Pathways of surface oceanic water intrusion into the Brazilian Equatorial Continental Shelf

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Abstract

The scope of this work is to improve the comprehension of the spatial hydrodynamics of the Brazilian Equatorial Margin using a dataset provided by the National Oceanic and Atmospheric Administration (NOAA). This study aims to analyze the surface intrusion of oceanic water into the Brazilian Equatorial Continental Shelf based on trajectories of surface drifters from the National Oceanic and Atmospheric Administration (NOAA). The Pará-Maranhão Basin sector presents the highest intrusion rate, with 35.8%, while the Foz do Amazonas Basin sector shows the lowest rate, with 3.5%. Additionally, the seasonal analysis revealed that most of the intrusions occurred during the summer (60%). This study is part of a project that aims to characterize the spatio-temporal variability of the hydrodynamics of the ACS. A high-resolution hydrodynamical model (ROMS) is being implemented in the region in order to investigate other forcing mechanisms relevant to the hydrodynamics of the continental shelf and cross-shelf exchanges. This project has financial support from National Council for Scientific and Technological Development (CNPq, process 406506/2022-1).

Introduction

Characterization of the Region

The Continental Shelves are shallow (<500m) and dynamic regions that present great ecological and economic relevance. The Brazilian Equatorial Continental Shelf (BES) is inserted in this context as a wide shallow region (<100m) located on the northern coast of Brazil between -55°W and -35°W, and is part of the Brazilian Equatorial Margin (BEM) (Figure 1) (ROSA, 2023). The BEM presents great potential for oil exploration (Almeida et al., 2020; Cruz et al., 2021) and fishing resources (Cruz et al., 2013; Araújo et al., 2022), and besides presenting great ecological and climatic importance on a global scale (Moura et al., 2016; Lavagnino et al., 2020; Louchard et al., 2021).

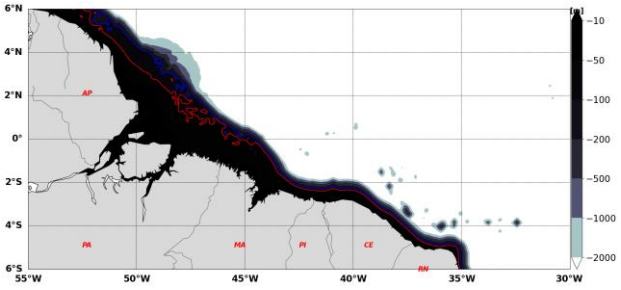

Figure 1 - *Bathymetric map of the Brazilian Equatorial Margin (BEM) covering the states of Amapá, Pará, Maranhão, Piauí, Ceará, and Rio Grande do Norte. The map shows depth contour lines defined for 100 and 50 meters in blue and red colors, respectively.*

The BEM is a region with high-energy hydrodynamics (DA SILVA et al., 2005), having as main hydrodynamic forcings: i) trade winds, ii) tides, iii) North Brazil Current (NBC), and iv) river discharge (Geyer et al., 1996; Nittrouer and DeMaster, 1996; Aguiar et al., 2022).

The trade winds represent an important forcing mechanism for the surface circulation of the BES and the adjacent oceanic region. The seasonal variation of the latitudinal position of the Intertropical Convergence Zone (ITCZ) leads to variability in the intensity and predominant direction of the trade winds on the Brazilian equatorial margin. During the austral winter, the ITCZ shifts to latitudes north of the equator (Adam et al., 2016) and the southeast trade wind belt is dominant, resulting in stronger currents parallel to the isobaths (Castro et al., 2006). On the other hand, during the austral summer, the northeast trade winds are predominant.

The North Brazil Current (NBC) is an important contour feature of the hydrodynamics of the BES and has an average position between the outer portion of the shelf (100 m isobath) and the continental slope (1000 m isobath), flowing towards the northwest (Johns et al., 1998).

Studies in the BES reveal that the flow of the NBC modulates the intensity and direction of the currents parallel to the isobaths in the outer portion of the shelf (Prestes et al., 2018) and advects low salinity waters from the Amazon River to the Caribbean region and/or the retroflection region (Aguiar et al., 2022).

Bounded by a stretch of over 2,200 km around the coast (PETROBRAS, 2023), and a region associated with predominantly strike-slip tectonics present in transform margins, the BEM has as one of its characteristics the presence of east-west and northwest-southeast margin segments, forming "stair-step" structures (GORINI, 1993).

BEM comprises the following basins: Potiguar, Ceará, Barreirinhas, Pará-Maranhão, and Foz do Amazonas (CARMO & FREIRE, 2017).

