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Sudden arrival of marine litter on the northeastern coast of Brazil: physical forcings and associated transport

Cintra Marcio M. [1], Silva-Cavalcanti Jacqueline S. [2], Araújo Maria Christina [2], Mazzini Piero L.F. [3], Rollnic Marcelo [4], Mendes David [1]

[1] Departamento de Ciências Atmosféricas e Climáticas, DCAC, Universidade Federal do Rio Grande do Norte (UFRN), Av. Senador Salgado Filho s/n, 59078-970, Natal RN, Brazil
[2] Federal Rural University of Pernambuco, R. Dom Manuel de Medeiros, s/n, Recife 52171-900, Brazil
[3] Virginia Institute of Marine Science, William and Mary, Gloucester Point, VA, USA
[4] Laboratório de Pesquisa em Monitoramento Ambiental Marinho (LAPMAR), Universidade Federal do Pará, Belém, PA, Brazil

Abstract :

This study made use of four asynchronously coupled numerical simulations (four Eulerian and four Lagrangian) to investigate an event of a sudden arrival of more than 50 tons of marine litter on the northeastern Brazilian coast. This material mysteriously landed on several beaches, compromising water quality and impacting tourism, therefore raising serious concerns about its origin from local authorities. A total of 87,030 virtual particles were released and had their trajectories investigated, as well as their relationship with major physical forcings, including tides, winds and the North Brazil Under Current (NBUC). The virtual particles followed predominantly towards the north/northwest, mainly due to the presence of the NBUC and southeast trade winds. This pattern indicated that the flow of marine surface litter followed the continental shelf northwards, and the role of winds was key in providing the conditions for oceanic originated material to being deposit along the coastline. This study provided important insights about the regional circulation and main forcings that act in the transport and deposition of floating materials that reach the shallow shelf of the Brazilian northeast. Further investigation on the variability of these forcings along the seasonal cycle seems to be extremely important and should be undertaken soon.

Highlights

► An unknown arrival of ~50 tons of marine litter over NE Brazil was investigated ► Wind stress plays an important role in the stranding of materials on local beaches ► The investigation of the material sources revealed a possible ocean origin

Keywords : Marine pollution, Plastic accident, Lagrangian transport, virtual particles

1. Introduction

Marine litter is a complex issue with significant implications for oceanic and coastal environments worldwide. Marine litter is defined as any persistent, manufactured, or processed solid material discarded, disposed of, or abandoned in the marine and coastal environment (UNEP, 2009). According to Frantzi et al. (2021), by 2050 it's expected that there will be 33 billion tons of plastic in the ocean.

Although oceanic activities can produce their own waste, most of the floating marine litter that arrive in coastal environments come from continental regions, with sources usually located in the vicinities of large urban centers (Rellán et al., 2023; Li et al., 2016). Rivers and estuaries are often identified as the main sources of litter on coastal beaches, and the primary routes for the input of litter in the oceans (Duarte et al., 2023; Galgani et al., 2016; Rech et al., 2014).

Once they arrive in the oceans, floating debris rapidly spread due to winds or the influence of ocean currents (UNEP, 2009). Data from the Global Programme of Action for the Protection of the Marine Environment from Land-Based Activities (GPA), and the UNEP Global Initiative on Marine Litter, estimate that approximately 80% of all marine plastic litter comes from land-based sources. Depending on their composition, density and shape, plastics can float or sink (Rellán et al., 2023). At sea, only 15% of marine debris remains in the water column; another 15% float on the surface and 70% are deposited to the bottom (García-Rivera et al., 2017).

The entry of debris into oceans due to accidents, regardless of which type, is associated with great potential danger to coastal environments, because this input leaves little response time for environmental agents because of the surprise factor. An interesting fact occurred involving the vessel Ever Laurel, a container ship that was carrying children's bath toys from Hong Kong to Washington, when floating plastic toys suddenly fell overboard in the central Pacific (Ebbesmeyer and Ingraham, 1994; Saliba et al., 2022). After this incident, plastic turtles, ducks, frogs, and beavers, which became known as the "Friend Floaters", traveled across the Bering Strait and into the Arctic until the first toys were seen off the coast of Alaska about 10 months later, remaining for decades in the marine environment (Hohn, 2012).

In 2019, a storm dropped 342 containers weighing approximately 3,257 tons overboard. Several consumer goods and packaging materials were spilled into the waters and washed ashore on the Dutch coast and Dutch and German Wadden Islands

(Dutch Safety Board, 2020). It is believed that, to this day, a quarter of this debris still remains in the North Sea (Stichting Noordzee, 2021).

Off the northeastern Brazilian coast, between April 20th and 30th, 2021, approximately 50 tons of floating marine litter (Figure 1) suddenly appeared on several beaches along the states of Paraíba and Rio Grande do Norte (IDEMA-RN, 2021). This type of event does not occur seasonally in the region and its sudden occurrence has made it a unique fact that demands careful attention. According to the surveys conducted by municipal agencies, the floating marine litter supposedly came from urban sources, containing items such as plastic packaging, leftover clothes and shoes, documents, bottles, masks, diapers, toys, and even hospital supplies[1]. According to the environmental agency of the state of Rio Grande do Norte (IDEMA-RN, 2021), seven cities were affected, involving 23 beaches, from Baía Formosa where the largest quantity first arrived (20th April), to Natal where the scattered remains arrived a few days later (24th April). The most relevant quantities were 38 tons in Baía Formosa, 6 tons in Canguaretama, 3 tons in Nísia Floresta and 1.5 tons in Tibau do Sul (Figure 1). In the state of Paraíba, arrivals were also reported in Conde, Cabedelo and João Pessoa. The investigations, carried out by the Brazil federal police, ruled out that the waste was of international origin, given the massive presence of materials from Pernambuco (IDEMA-RN, 2021). The following hypotheses are being investigated: whether a company that works with waste dumped the material into the sea, accidentally or not; waste was dumped by a vessel, accidentally or not; the material was carried offshore through high flow from some estuary due to a rain event. Despite the clues suggesting that the litter was presumably originated from the state of Pernambuco, no public authority has confirmed the origin of the material nor the occurrence of any accident in the region, and so far, there has been no information proving that the source of marine litter was indeed Pernambuco.

[1] https://g1.globo[1].com/ciencia-e-saude/noticia/2021/04/23/lixo-praias-nordeste-o-que-se-sabe.ghtml. (Accessed on November 14, 2023).

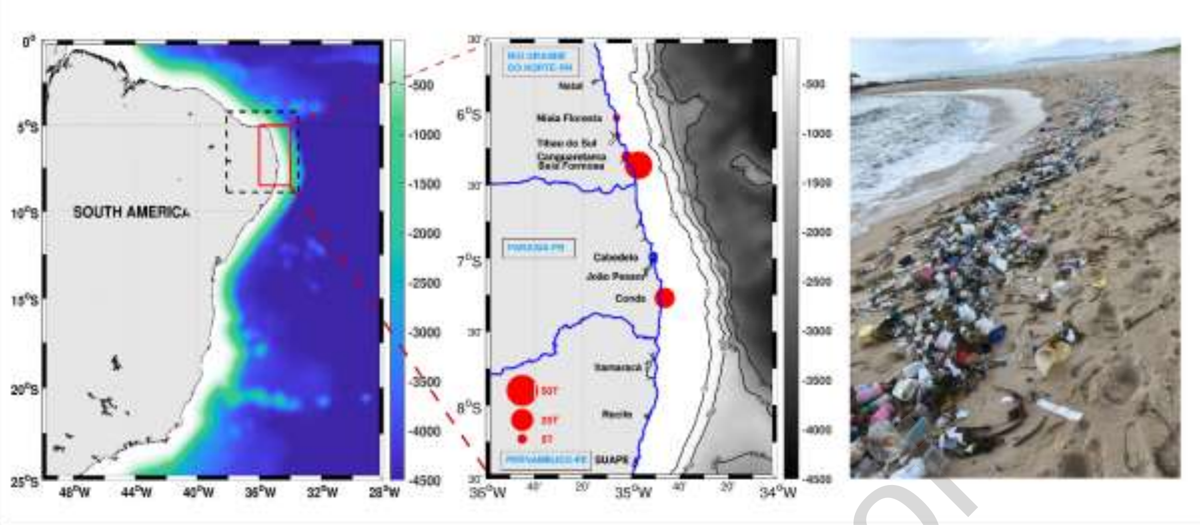

Figure 1: Left panel: Delimitation of the 3D hydrodynamic model and Lagrangian model domains (black dashed line) and area analyzed in the northeastern region of Brazil (continuous red line); Middle panel: Analysis area with the amounts of floating marine litter accumulated on the beaches in tons (red bubbles); Right panel: Picture of the marine litter that has appeared on the Rio Grande do Norte shoreline (Photograph taken by Tatiana M. L. de Azevedo, source: personal communication).

