

## Special Edition

# Forecast modelling of vegetable oil spill events at Paranaguá Port, Brazil

Modelagem da previsão de eventos de derramamento de óleo vegetal no Porto de Paranaguá, Brasil

Luiz Gustavo Schmidt <sup>1</sup> , Eduardo de Paula Kirinus <sup>1</sup> 

<sup>1</sup> Universidade Federal do Paraná, Curitiba, PR, Brazil

## ABSTRACT

O Porto de Paranaguá é o principal porto brasileiro para as exportações de óleo de soja, respondendo por quase 70% de todos os embarques em 2021. Embora menos comuns do que os derrames de óleo mineral, os derrames de óleo vegetal podem ter efeitos ambientais igualmente devastadores. Esse risco reforça a necessidade de planejamento e gestão eficazes das atividades que envolvem o manuseio de óleos vegetais na região. Para atender a essa necessidade, este estudo objetivou descrever o comportamento de derramamentos de óleo de soja no complexo estuarino de Paranaguá frente a uma abordagem de modelagem em modo de precisão. O sistema utiliza o sistema de modelagem numérica tridimensional openTELEMAC-MASCARET para resolver equações do movimento, acoplado o módulo hidrodinâmico (Telemac-3d) com o módulo de óleo (ECOS). O sistema é automatizado por meio de rotinas computacionais escritas em Python e na linguagem de comando bash, permitindo que os usuários iniciem simulações e gerem mapas de dispersão para rastrear o óleo de soja em cenários hipotéticos de derramamento. Os resultados do processamento foram satisfatórios, demonstrando o potencial desta ferramenta em contribuir para a minimização dos impactos do derramamento de óleo de soja na Baía de Paranaguá. Este sistema pode apoiar uma melhor tomada de decisão nos esforços de resposta, reduzir os danos ambientais e aumentar a proteção dos ecossistemas locais.

**Keywords:** Modelo de previsão, Derrames de óleo, Óleo de soja, Telemac-3d, ECOS, Python

## RESUMO

The Port of Paranaguá serves as Brazil's primary outlet for soy oil exports, accounting for nearly 70% of all shipments in 2021. While less common than mineral oil spills, vegetable oil spills can have similarly devastating environmental effects. This risk underscores the need for effective planning and management of activities involving vegetable oil handling in the region. To address this need, this study developed results based on a forecasting setup focused on describing the behaviour of soy oil

spills in the estuarine complex of Paranaguá. The system uses the open TELEMAC-MASCARET three-dimensional numerical modelling system to solve oil movement equations, coupling the hydrodynamic module (Telemac-3d) with the oil module (ECOS). The system is automated through computational routines written in Python and the bash command language, enabling users to initiate simulations and generate dispersion maps to track soybean oil in hypothetical spill scenarios. The processing results were satisfactory, demonstrating the potential for this tool to contribute to minimising the impacts of soybean oil spills in the Bay of Paranaguá. This system can support better decision-making in response efforts, reduce environmental damage, and enhance the protection of local ecosystems

**Palavras-chave:** Forecast modelling, Oil spill, Soy oil, Telemac-3d, ECOS, Python

## 1 INTRODUCTION

Coastal areas are crucial for many reasons, including providing habitat for various aquatic and terrestrial species, supporting local economies, and serving as popular recreational destinations. However, these areas are also vulnerable to various threats, including oil spills. While crude oil spills have received significant attention due to their devastating impacts on the environment, vegetable oil spills are often overlooked. Nonetheless, vegetable oil spills can still have severe consequences. For example, in 2018, a vegetable oil spill in the Saronic Gulf in Greece (KOLOLOUSSIS E KARATHANASSII, 2018) affected over 20 kilometers of coastline, leading to the closure of several beaches and significant harm to marine life.

Although vegetable oil spills are less frequent than mineral oil spills, their environmental impact can be just as severe (RIGGER, 1997). The presence and maintenance of suspended oil in the water column or on the surface can cause significant harm (Mudge, 1995). Despite the different properties of mineral and vegetable oils, their transport and drift patterns are similar (CEDRE, 2014).

In Brazil, the main vegetable oil is derived from soy, about 9,57 million tons (Mt) were produced in 2021, where 7,92 Mt were demanded by the intern market and 1,65 Mt were exported (CONAB, 2022). The state of Paraná is the exit door of soy oil in the country, about 70% of all exported soy oil in 2021 was moved by there (about 1,125 Mt in absolute numbers) (ABIOVE, 2022). The Cattalini company, that makes part of

Paranaguá and Antonina Ports Administration (APPA), located inside the Paranaguá Estuary Complex (CEP) is responsible for the liquid bulk movement, including soy oil.

