currents in the eastern basins (regions II and III) are located seaward of the 2000 m isobath. Surface current speeds greater than 0.75 m/s (about 1.5 kts) are likely near the continental shelfbreak in all portions of the BEM.

3.2 Inferences from a numerical ocean model

As shown, surface drifters provide excellent spatial coverage of the upper ocean velocity field and enable both geographic and statistical analyses. Unfortunately, the existing surface drifter dataset is not sufficiently dense to fully resolve temporal changes associated with the annual cycle of flow in and near the NBC. To explore these temporal
variations as well as to explore the subsurface circulation within the BEM we now utilize a high-resolution global numerical ocean model that assimilates both in-situ and remotely-sensed observations.

Seven years of output from the 1/12-degree global HYCOM model were extracted in subdomains corresponding to the three analysis regions described above. The annual cycle of modeled surface current speed was computed by averaging all model output on a daily basis (Figure 8). Interestingly, there appears to be little relationship between the annual cycle of local wind forcing (Figure 2) and modeled surface current speed (Figure 8). For example, the largest modeled surface current speeds in the Foz do Amazonas domain (region I; July - December) coincide with the period of weakest wind forcing. In general agreement with our drifter-based results, the HYCOM model indicates that surface currents in excess of 0.75 m/s (about 1.5 kts) are possible throughout the BEM and at any time of year. The 1/12-degree global HYCOM model coarsely reproduces the cross-shore structure of the NBC as observed with surface drifters (Figure 7) but tends to underestimate current speed when compared directly with observations. For example, in the Foz do Amazonas Basin (Region I), the modeled average alongshore flow over the 500 m isobath is approximately 0.6 m/s – substantially slower than the observed average of 1.2 m/s (see Figure 7, left panel). The underestimation of surface current intensity by HYCOM due to insufficient lateral resolution of western boundary current structure has been previously identified by several authors (e.g. Shaji et al., 2005; Van Zwieten et al., 2014).

Figure 7: Drifter-derived mean cross-shore NBC velocity structure (as a function of water depth) in the three BEM analysis regions defined above in Figure 1. The continental shelfbreak is found near the 200 m isobath. To highlight the large range of velocity values comprising these mean cross-shore profiles all available data points are shown in grey. The light black lines indicate three standard errors about the mean.

Figure 8: Annual cycle of near-surface current speed from HYCOM 1/12-degree global ocean model for each of the three analysis domains defined in Figure 1, above. The bold black line indicates the 7-year (2007-2013) mean annual cycle based on daily averages. The light black lines encompass one standard deviation about the mean. The red line depicts the maximum modeled speed for each day over the seven year period.

Although the modeled velocity amplitudes differ from observations, the numerical model captures the full three-dimensional ocean circulation and can provide insight into the subsurface velocity field unattainable with surface
drifters alone. Figure 9 illustrates annual mean profiles of horizontal current speed near the core of the NBC within the three BEM study regions. Note particularly the rapid decrease in speed below approximately 200 m, a depth comparable to the main thermocline in the western tropical Atlantic (see e.g. Fratantoni et al., 1995). In Regions I and III the mean current becomes vanishingly small below 1000 m depth. At the approximate position of the NBC core in Region II the water depth is greater and there is evidence of an increase in speed near 2000 m depth. The southeastward direction of this flow (not shown) suggests it is related to the observed Deep Western Boundary Current mentioned above. While only 0.1 m/s in strength, the 180-degree reversal of current direction with depth could complicate operations requiring coordination between the surface and the sea floor.

Figure 9: Profiles of the annual average modeled vertical structure of horizontal velocity for a selected location near the core of the NBC in each of the three BEM analysis regions. The thin black lines encompass one standard deviation about the mean profile. In all regions the surface current decreases rapidly with depth over the upper 200-300 m. Approximate profile locations are denoted by blue stars in the map at right.

To conclude this section we note that both in-situ observations (here, surface drifters) and numerical models have advantages and limitations. We next briefly describe a strategy for operational ocean prediction which makes use of a combination of tools, observational and numerical, to understand and predict the complex ocean environment.