One of the biggest challenges in addressing the problem of marine plastics and other types of wastes is the many routes they can take to enter the marine system (Pruter, 1987; Ryan et al., 2009). This renders the knowledge and realistic reproduction of regional hydrodynamics, essential for understanding the pathways of materials, aiming to help in the mitigation of potential occurrences such as the disposal of large amounts of waste at sea.

The goal of this paper is twofold: 1) to identify the most probable regions where the litter that got stranded at Baía Formosa was originated, and 2) to disentangle the relative roles of different physical forcings (winds, tides) in transporting the litter to its final destiny: Baia Formosa.

Given the uncertainties regarding the origin of more than 50 tons of litter that were removed from the beaches of Rio Grande do Norte and Paraíba, our study will consider all the numerical domain south of where the litter was found as a possible source of these materials. This choice was made based on the main surface forcings (oceanic current, winds, and wind drift current) having a northward resultant acting on the regional hydrodynamics.

2. Methods

2.1. Models and coupling scheme

2.1.1. Regional 3D numerical simulation

To simulate the hydrodynamic conditions of the east coast of northeast Brazil, the Coastal and Regional Ocean Community model (CROCO) was used, which is an oceanic modeling system built upon the Regional Ocean Modeling System (ROMS) (Shchepetkin and McWilliams, 2009, 2005). This model solves Reynolds-averaged Navier–Stokes equations on a free surface and terrain-following grid and is designed to study realistic, fine-scale processes from the regional ocean to the littoral zone, as is the case studied here, where we have a western boundary current and a shallow-narrow continental shelf interacting dynamically.

For this study, four 3D experiments using CROCO were conducted (Figure 2), the control simulation (using all forcings), covering 28 months (January 2019– April 2021, with two years of spin up prior to that) of hydrodynamic conditions over the regional domain, which consists of an area between 8.9°S-4.2°S and 33.5°W-38.1°W (Figure 1). The implemented grid has 239 x 233 horizontal points (~2 x 2km) and includes 30 vertical sigma-layers. Model bathymetry was built using an interpolation between the ETOPO2[2] dataset and nautical charts from the Brazilian Navy[3] to improve the bathymetry over shallow regions. Lateral boundary conditions were constructed using the Mercator Ocean International physics and forecast product, which provides physical variables with 1/12° of horizontal resolution and 50 vertical levels at 6 hour intervals. Data from the European Center for Medium-Range Weather Forecast (ECMWF-ERA5[4]) with an hourly frequency were used to force CROCO at the surface. Tidal forcing was obtained using the TPXO 9 global database (Egbert and Erofeeva, 2002), which provides the amplitudes and phases of sea surface elevation and

[2] http://www.ngdc.noaa.gov/mgg/global/etopo2.html (Accessed on February, 2023)
[3] https://www.marinha.mil.br/chm/dados-do-segnav-cartas-nauticas/cartas-nauticas. (Accessed on November 14, 2023)
[4] ERA5, Copernicus Marine Service Information (CMEMS). Marine Data Store (MDS). DOI: 10.48670/moi-00016 (Accessed on February, 2023)

barotropic currents of the main tidal components (M_2, S_2, N_2, K_2, K_1, O_1, Q_1, P_1, Mf, Mm). The configuration used here was based on successful modeling implementations performed to simulate the North Brazil Under Current (NBUC) interactions with the continental shelf of the Southwest equatorial Atlantic margin (Damasceno et al., 2022), now using interannual forcings. All four simulations used the same grid and configurations, the only differences were in respect to the tides and wind forcings. A Control Experiment (CTL) was constructed with all forcings (tides and winds), then Experiment 1 (EXP1) had the tides turned off, Experiment 2 (EXP2), had the surface wind stress set to zero at all grid points, and Experiment 3 (EXP3), had both wind stress and tidal forcing turned off. Simulations EXP1, EXP2 and EXP3, where restarted from the control simulation (CTL) in January 2021 to integrate the new forcing configurations over the domain until April 2021. All comparisons and calculations were focused in April 2021 for all experiments (Figure 2, Experiments scheme). The integration time step for all hydrodynamic simulations was 120s and output records had hourly frequency.

The evaluation of the model performance was carried out by comparing model output with a measured velocity transect that cuts perpendicularly through the continental shelf, along with 16 vertical profiles of temperature and salinity. Observation of currents were obtained with a shipboard acoustic Doppler current profiler (ADCP) and temperature and salinity were obtained from a conductivity-temperature-depth (CTD) instrument (Appendix 1). These measurements were carried out during an oceanographic cruise in April 2017 and compared with numerical results of April 2021; a complete presentation of this data can be found at Bertrand (2017). Although some interannual effect can be considered, overall, the profiles fit well. The NBUC core is well defined at ~200m of depth with speeds of 1.2 m s^{-1} in both data. Spatial structure of modeled velocity in the cross-section presented a slight eastward displacement (~10km) in contrast to observations, resulting from the smoothing and disparity of the bathymetry. A region over the continental slope with meridional velocity of 0.5 m s^{-1} was noted, which influence on the surface up to ~500m of depth. In the numerical results, this same region extended up to ~600m. From the first 15km along the profile, speeds of 0.25 m s^{-1} can be noted at surface in both data. The vertical temperature profiles ranged from 28°C to 29°C inside the isothermal layer. The mixed layer depth occurred at approximately 80m for both data with the beginning of the thermocline well reproduced by the numerical model. The shallowest vertical profiles of temperature presented the lowest values (e.g. 0.25 - 0.68°C) of the Root Mean Square Error (RMSE) while those located at greater depths presented higher RMSE (e.g. 0.86 – 2.3°C). This was due to the errors within the isothermal layer remaining between -1°C and 1°C, while the largest discrepancies occur between 200-400m depth, where 2-3°C of difference was noted. The vertical salinity profiles presented RMSE between 0.09 and 0.72. At the surface, numerical results range from 36.4 to 37.4, while the CTD data range from 36.1 to 37.3. The maximum salinity at the subsurface was verified in both data and the same mismatch verified for temperatures after the 200m depth was noted for salinity profiles (+0.5 for numerical salinity). In general, the vertical thermohaline structure was well represented in the numerical simulation.

The surface winds used to force the numerical simulation (ERA5) were compared with winds from the Advanced Scatterometer (ASCAT -L3), both with 1/4° spatial resolution (Appendix 2). The ERA5 data were first daily averaged and then the mean and standard deviation for the month of April 2021 were compared with the ASCAT data (Bentamy and Croize-Fillon, 2012). Both ERA5 and ASCAT showed southeast winds covering the entire study area during April 2021. Wind speeds had similar spatial structure, with the highest intensities (~7 m s^{-1}) observed north of Natal near the coast and the lowest intensities (between 4 and 5 m s^{-1}) southward of João Pessoa. Standard deviations demonstrated that both data sets presented greater variability in the northwestern portion of the domain, northward of Natal, while the other regions were more stable (STD < 1 m s^{-1}).