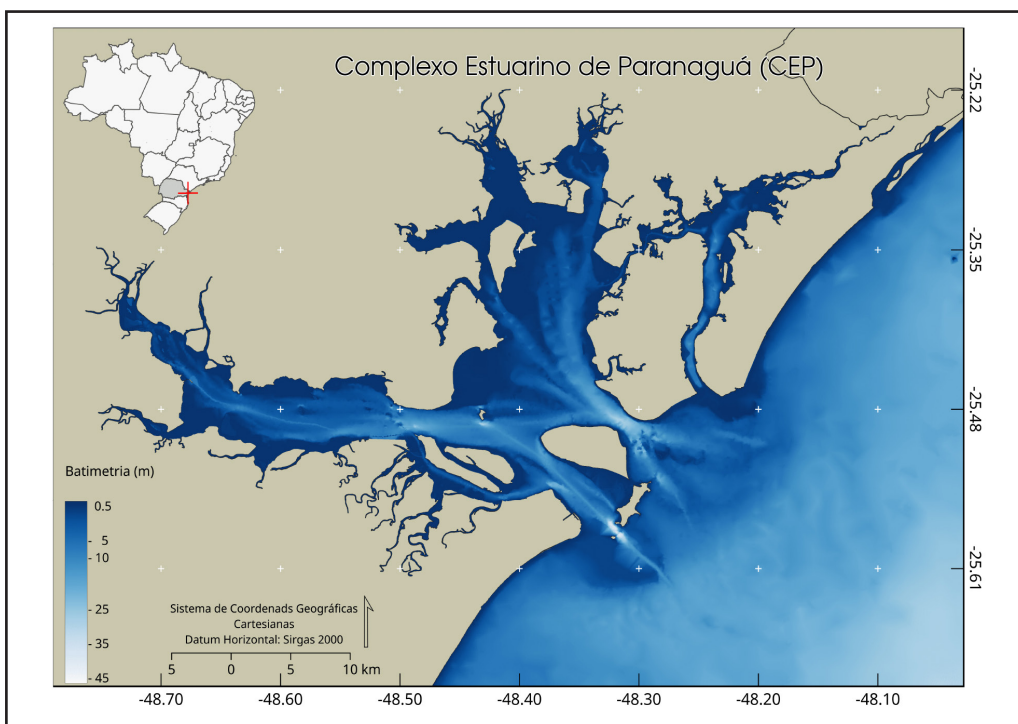
Due to the high risks associated with the vegetable oil spill in CEP, this work aimed to contribute to analyzing oil spill forecasts to understand patterns of drift and strand preferred locals. These results can contribute to increasing the efficiency of environmental response activity, enabling better chances of total and quick oil removal from the water ambient

## 2 MATERIALS AND METHODS

### 2.1 study area

The study area is located on the south Brazilian coast, between the latitudes of  $-24.50^{\circ}$  and  $-27.30^{\circ}$ S and longitudes of  $-48.75^{\circ}$  and  $-46.10^{\circ}$  W, including all the Estuarine Complex of Paranaguá area and near shore, figure 1 shows a map of the area.

Figure 1 – Paranaguá Estuarine Complex



Source: Oil Spill Forecast

This estuary has 600 km<sup>2</sup> of liquid area, which gives a huge environmental diversity, including tidal flats and channels.

Shallows, rocky shores, salt marsh, and mangroves (Mantovanelli, 1999). The climate is considered as humid tropical, defined by high rainwater (almost 2000 mm.year<sup>-1</sup>) and mean air temperature above 22°C (LANA et al., 2001). The driest months are between June and August and wetter months are between January and March (IAP, 2012).