4. Strategies for Mitigation

Mitigating the impact of strong and variable ocean currents on field operations (including seismic surveys, drilling, ROV operations, and spill response) requires careful pre-activity preparation as well as tools for maintaining constant situational awareness during all phases of exploration and production. An oceanographic site study focused on a specific lease area is the first and most effective method to estimate the potential impact of currents at a particular location. Such a study can be based on historical observations, numerical model output, or new measurements collected specifically to support a particular effort. Moored velocity observations, especially those spanning more than one annual cycle in duration, are likely to be of greatest utility in determining expected and extreme current speeds to be experienced at a specific target location or for detailed engineering design work. If, on the other hand, the goal is to provide a general assessment of the local current environment and/or to illustrate the likely pathways of pollutants following an incident, then surface drifters (such as described above) may be the most cost-effective investigative tool.

Unlike pre-activity surveys, the support of ongoing operations requires a holistic understanding of the constantly changing regional ocean circulation including a short-term predictive capability. The ideal tool for this task is a data-driven ocean forecasting system, overseen by trained and experienced oceanographers, which assimilates in-situ and remote observations into a consistent view of ocean conditions. Continuous direct measurement of ocean currents and stratification (the vertical structure of temperature, salinity, and density) are critical to the effective operation of such a system. Unfortunately, observational assets deployed as part of the Global Ocean Observing System (GOOS; e.g. profiling floats, surface drifters) are relatively sparse in the BEM and have a low residence time along the energetic western boundary. A dedicated observational system designed specifically for the challenges of the equatorial margin is therefore required.
The components of an observing system in the BEM should include a combination of elements to measure the critical meteorological and oceanographic parameters required to support a robust prediction system. These include surface velocity, subsurface velocity, stratification (vertical profiles of temperature and salinity with depth), wind speed and direction, and wave height, period, and direction. As described above, satellite-tracked surface drifters are an efficient means of measuring the near-surface currents over broad geographical areas, especially if they can be efficiently and strategically deployed via aircraft or ships of opportunity. Occasional subsurface velocity and stratification measurements may be obtained using expendable profiling floats such as those associated with the international Argo program (http://www.argo.ucsd.edu). Vessel- or air-deployed expendable bathythermographs (e.g. Flagg et al., 1986) have been proven effective in this region and may be cost-effective for occasional stratification measurements. Detailed temporal measurements of subsurface velocity and stratification may be best acquired using moored sensors located in and near regions of particular operational interest. However the design of moorings for deployment in and near the boundary current is likely to be challenging, particularly when real-time telemetry of measured data is required. Both the subsurface mooring elements and the surface buoys typically used for telemetry and as platforms for wind and wave measurement must be carefully specified for use in high-current environments such as the NBC. Opportunities exist to apply recent technological innovations such as high-endurance autonomous underwater and surface vehicles. However, the ability to effectively operate robotic vehicles in a western boundary current regime such as the NBC has yet to be demonstrated.

Based on experience to-date, the most effective means to synthesize available observations into a consistent picture of present and future ocean conditions involves the combination of expendable, air-deployed in-situ measurement devices combined with satellite remote sensing, a validated assimilating numerical ocean model, and well-trained, experienced oceanographic analysts. We believe that the development of such an observation-driven, model-aided regional forecast system for the BEM provides the most effective method for maintaining situational awareness of ocean conditions and thus for mitigating the potential risks associated with oil and gas operations.

5. Conclusion

In this article we provided a synthesis of current knowledge regarding winds, waves, and ocean currents in Brazil’s equatorial margin based upon historical and recent in-situ observations and a high-resolution numerical ocean model. We used these data sources to describe how the North Brazil Current dominates the surface circulation in the BEM and constitutes a significant hazard to safe and efficient operations in this region, especially in the highly-energetic Foz do Amazonas basin adjacent to the French Guiana border. Finally, we described a notional ocean observing and prediction system for the unique operational challenges of the equatorial margin and the need to improve operational efficiencies, increase safety, and protect the environment in a high-current regime.

6. References