2..1.2. Lagrangian simulation (virtual litter particles)

The Lagrangian simulations were performed using the free modeling tool Ichthyop[5] v.3.3 (Lett et al. 2008), coupled offline with the regional ocean model described above (CROCO model). The simulation results of April 2021 were used to perform the off-line coupling with Ichthyop. Each litter particle was simulated as a virtual inert particle floating at sea surface being advected by surface currents (computed by the CROCO

[5] https://doi.org/10.5281/zenodo.4243813

model). A full description of the Ichthyop tool and its capabilities can be found in Lett et al. (2008). All particles were deployed at the surface, with a density of 0.92 $g.cm^{-3}$, i.e., floating particles. This density lies in the medium range of the ‘low-density polyethylene’, according to Morét-Ferguson et al. (2010). This group of materials best represents the litter that landed on the beaches of the Brazilian coast in the studied event. The direct effect of the wind drag on individual particles was 0.03, following Yoon et al. (2010). A horizontal dispersion rate of $1.e^{-9}$ was applied following Peliz et al. (2007). The integration time step for all Lagrangian simulations was 60s and outputs were recorded every hour.

2.2. Study area and litter drift release scheme

Our study was carried out along the eastern shelf of northeastern Brazil and comprises three states, Rio Grande do Norte, Paraíba and Pernambuco. This region consists of a shallow continental shelf (Figure 2, release map) where variations in bathymetry (canyons, plateaus, changes in coastline) significantly alter the coastal circulation through the interaction with the main forcings: winds, tides, waves, and western boundary current (Aguiar et al., 2022; Damasceno et al., 2022). Considering the event mentioned above, numerical simulations (3D Eulerian and Lagrangian) were developed over the same domain (Figure 1 - black dashed line) while the analysis of the results was developed in a more restricted area of interest (Figure 1 solid red line).

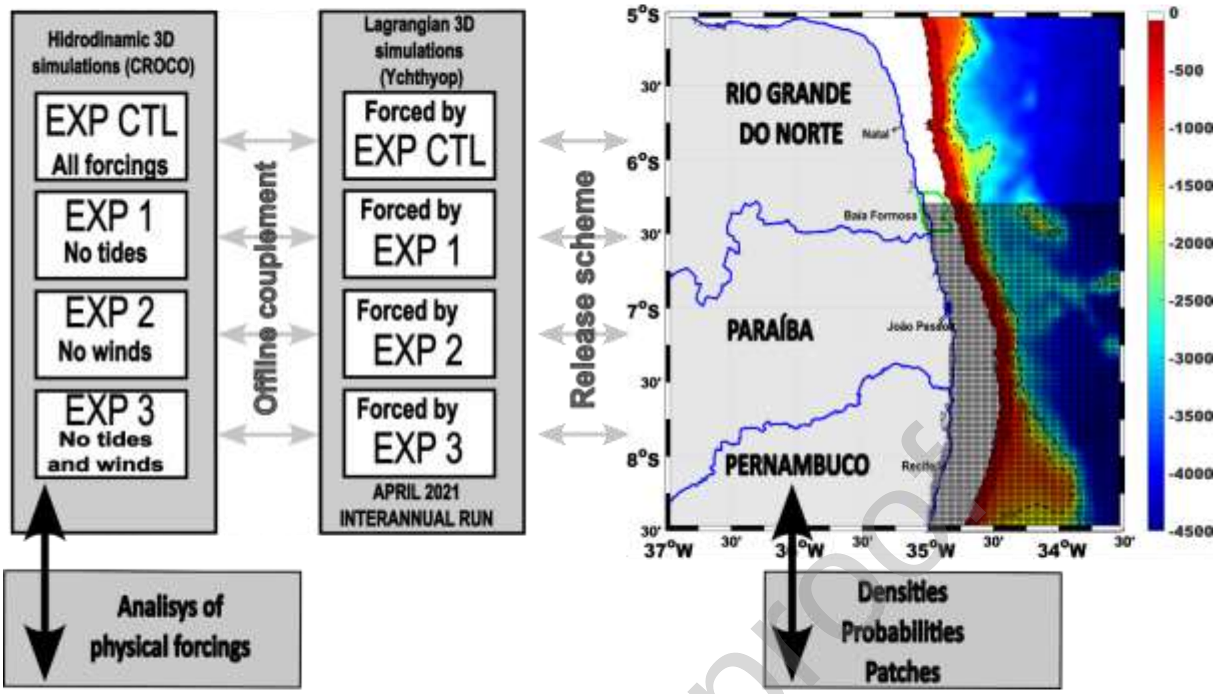

Figure 2. Schematic representation of experiments configuration and coupling. On the release scheme (local map), the starting points (black circles) and the evaluated area regarding litter end-point along the coastline of Baía Formosa (green polygon) are presented. The colored shading represents local bathymetry (m), and the continental shelf (delimited by the 70m depth) is in white.

The virtual particles were released at all grid points south of 6.3°S (8,703 points) where most significant amounts of marine litter (38 tons) were stranded, near Baía Formosa. Considering that the largest volume that arrived on the coast was in this region, and that part of the litter that spreaded in the vicinity likely passed through this area, we chose to focus our efforts on evaluating the arrival of particles in this region (Figure 2, green Polygon). Four Lagrangian simulations were conducted based on each Eulerian 3D experiments (CTL, EXP1, EXP2 and EXP3). All Lagrangian simulations started on 9 of April 2021 and the release of virtual particles occurred 24h after the simulation started. Ten consecutive releases allowed 87,030 virtual particles traveling through the domain during April 2021. Since our intention was to evaluate the arrival of particles on beaches, the behavior of particles when reaching the shoreline was defined in model setup as “beaching”. With this configuration, if any particle reached a non-water cell from time t to time t+1, it was flagged as “beached” and it remained in that dry position for the remainder of the simulation. It is important to note that beaching estimates are likely biased high, since not all particles that arrive at the most inshore grid necessarily beach. Future work should focus on developing coupled shelf and high-resolution surf-zone models to explicitly resolve beaching processes and improve our general understanding of marine litter dynamics and fate.

3. Results and Discussion

3.1. Dynamical characterization

In order to characterize physical forcings in the study region, Figure 3 shows the monthly mean value (April 2021) of the tidal amplitudes and velocities (M_2, S_2), surface wind stress, and surface current velocity. The semidiurnal lunar component of tides (M_2) is the main tidal component in the region, with the highest amplitudes and velocities (Figure 3a). There is a noticeable spatial difference in tidal ranges, for both M_2 and the semidiurnal solar component (S_2), which have their highest values north of 5°30’S, 0.8 m and 0.3 m, respectively (Figure 3a, b). Tides in the region reach their highest amplitude and velocity where the continental shelf reaches its maximum width (Aguiar et al., 2022). In the region between Recife-PE and Itamaracá-PE, tidal current velocities (~0.3 m s^{-1}) comparable to those of Touros high were observed; this differs from the surrounding velocities, which are quite lower. There is a great discrepancy in surface velocities (Figure 3c) between values on the continental shelf and the oceanic values of the Western Boundary current, which flows skirting the continental slope. The dominance of the north flow of the North Brazil Undercurrent (NBUC), which flows from the south domain along the continental slope, is evident, reaching surface velocities of approximately 0.45 m s^{-1}. These results are in accordance with the pattern expected for the region, previously described by Damasceno et al. (2022) and Aguiar et al. (2022).