Tides and rivers discharge commands the hydrodynamic at the estuary, tides are characterised as semi-diurnal meso-tides with

1.5m of amplitude and almost 70% of the coastal drainage basin area flow out to the estuary, consequently, the ebb currents are intenser then flood currents (Marone e Jamiyanaa, 1997), achieving the maximum value of 0.9 m.s<sup>-1</sup> and 0.5 m.s<sup>-1</sup>, respectively. Wind patterns are defined by weather fronts and South Atlantic High, in winter the predominant direction are S/SE and summer ENE/E, mean velocity of 4 m.s<sup>-1</sup> (Oliveira and Dourado, 2010)

## 2.2 Open TELEMAC-MASCARET

Open TELEMAC-MASCARET started as a numerical model for dams, thermal and nuclear power stations at the Research and Development Department of Electricité de France (EDF) (HERVOUET, 2007), and nowadays is a powerful open-source integrated modelling tool for use in the field of free-surface flows. Open TELEMAC-MASCARET is formed by a conjunction of modules in two or three dimensions that can be used to study hydrodynamics, sediment transport, river floods, waves generated by winds, transport of oil spills and pollutants, renewable energy and more.

This present work was developed using this numerical modelling system in the v6p3r2 version, specifically by using the three-dimensional hydrodynamic module TELEMAC-3D and the module for oil spill behaviour and weathering ECOS.

## 2.3 TELEMAC-3D

By solving the Navier-Stokes equations considering local variations in the free surface of the fluid, the hydrodynamic model uses the finite element method and sigma coordinates for the vertical discretization, the way that bottom and surface features are all covered, solving the hydrodynamic equations (equations 1 to 4) at each mesh node. (Hervouet, 2007).