Resource Exploration

The BEM has a great prominence in terms of exploration of petroleum, natural gas, and biofuels (CAVALCANTI, 2018). According to Filho (2021), there is an expectation regarding the petroleum potential of the region, which can be justified based on the petroleum conditions found in the Jubilee field, in the deep waters of Ghana, on the West Coast of Africa, which have analogous margins to the Maranhão Basin. Furthermore, Filho (2021) also describes that the discovery of Zaedyus in the deep waters off French Guiana, near the Amapá border, and the commercial oil accumulations found in 2015 by ExxonMobil, Repsol, and Tullow in Guyana, and by Apache and Petronas in Suriname in 2019, further intensify the idea of an extension of these hydrocarbon accumulations along the Brazilian coast. The exploration of oil, despite its importance in the energy sector, can be classified as one of the most polluting activities (EUZÉBIO, et al., 2019), due to contamination by crude oil and its derivatives, which contain toxic compounds in high concentrations, representing a major global problem (HEIDERSCHEIDT et al., 2016). One of the largest oil spill incidents occurred on the Brazilian coast in the years 2019 and 2020, affecting about 11 states and approximately 2,890 km of its tropical coast, as pointed out by Soares et al. (2022). These events highlight the need for more caution in the exploration process, since the potential risk of spills can seriously harm biodiversity, local economies, and the quality of life of affected populations (COELHO LESSA et al., 2022).

Despite the important scientific contributions made in understanding the hydrodynamics of the BEM, there is still a lack of studies addressing the intrusion of oceanic water into the continental shelf in terms of: i) identification of preferential pathways, and ii) temporal variability of the intrusions.

Knowledge about the spatiotemporal variability of the hydrodynamics of the Brazilian Equatorial Shelf (BES) is crucial for the development of management and environmental protection measures in the region. This study aims to analyze the surface intrusion of oceanic water into the Brazilian Equatorial Continental Shelf. This involves: i) identifying preferential pathways for surface oceanic water intrusion in 5 sectors of the Brazilian Equatorial Shelf, and ii) investigating the seasonal variability (summer/fall and winter/spring) of the intrusions in the area. This study is based on trajectories of surface drifters from the National Oceanic and Atmospheric Administration (NOAA).

Method

Data Description

This study used hourly trajectory and velocity data collected by surface drifting buoys from the Global Drifter Program (GDP, https://www.aoml.noaa.gov/phod/gdp/hourly_data.php) drifters worldwide, which consists of a valuable dataset for studying oceanic processes (Elipot et al., 2016; Elipot et al., 2022). There are a total of 17,324 drifters between the years 1987 and 2020. The drifters with trajectories within the area located between 55°W - 30°W and 6°S - 6°N were selected, covering the entire BES and adjacent oceanic region (Figure 1). Figure 2 shows the percentage distribution of the locations of GDP drifters, indicating that only 3.5% of the total drifters studied had their trajectories identified in the BEM.

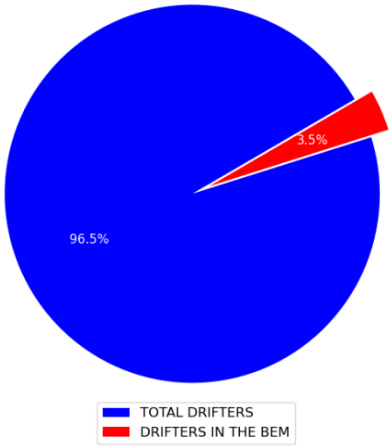

Figure 2 - *Percentage distribution of the location of trajectories of drifters from the Global Drifter Program (GDP).*

Figure 3 provides important information about the trajectories of the drifters in the BEM, allowing a more detailed analysis of the advection by the acting currents. It is possible to observe that the thin line of red color represents the trajectories of the drifters over the period from 2000 to 2020. These trajectories clearly show how drifters are transported by water along the continental shelf, highlighting the importance of ocean circulation and tidal currents in coastal dynamics. In addition, the analysis of the trajectories of the drifters can help to identify areas of greater influence of the currents, allowing a better understanding of the oceanic processes in the region and assisting in the investigations on the intrusion of ocean water in the BES.