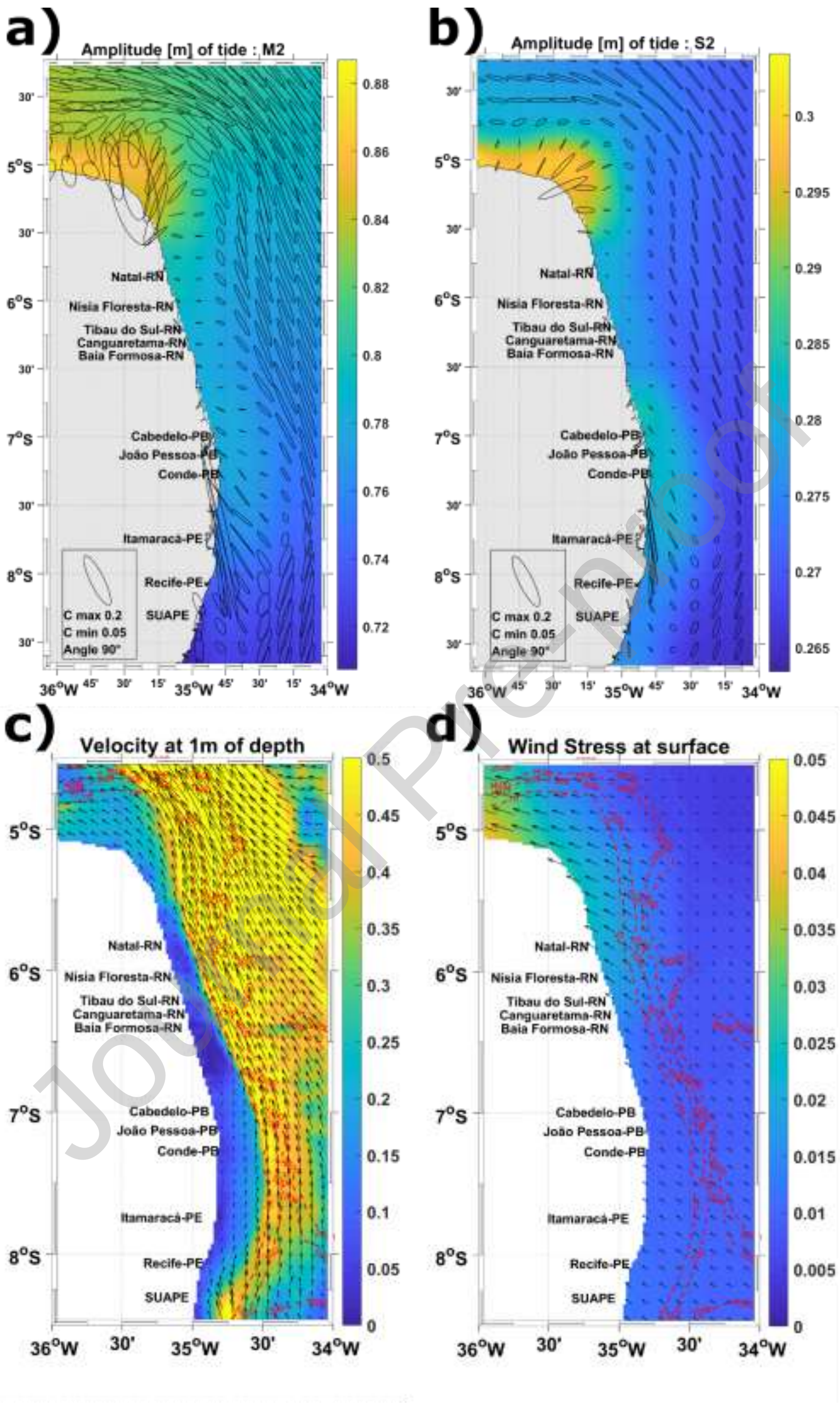

Figure 3. Tidal range (m) superimposed on tidal ellipses for components; (a) M_2 and (b) S_2; (c) Monthly mean velocity (m s^{-1}) at 1m depth superimposed on directional vectors; (d) Monthly mean wind stress at surface (N m^{-2}).

Northward of ~6°S, NBUC receives contributions from the central branch of the South Equatorial Current (SECc), which makes the velocities increase to values exceeding 0.5 m s^{-1}. While the western boundary current flow exerts dominance under oceanic conditions, the continental shelf has a weaker flow, with velocities that range from 0.1 m s^{-1} to 0.3 m s^{-1} (e.g. Schettini et al., 2017) (Figure 3c). Moreover, even though the oceanic current exerts influence on the flows over the shelf, this circulation also depends greatly on the friction of winds and tidal currents. Wind stress at the surface is shown in Figure 3d, approximately 0.015 N m^{-2} northwestwards, except in the northern portion of the domain, where it increases to 0.04 N m^{-2}. This region undergoes a strong influence of trade winds from the southeast, and the northern part of the domain is where there is an acceleration of winds (Aguiar et al. 2022).

3.2. Marine litter release, spatial density and paths

Shelf circulation results from the interaction of the various physical forcings discussed above, and since they potentially carry significant amounts of marine litter that reached the coast of the states of Paraíba and Rio Grande do Norte, they shall be the focus of the present study. For that purpose, virtual particles were used to simulate the movement of surface marine litter, and therefore, allow the assessment of the transport of these particles along the coastal regions, most specifically at Baía Formosa (Rio Grande do Norte) were the largest quantities arrived.

After virtual particles were released (April 10th, 2021), they followed predominantly northward trajectories, considering that the combinations of the forcings in this region (wind and oceanic current) result in northward net surface shelf circulation. Throughout their paths, the density of particles (particles m^{-2}) was evaluated in six different areas (Figure 4). These areas consist of two regions for each state where there were particle releases (Pernambuco, Paraíba, and Rio Grande do Norte, see Figure 2) and they were divided in inner shelf (coastline to 30 m isobath) and outer shelf (30 m isobath to the shelf break, at the 70 m isobath). The initial particle density after all releasing events was 2.19 particles m^{-2} for the entire domain of releases (Figure 2). Particle density was the highest in the state of Rio Grande do Norte, reaching 0.5 particles m^{-2} three days after the release in the outer shelf (dashed blue line) and 0.65 particles.m^{-2} five days after release over the inner shelf (continuous blue line). In this state (Figure

4, blue areas), particles reached a maximum in density first on the outer shelf and subsequently on the inner shelf, indicating a significant contribution from oceanic environments, including materials released in the southernmost portions of the domain. While on the outer shelf the densities tended to zero after the passage of materials, on the inner shelf the value of 0.24 particles m^{-2} stabilized after approximately nine days, indicating the contribution of the particles that reached the coast (beaching).

Heading south, the states of Paraíba and Pernambuco (Figure 4, yellow and green areas, respectively), presented a decreased in particles density as well as the occurrence of the maximum values at the outer and inner shelves occurred in a short period of time (approximately 1 day). The verified pattern over these two regions, indicate a most dynamically interaction of the forcings with the particles, where the particles have followed northward more intensively. The Paraíba outer shelf reached 0.47 particles m^{-2} along the end of the third day after release and the inner portion reached 0.3 particles m^{-2} in the middle of the following day.

Over the southernmost region evaluated, the Pernambuco state, the maximum of particle densities verified on the inner shelf occurred during the release day (0.21 particles m^{-2}) while the outer shelf reached 0.23 particles m^{-2} towards the end of following day.

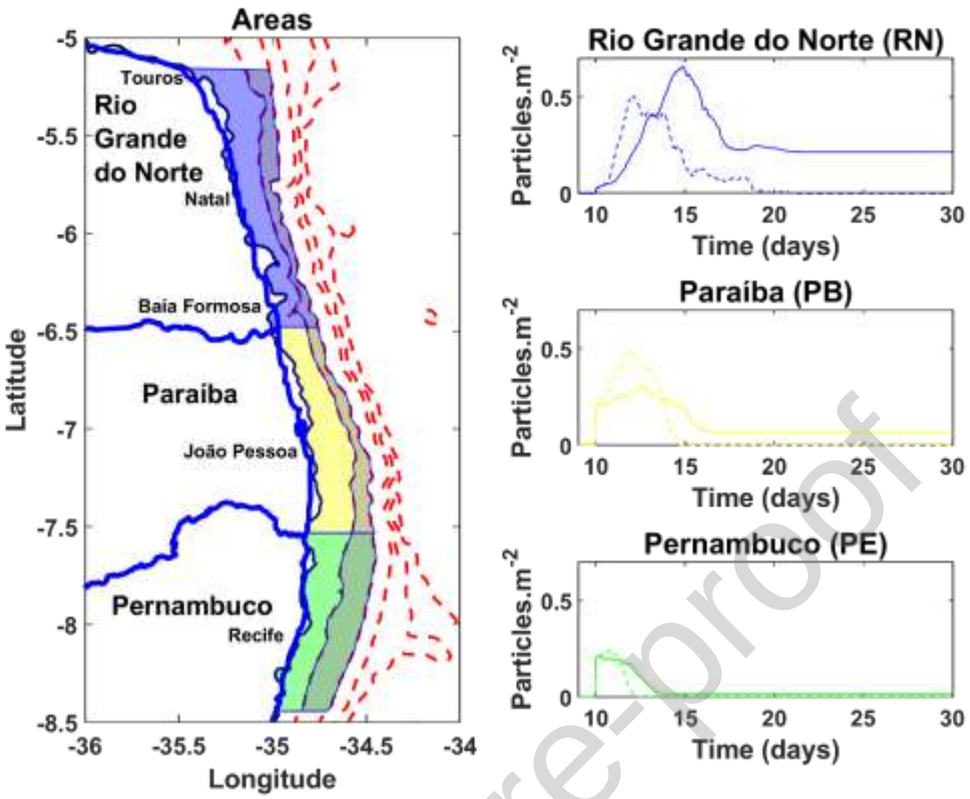

Figure 4. Particle density over time in three states of northeastern Brazil along the continental shelf (inner shelf [solid line] and outer shelf [dashed line])