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} \quad (1)$$

$$\frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} + w \frac{\partial u}{\partial z} = -\frac{1}{\rho} \frac{\partial p}{\partial x} + \nu \nabla^2 (u) + F_x \quad (2)$$

$$\frac{\partial v}{\partial t} + u \frac{\partial v}{\partial x} + v \frac{\partial v}{\partial y} + w \frac{\partial v}{\partial z} = -\frac{1}{\rho} \frac{\partial p}{\partial y} + \nu \nabla^2 (v) + F_y \quad (3)$$

$$\frac{\partial w}{\partial t} + u \frac{\partial w}{\partial x} + v \frac{\partial w}{\partial y} + w \frac{\partial w}{\partial z} = -\frac{1}{\rho} \frac{\partial p}{\partial z} - g + \nu \nabla^2 (w) + F_z \quad (4)$$

Where  $u, v$  e  $w$  represents the velocity components, while  $x, y$  and  $z$ , represents the cartesian plane,  $t$  the time,  $g$  gravitational acceleration,  $F_x, F_y$  e  $F_w$  are font therm in  $x, y$  e  $z$ , respectively.  $\nu$  is the kinetic viscosity coefficient,  $\nabla^2(u), \nabla^2(v)$  e  $\nabla^2(w)$  are the Laplacian operators in cartesian planes.

## 2.4 ECOS

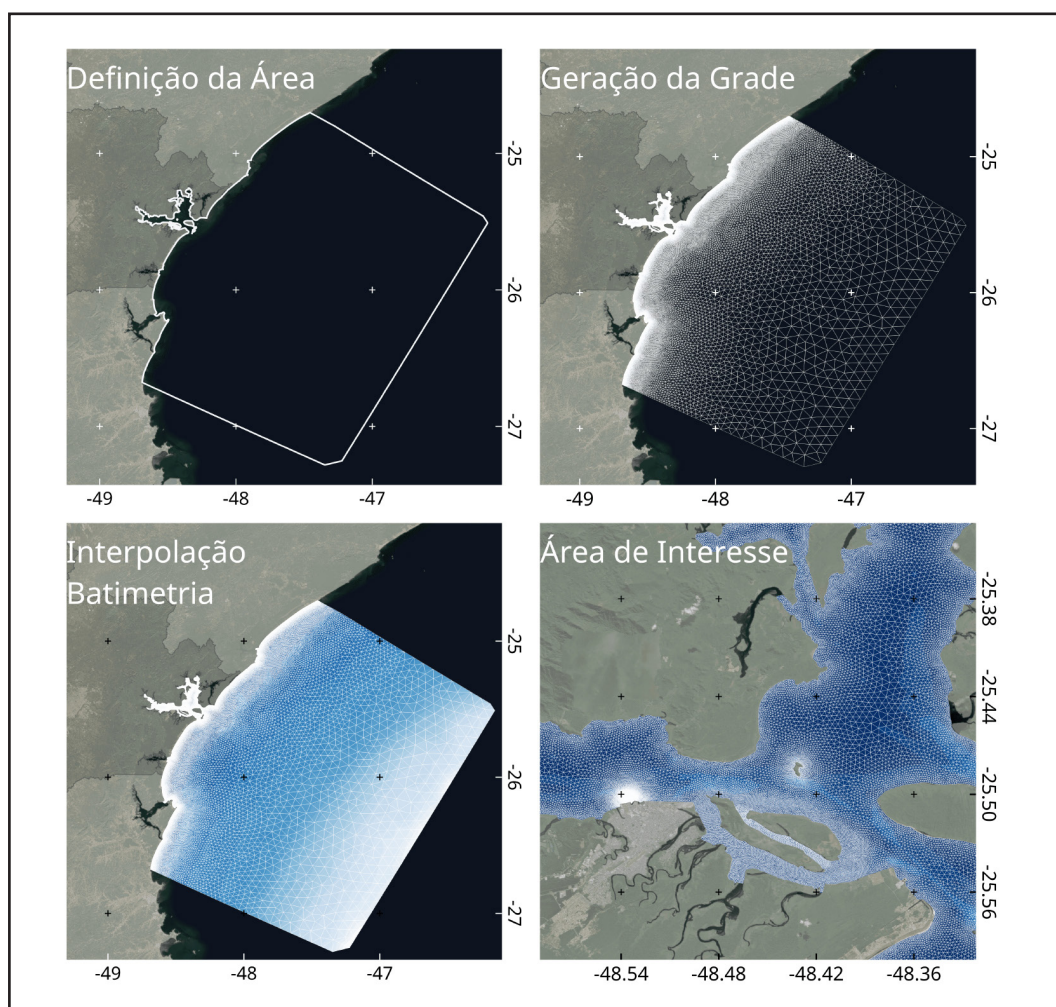
The oil model (ECOS - Easy Coupling Oil System) treats the oil as discrete Lagrangian particles to describe the advection, scattering, and turbulence properties. The dispersion is evaluated considering the oil as a non-homogeneous stain, according to Marques et al. (2017). The positioning of oil particles depends directly on the currents, wind, scattering effect, and turbulent diffusion. ECOS was developed at FURG (Federal University of Rio Grande) and since 2010 is registered in INPI (Nacional Institute of