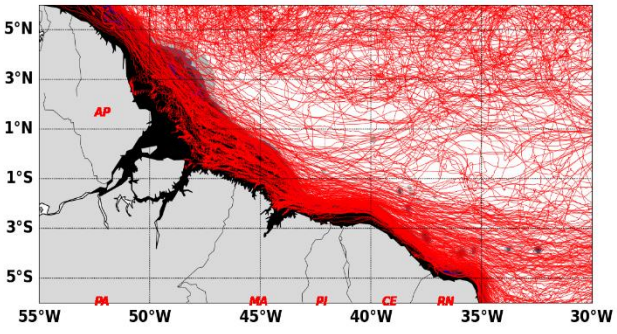

Figure 3 - *Trajectories traversed by the drifters identified in the BEM.*

Analysis

The depth of the BES break is defined in the scientific literature as being on average at the 100m isobath (Nittrouer and DeMaster, 1986), but it can be as deep as 300m in the AP Shelf sector (Lavagnino et al., 2020). Taking these values into account, the bathymetric gradient of the PEB and adjacent oceanic region was calculated using ETOPO1 bathymetry (Figure 4) to illustrate that the 100m contour (blue line) is a good approximation for the transition between the shelf (lower gradient) and the continental slope (higher gradient). Considering that a portion of the CNB flows near the outer portion of the continental shelf (Schott et al., 2005), this study adopted as a criterion for intrusion into the Brazilian Equatorial Continental Shelf the detection of drifters at or below 50 m isobath (red line) and remaining at or below this isobath for at least 1 day.

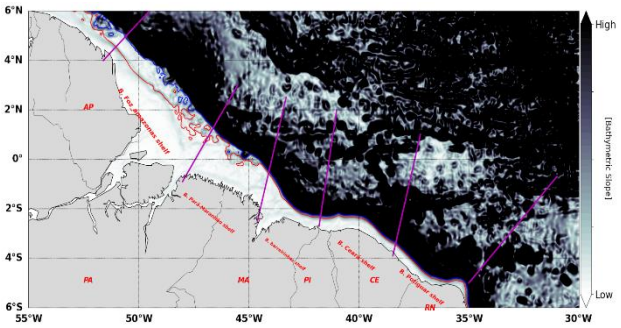

Figure 4 - *Map of the bathymetric gradient of the BEM. The bathymetric contours of 100 and 50 m are illustrated in blue and red lines, respectively. The boundaries of the oil exploration basins are indicated by the magenta lines.*

The 478 drifters with trajectories in the MEB were selected, of which 229 drifters exhibited intrusion into the continental shelf, representing 33.7% of the total (Figure 5).

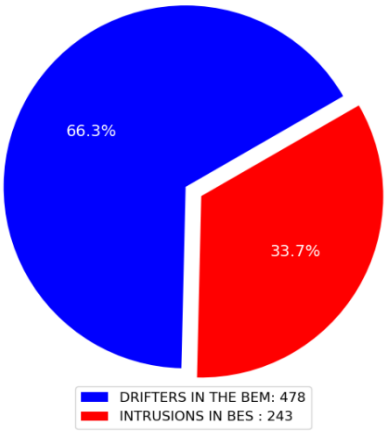

Figure 5 - *Percentage of intrusion of drifters into the Brazilian Equatorial Shelf (BES).*

Five specific sectors were defined for quantifying the number of intrusions. These regions were delimited based on the offshore basins boundaries: Potiguar, Ceará, Barreirinhas, Pará-Maranhão, and Foz do Amazonas (Fig. 4). From this subdivision, an analysis was carried out to identify preferential regions for oceanic water intrusion into the BES.

Results

The characterization of the temporal distribution of the measurements carried out by the GDP drifters (Figure 6) reveals that the trajectories collected in the BEM occurred between the years 2000 and 2020. The year 2010 had the highest number of drifters registered in the region, totaling 97 units. On the other hand, the years 2000, 2001, and 2002 had the lowest number of drifters, with only one drifter identified in each year.

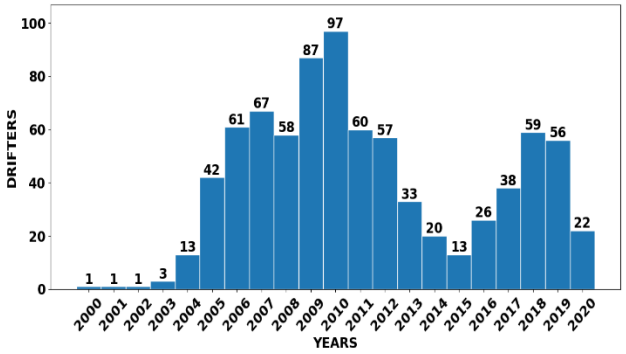

Figure 6 - *Histogram of the number of drifters identified in the MEB during the years 2000 to 2020.*

The histogram presented in Figure 7 illustrates the distribution of drifters over the months, from 2000 to 2020. The month with the highest number of records was November, with the identification of 333 drifters, followed by October, with only one drifter less. In contrast, the lowest number of records was observed in February, totaling 268 drifters.