Overall, after release of virtual particles, there was a predominant transport directed northwards throughout the study area. The highest densities were observed in the state of Rio Grande do Norte, which, in a way, reinforces the need for investigations into the physical forcings that lead the state to have this attractive potential for oceanic surface particles. The states of Pernambuco e Paraíba showed a high capability to disperse while Rio Grande do Norte, a higher capacity to retain surface material over the inner shelf and coastal areas.

The present study aimed to represent the hydrodynamic conditions in April 2021 to simulate the distribution of surface marine litter that arrived on the coast of the Rio Grande do Norte. The only information reported from local authorities about this event was the time and location where this litter arrived on the beaches, but to date, no record of its origin has been announced. The release sites were therefore hypothesized to cover the entire simulation domain south of the Baía Formosa region. This configuration made it possible to investigate all points within the domain with any chance of reaching the region.

To inspect likely locations of origin of this mysterious material, the probabilities of arrival at Baía Formosa (Figures 2 and 5 green polygon) were calculated. Thus, the probabilities of virtual particles arriving at this area were calculated for each originating zone (each release points, see Figure 2 release map). The particles releases were performed for four different types of numerical experiments (Lagrangian simulations) according to the different combinations of hydrodynamic forcings defined by the previous Eulerian simulation. Figure 5a shows the probabilities of surface marine litter to reach and remain in the Baía Formosa region at the end of our control simulation (EXP CTL -with all physical forcings). It is possible to note that a region with high probabilities (>90%) develops southwesterly from Baía Formosa to approximately 7.5°S close to the shelf break region (34.6°W). Southward of this region, a path with probabilities varying from 15 to 60% is observed following the region of influence of the NBUC in the meridional axis (Figure 5a). During the EXP1 (no tides) the pattern of probabilities was similar to those found in CTL experiment. On this experiment (EXP1), the diagonal region starting in Baía Formosa and extending southwards was also present, with a second region of high probabilities between 7.5°-8°S near the shelf break region over the Recife high (Figure 5b).

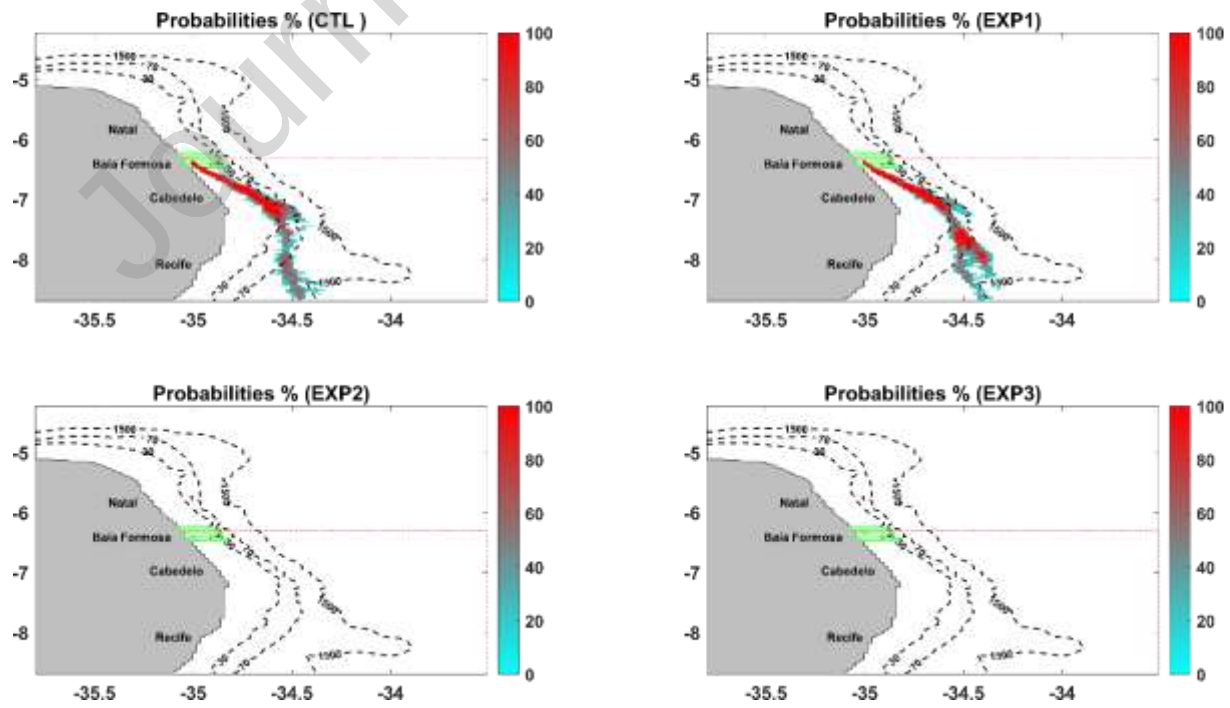

Figure 5. Probabilities of virtual particles reaching the end-point in Baía Formosa (green polygon) starting from each numerical grid point of the hydrodynamic mesh inside the red line (Figure 2- map). Probabilities in % were calculated separately for each experiment (different forcings, see Figure 2 schematic boxes).

Over the next two experiments, EXP2 (no winds) and EXP3 (no winds and no tides) (Figures, 5c and 5d, respectively) a region with high probabilities was not found, only a few points released inside the polygon presented probabilities around 30% or less. This pattern highlights the crucial role of wind forcing to reproduce the findings of the experiments CTL and EXP1 (a region with high probability).

Based on the pattern of probabilities found, which indicated a region south of Baía Formosa extending until the shelf break as a region with the highest probability of spreading and driving surface particles to reach the ending point of interest, where significant amounts of waste of unknown origin were found, Figure 6 shows the paths of some particles that started in these regions (probabilities > 90%) and their velocities throughout the path. The number of particles was restricted in the figure to allow the paths traveled to be visualized.

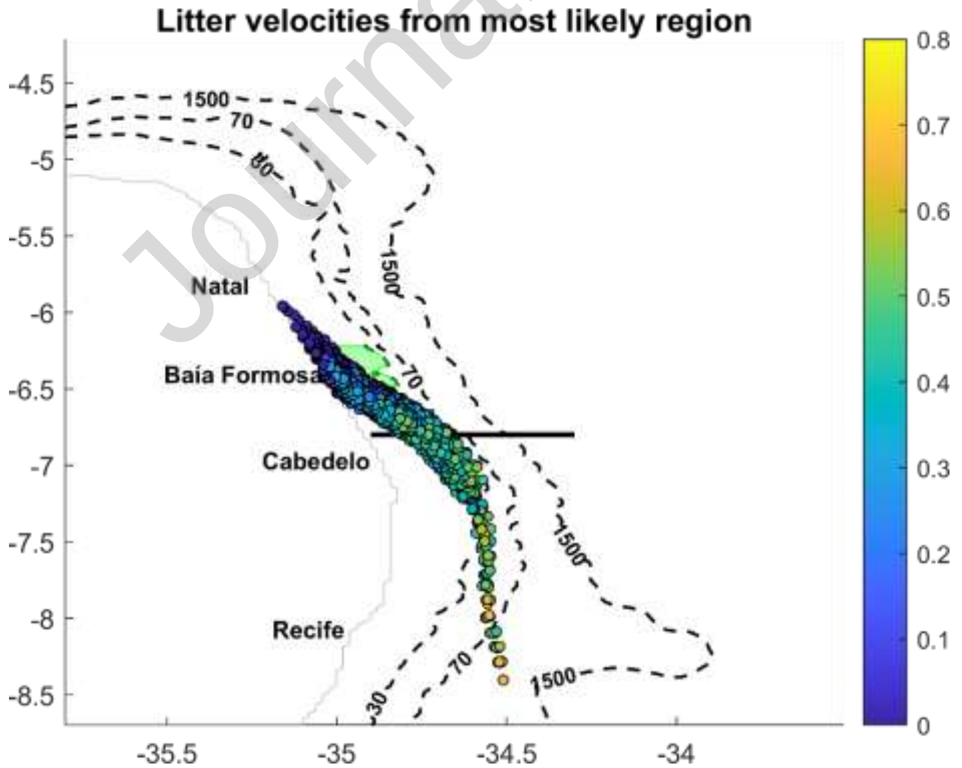

Figure 6. Pathways of virtual particles released (Experiment CTL only) from the most likely region (probability to reach the Baía Formosa region > 90%). The color scale represents the instantaneous velocities (m s^{-1}) along this path. The number of particles has been reduced for proper visualization. The continuous black line represents the section for analysis of temporal evolution of physical forcings (Figure 8).

It is possible to notice that the virtual particles that were released into the axis of influence of the NBUC (meridional axis), traveled northward until approximately 7.4°S with speeds varying between 0.4 m s^{-1} and 0.6 m s^{-1}. After passing through this latitude, most of virtual particles turned westward reaching the inner shelf of Paraíba and after the Rio Grande do Norte, at Baía Formosa. Along this trajectory, the velocities were decelerating, to 0.5 m s^{-1} to 0.4 m s^{-1} when reaching the inner shelf, and less than 0.2 m s^{-1} near the coastal areas. This westward turn at approximately 6.8°S, seems to be decisive for marine litter to finally reach the area of interest of this investigation, the physical forces that conditioned this pattern will be discussed next. The paths taken and the density of the virtual particles can be visualized in greater detail by a provided animation (see supplementary material).

3.3. Physical forcings acting over surface marine litter along northeastern Brazilian coast

Although the identification of the most likely zones for waste release into the sea to originate the studied event is important, the second major objective of this study was to understand the roles of the major forcings in transporting this type of marine litter through the coastal regions affected. Figure 7 presents ocean surface velocities and wind stress comparing two regions that were most affected by the arrival of the marine litter at the coast. The oceanic current that skirted the continental slope as a western boundary current (NBUC) presented its influence during the entire evaluated month and this was noted in both regions, at Paraíba (PB) and Rio Grande do Norte (RN). This boundary current flows northward with velocities ranging from 0.2 to 0.5 m s^{-1}.

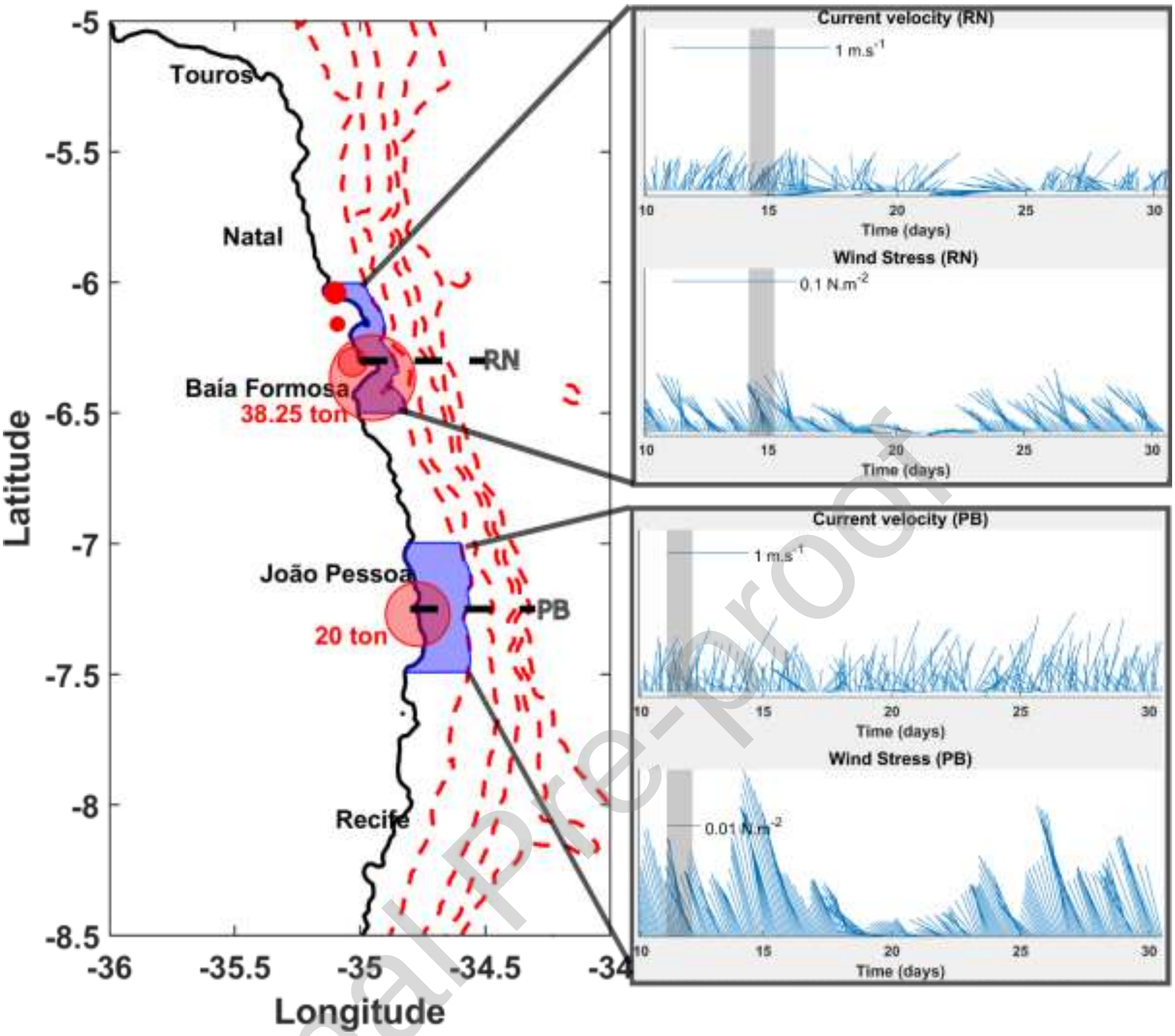

Figure 7 Map of northeast Brazilian coast highlighting two regions where surface forcings (winds stress and surface currents) are presented as daily mean time evolutions. Stick plots: surface mean velocity (m s^{-1}) and wind stress (N m^{-2}) along April 2021 over the sections indicated by the dashed black lines. The red bubbles indicate the litter quantities that arrived at the coast and red dashed lines are the isobaths of 30, 70, 100, 500, and 1000 m. The shaded gray bar represents the day with maximum particles density over the inner shelf for each state (see Figure 4).

The PB region showed more intense current velocities than in RN. Surface wind stress also showed a relatively constant direction, from southeast, while intensities were higher in the RN region than in PB (southeast trades influence). In the days that preceded the litter arrival in those regions, wind stress presented values around 0.05 N m^{-2} in RN, while in PB this influence was around 0.02 N m^{-2} (Figure 7, right panels).