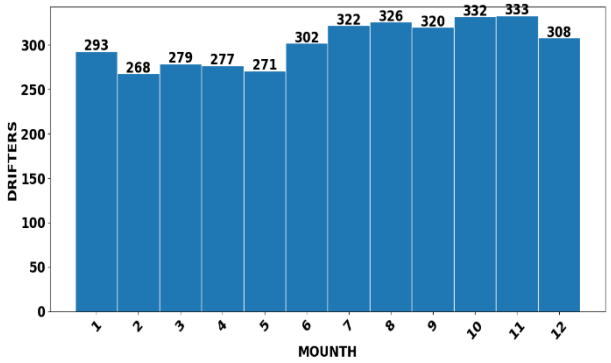

Figure 7 - *Histogram of the number of drifters identified in the BEM during the months of January to December, between the years 2000 and 2020.*

The heterogeneous monthly distribution of drifter measurements was taken into consideration in the analysis of seasonality of intrusion rates on the continental shelf. Figure 8 displays the location and seasonal period of intrusion occurrences in the BES. The orange dots represent the intrusions that occurred during the summer season (June to November), while the green dots are related to the intrusions in the winter season (December to May). The analysis of seasonality indicates that the

majority of intrusions (60.02%) occurred during the summer, which is probably associated with the action of the north/northeast trade winds.

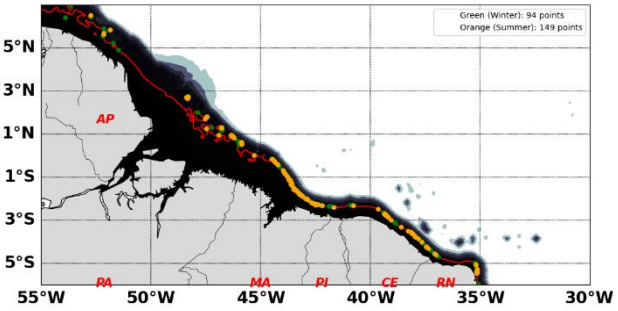

Figure 8 - *Location of the occurrence of intrusions into the BES. The orange and green dots represent intrusions that occurred during the summer and winter, respectively.*

Figure 9 illustrates the number of intrusions along the 5 sectors of the BES. The sector with the highest intrusion is the Barreirinhas Basin, accounting for 35.8%, followed by Potiguar (34.5%), Pará-Maranhão (15.7%), and Ceará (10.5%). The Foz do Amazonas Basin sector had the lowest percentage of intrusion (3.5%).

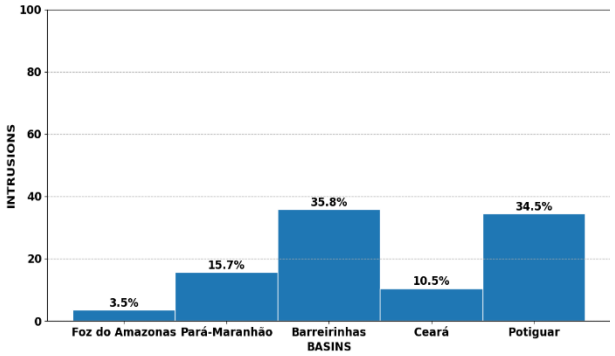

Figure 9 - *Histogram of the number of drifter intrusions in the BES sectors (*Potiguar, Ceará, Barreirinhas, Pará-Maranhão, and Foz do Amazonas).

The spatial variability of intrusions may be associated with variations in the morphology of the BES. Furthermore, the NBC may play a modulating role in intrusion rates. For instance, the lower occurrence of intrusions in the Foz do Amazonas Basin may be associated with the proximity of the NBC retroflection region. The Barreirinhas basin presents a higher occurrence of intrusions, because the NBC, which flows between the 100 and 1000 meter isobaths, is closer to the 50-meter isobath due to the variation of the BES morphology.

Conclusions

The present study presents relevant results on the interaction processes between the ocean and the Brazilian equatorial continental shelf. This information has direct application in the field of Petroleum Exploration Engineering. An important finding made in this study was the spatial variability of ocean water intrusion rates between different sectors of the BES. The Pará-Maranhão Basin sector had the highest intrusion rate, with 35.8%, while the Foz do Amazonas Basin sector had the lowest rate, with 3.5%. Additionally, the seasonal analysis revealed that most of the intrusions occurred during the summer, representing 60.02% of the total. To further improve our understanding of these results, future analyses will incorporate Lagrangian numerical modeling.

Acknowledgments

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