Figure 8 presents the meridional and zonal velocity components from a section between Baía Formosa and Cabedelo (see Figure 6). This section was strategically chosen to analyze the region where most of virtual particles turned westward leaving the influence of the oceanic boundary current and entering the shelf circulation regime. During this analysis, simulations were performed with specific configurations in relation to the main hydrodynamic forcings, with the aim of understanding the role of each one separately. The control experiment (CTL), with all physical forcings included (Figure 8a) presented a pattern of currents similar to EXP1 (no tides) (Figure 8b), which suggests that tidal currents were not a significant driver of the marine litter to Baia Formosa. The westward turn of the virtual particles after passing through 7.5°S, can be attributed to the winds acting on the ocean surface. The CTL and EXP1 simulations presented significant zonal velocities (-0.5 m s^{-1} to -0.3 m s^{-1}) between the shelf break (~20km of the section, Figure 8e) and offshore section ahead, which were not present in the simulations without wind-forcing (EXP2 and EXP3). There is a discrepancy of about 10 km along the section between CTL and EXP1, where during the EXP1 these zonal contributions are noted just after the first 30 km approximately. During the EXP1 (no tides) the NBUC axis of influence at surface is clear 10 km offshore in relation to CTL simulation.

When we look to the experiments without wind, EXP2 and EXP3, a completely different transport pattern arises (Figures 8c and 8d, respectively). In these two experiments the zone of influence of the oceanic boundary current (clear on the meridional velocity component) occurs markedly on the first 40 km along the section, which is 20 km of difference from the CTL experiment, that showed its position is above the shelf break, as expected. In experiments EXP2 and EXP3, the zonal component of velocity was significantly decreased (-0.15 m s^{-1} to -0.3 m s^{-1}) over the same area of action of the oceanic current, suggesting that these are oscillations of the NBUC itself along its path.

Strong oscillations around a low mean were identified in the first 5 km of the section for all experiments (Figures 8a-d), indicating the influence of bathymetry in producing convergence and divergence of the flow.

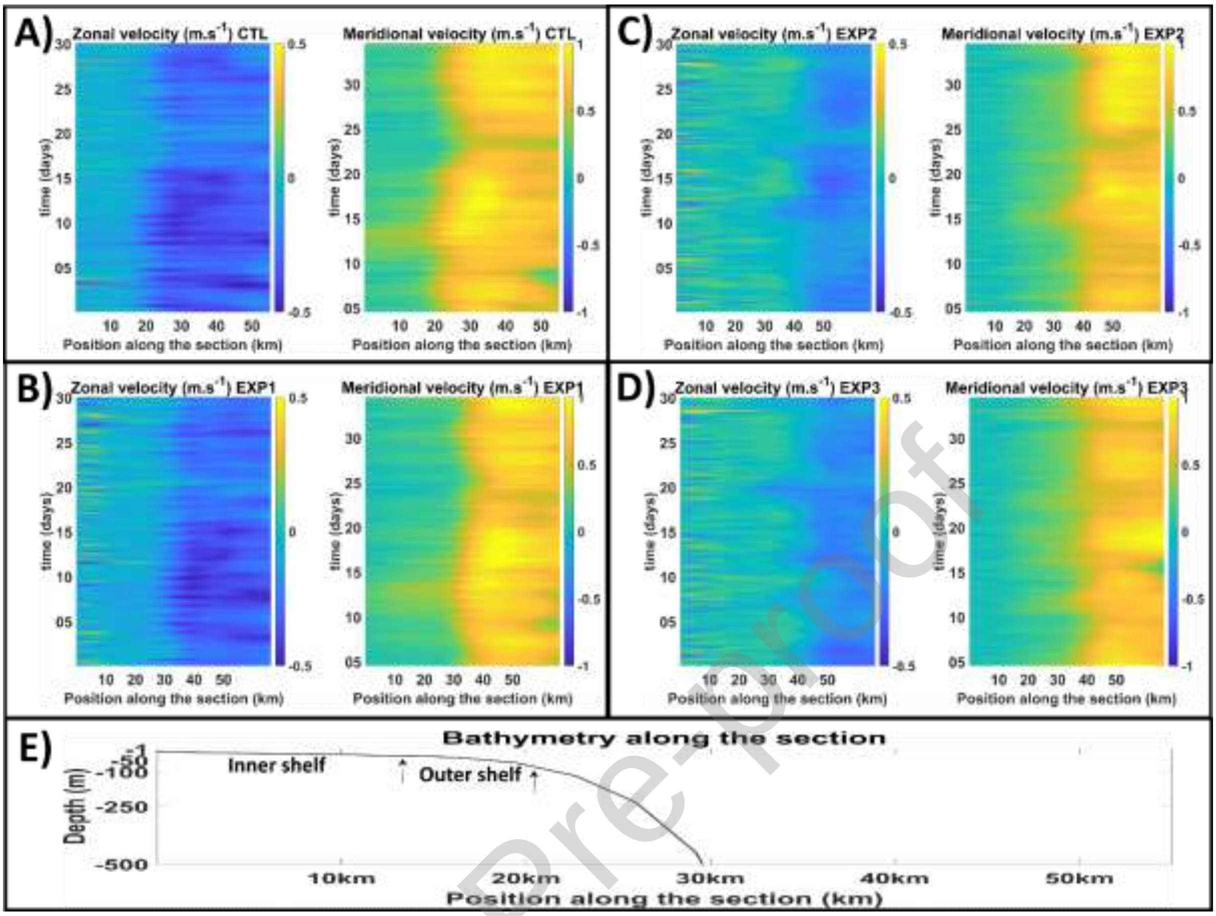

Figure 8. Upper panels: Hovmöller diagrams along the section (Figure 6) for zonal velocity (left panels) and meridional velocity (right panels) for each experiment (A to D). Lower panel: Bathymetry along the section with the boundary between inner shelf and outer shelf and shelf break limit indicated by the black arrows.

Analysis conducted here, of physical forcings that act on the continental shelf of northeastern Brazil, of the virtual particles trajectories and their spatial distribution, suggest that the litter that arrived at Baia Formosa most likely originated at sea, between the inner and the outer shelves (near the 30m isobath), between northern Pernambuco and southern Conde (in Paraíba). The fact that no litter was reported on the beaches of northern Pernambuco further support these findings, indicating that this material must not have been disposed of in estuaries or any other coastal areas.

4. Summary and Conclusions

With the goal of identifying possible places of origin of the material that reached beaches at the northeastern Brazilian coast in April 2021, and obtaining a better understanding of the physical forces that drove these trajectories, a total of eight simulations (four Eulerian hydrodynamic simulations coupled with 4 offline Lagrangian simulations) were carried. Several analyses were conducted to evaluate probable pathways, densities along the coast, and the likelihood of litter being stranded in the coastline. Focus was given on understanding the physical forcings that would be the major drivers of the transport of this material to the beaches of Rio Grande do Norte (Baía Formosa) where 35.8 tons of marine litter unexpectedly arrived.

The virtual particles were released at regularly spaced intervals (~2km) over the entire numerical model domain, southward of the location where litter was reported in vast quantities (Baía Formosa - Rio Grande do Norte). A total of 87,030 virtual particles were released at ten consecutive time steps after the first day of simulation (10th April 2021), and their positions reported at hourly intervals. Results showed that an offshore location would be the most probable source to reproduce the pattern observed in the event, with specific end-points for large amounts of litter stranded at Baía Formosa. The absence of any trace of marine litter south of the locations where litter arrived corroborates this hypothesis. This is consistent with a waste incident from oceanic origin, or a potential spontaneous criminal litter release in oceanic waters. Following the event, Brazilian federal police ruled out origins from international waters given the significant amounts of materials belonging to a Brazilian state, and oceanic disposal, criminal or not, is one of the hypotheses under investigation currently.

As the materials considered remained in the first 2 m near the surface, the major forcings acting on this floating litter were wind stress and the influence of the North Brazil Undercurrent (NBUC), particularly near the continental shelf break and the outer shelf. The analysis of physical forcings over a strategic region (where the virtual particles turned west towards Baía Formosa) in different experiments, in which the forcings (winds and tides) were turned on and off, revealed that surface wind stress plays the major role in transporting the marine litter westward, and consequently placing them on the path to Baía Formosa.

References

Aguiar, A.L., Marta-Almeida, M., Cruz, L.O., Pereira, J., Cirano, M., 2022. Forcing mechanisms of the circulation on the Brazilian Equatorial Shelf. Cont Shelf Res 247, 104811. https://doi.org/10.1016/J.CSR.2022.104811

Bentamy A., Croize-Fillon, D. 2012. Gridded surface wind fields from Metop/ASCAT measurements. *International Journal Of Remote Sensing*, 33(6), 1729-1754. doi:10.1080/01431161.2011.600348

Bertrand, A. 2017. ABRACOS 2 cruise, RV Antea, https://doi.org/10.17600/17004100

Damasceno, Ú.M., Cintra, M.M., Gomes, M.P., Vital, H., 2022. Interactions between the North Brazilian Undercurrent (NBUC) and the Southwest Atlantic Margin. Implications for Brazilian shelf-edge systems. Reg Stud Mar Sci 54. https://doi.org/10.1016/j.rsma.2022.102486

Duarte, L. F. A.; Ribeiro, R. B.; Medeiros, T. V.; Scheppis, W. R.; Gimiliani, G. T. 2023. Are mangroves hotspots of marine litter for surrounding beaches? Hydrodynamic modeling and quali-quantitative analyses of waste in southeastern Brazil. Regional Studies in Marine Science 67 (2023) 103177

Dutch safety board, 2020. Safe container transport north of the Wadden Islands.

Ebbesmeyer, C.C., Ingraham, W.J., 1994. Pacific toy spill fuels ocean current pathways research. Eos, Transactions American Geophysical Union 75. https://doi.org/10.1029/94EO01056

Egbert, G.D., Erofeeva, S.Y., 2002. Efficient inverse modeling of barotropic ocean tides. J. Atmos. Ocean. Technol. 19, 183–204. http://dx.doi.org/10.1175/1520-0426(2002)019<0183:EIMOBO>2.0.CO;2.

Frantzi, S., Brouwer, R., Watkins, E., van Beukering, P., Cunha, M.C., Dijkstra, H., Duijndam, S., Jaziri, H., Charles Okoli, I., Pantzar, M., Rada Cotera, I., Rehdanz, K., Seidel, K., Triantaphyllidis, G., 2021. Adoption and diffusion of marine litter clean-up technologies across european seas: legal, institutional and financial drivers and barriers. Mar. Pollut. Bull. 170. https://doi.org/10.1016/j.marpolbul.2021.112611.

Galgani, F.; Hanke, G.; Maes, T. 2016. Global distribution, composition and abundance of marine litter. *In* Marine Anthropogenic Litter. Bergmann et al. (eds.). Springer International Publishing AG. 447p. ISBN: 9783319376530. doi 10.1007/978-3-319-16510-3_2

García-Rivera, S., Sánchez Lizaso, J.L., Bellido Millán, J.M., 2017. Composition, spatial distribution and sources of macro-marine litter on the Gulf of Alicante seafloor (Spanish Mediterranean). Mar. Pollut. Bull. 121, 249–259. https://doi.org/10.1016/j.marpolbul.2017.06.022.

Hohn, D., 2012. Moby-Duck: The True Story of 28,800 Bath Toys Lost at Sea and of the Beachcombers, Oceanographers, Environmentalists, and Fools, Including the Author, Who Went in Search of Them. Viking, New York.

IDEMA-RN, 2021. Ações Governo do RN: Enfrentamento aos resíduos sólidos encontrados no litoral potiguar. Retrieved from: chrome-extension://efaidnbmnnnibpcajpcglclefindmkaj/http://www.adcon.rn.gov.br/ACERVO/idema/DOC/DOC000000000258590.PDF

Ivar do Sul, J.A., Costa, M.F., Silva-Cavalcanti, J.S., Araújo, M.C.B., 2014. Plastic debris retention and exportation by a mangrove forest patch. Mar Pollut Bull 78, 252–257. https://doi.org/10.1016/j.marpolbul.2013.11.011

Lett, C., Verley, P., Mullon, C., Parada, C., Brochier, T., Penven, P., Blanke, B., 2008. A Lagrangian tool for modelling ichthyoplankton dynamics. Environmental Modelling and Software 23. https://doi.org/10.1016/j.envsoft.2008.02.005

Li, W.C.; Tse, H.F.; Fok, L. 2016. Plastic waste in the marine environment: A review of sources, occurrence and effects. Science of the Total Environment 566–567 (2016) 333–349

Morét-Ferguson, S., Law, K.L., Proskurowski, G., Murphy, E.K., Peacock, E.E., Reddy, C.M., 2010. The size, mass, and composition of plastic debris in the western North Atlantic Ocean. Mar Pollut Bull 60, 1873–1878. https://doi.org/10.1016/j.marpolbul.2010.07.020

Peliz, A., Marchesiello, P., Dubert, J., Marta-Almeida, M., Roy, C., Queiroga, H., 2007. A study of crab larvae dispersal on the Western Iberian Shelf: Physical processes. Journal of Marine Systems 68, 215–236. https://doi.org/10.1016/J.JMARSYS.2006.11.007

Pruter, A.T., 1987. Sources, quantities and distribution of persistent plastics in the marine environment. Mar Pollut Bull 18. https://doi.org/10.1016/S0025-326X(87)80016-4

Rech, S.; Macaya-Caquilpán, V.; Pantoja, J.F.; Rivadeneira, M.M.; Madariaga, D. J.; Thiel, M. 2014. Rivers as a source of marine litter – A study from the SE Pacific. Marine Pollution Bulletin, 82, 66–75. doi.org/10.1016/j.marpolbul.2014.03.019

Rellán, A. G.; Ares, D. V.; Brea, C. V.; López, A. F.; Bugallo, P.M. B. 2023. Sources, sinks and transformations of plastics in our oceans: Review, management strategies and modelling. Science of the Total Environment 854, 158745. doi.org/10.1016/j.scitotenv.2022.158745

Ryan, P.G., Moore, C.J., Van Franeker, J.A., Moloney, C.L., 2009. Monitoring the abundance of plastic debris in the marine environment. Philosophical Transactions of the Royal Society B: Biological Sciences. https://doi.org/10.1098/rstb.2008.0207

Saliba, M., Frantzi, S., van Beukering, P., 2022. Shipping spills and plastic pollution: A review of maritime governance in the North Sea. Mar Pollut Bull 181, 113939. https://doi.org/10.1016/J.MARPOLBUL.2022.113939

Schettini, C.A.F., E.C. Domingues, E.C. Truccolo, J.C. Oliveira Filho, and P.L.F. Mazzini. 2017. Seasonal variability of water masses and currents at the eastern Brazilian continental shelf (7.5-9 o S). Regional Studies in Marine Science, 16, 131-144, ISSN 2352-4855, doi:10.1016/j.rsma.2017.08.012.

Shchepetkin, A.F., McWilliams, J.C., 2005. The regional oceanic modeling system (ROMS): a split-explicit, free-surface, topography-following-coordinate oceanic model. Ocean Model., 9: 347–404, http://dx.doi.org/10.1016/j.ocemod.2004.08.002.

Shchepetkin, A.F., Mcwilliams, J.C., 2009. Computational kernel algorithms for fine-scale, multi-process, longtime oceanic simulations. Handb. Numer. Anal., 14: 121–183, http://dx.doi.org/10.1016/S1570-8659(08)01202-0

Stichting Noordzee, 2021. Jaarverslag 2021.

UNEP, 2009. Marine Litter: A Global Challenge. Nairobi, UNEP pp. 232. Retrieved from: http://oceansandplastics.info/wp-content/uploads/2015/09/OAP-UNEP-2009-Marine-Litter.pdf.

UNEP, 2005. Marine Litter: A analytical overview. Nairobi, UNEP pp.58. Retrieved from: https://www.unep.org/resources/report/marine-litter-analytical-overview

Yoon, J.H., Kawano, S., Igawa, S., 2010. Modeling of marine litter drift and beaching in the Japan Sea. Mar Pollut Bull 60, 448–463. https://doi.org/10.1016/j.marpolbul.2009.09.033

Declaration of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Highlights

- An unknown arrival of ~50 tons of marine litter over NE Brazil was investigated
- Wind stress plays an important role in the stranding of materials on local beaches
- The investigation of the material sources revealed a possible ocean origin