Industry Property) by the register number BR 51 2013 00013 Marques et al. (2013).

## 2.5 Numerical mesh

A non-structured finite element mesh covers the Estuarine Complex of Paranaguá and a close coastal area until the depth of 175m. The mesh owns 81.000 nodes, the triangles can variate in size from 9.000m to ocean areas to 15m to the specific oil spill initial hypothetical area, six sigma levels were defined to well cover the inside estuary features. Figure 2 shows the mesh and their limits (up left), the triangle finite element mesh (upright), the bathymetry (down left), and the specific study area (down right).

Figure 2 – Finite element mesh developed to source area

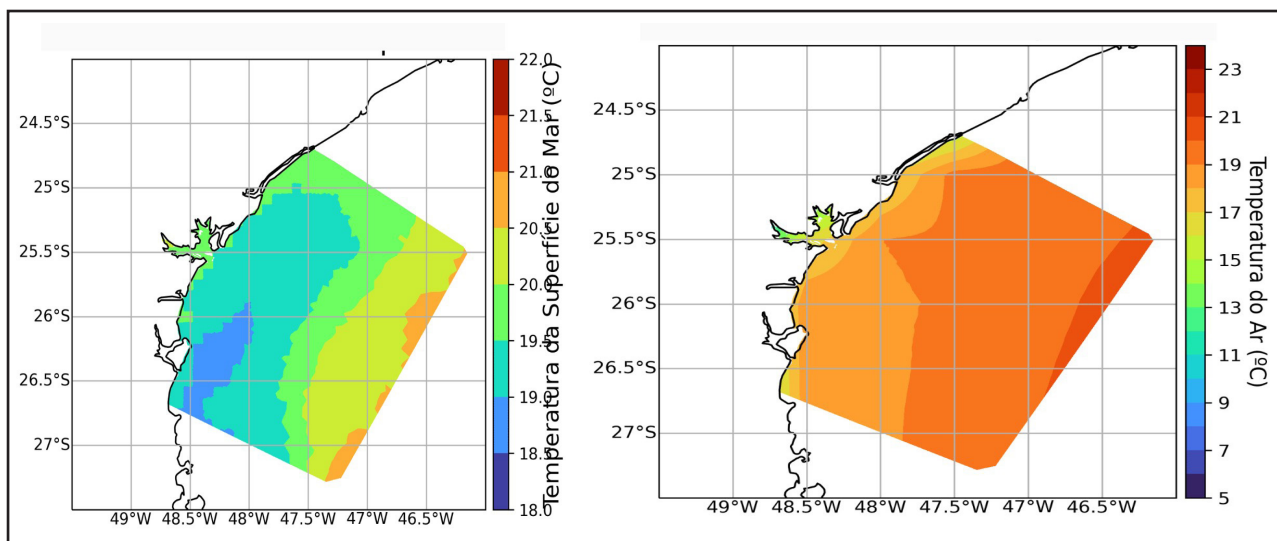


Source: Oil Spill Forecast

## 2.6 Initials and boundary conditions

Global atmospheric and oceanic forecast models support the data used as conditions in this work, being respectively GFS (Global Forecast System) and RTOFS (Real Time Ocean Forecast System), in addition, the rivers flow are considered constant by the mean of the HidroWeb data (ANA, 2018). The raw data are acquired by OPeNDAP (Open Source Project for a Network Data Access Protocol) protocol from the global model's output, stored in NOMADS (NOAA Operational Model Archive and Distribution System) and managed to boundaries and initial conditions to forecast local simulation, the figure 3 represents the ocean and weather raw data interpolated to the numerical mesh.

Figure 3 – Initials conditions from ocean temperature (Left) and air temperature (Right)



Source: Oil Spill Forecast

Raw data interpolation consists in fill all the nodes of the numerical mesh with the nearest neighbour method based on global forecast data.

## 2.7 Simulation Setup

All simulations were done in a forecast setup, that relies on python scripts to start the model coupling, resulting in two days of output results daily, the parameters

adopted for the runs were established through performance and validation tests.

Telemac-3D and ECOS setup included parallelism of 16 cores, with a time step of 90s and an hourly recording step. The modules work in a coupling mode, calculating the hydrodynamic in a temporal loop, Telemac-3d is able to estimate at each node the oceanic environmental conditions, that are exported to the oil model in order to calculate the oil weathering properties.

A standard spill was defined for the forecast simulations, starting every 00h of the next day of simulation day, with 12.345 particles representing 1m<sup>3</sup> of soy oil, at the place where liquid bulk was most manipulated in Paranaguá Port.

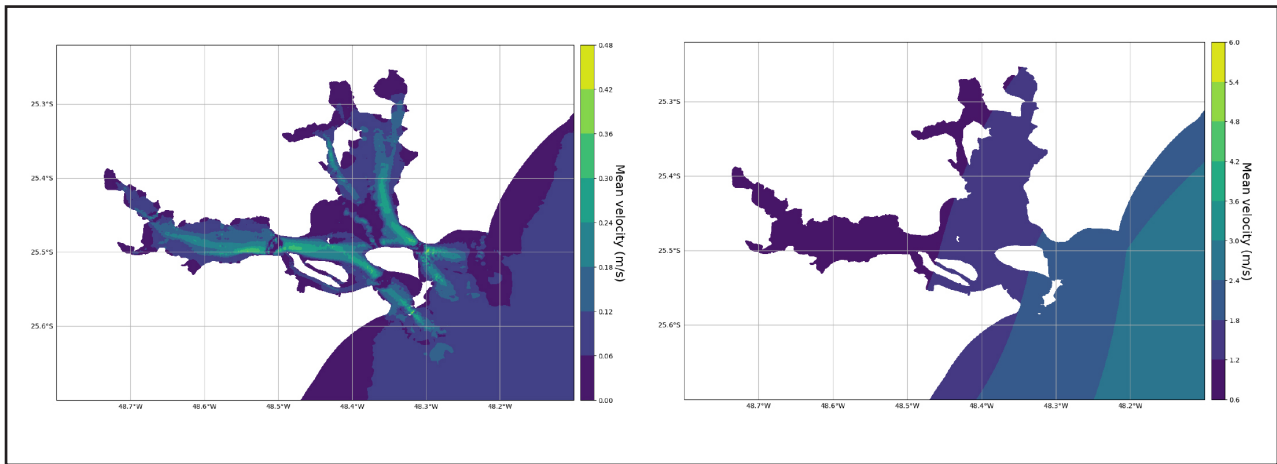
## **3 RESULTS AND DISCUSSION**

### **3.1 General approach to model results**

The study of hydrodynamic patterns is crucial for understanding the behavior of water and oil in different aquatic environments, including estuaries, coastal zones, and offshore areas. In particular, the intensity and distribution of winds and currents play a fundamental role in promoting the dispersion of an oil drift.

In order to further analyse this assumption, the simulations from September to December were approached by its average conditions (Figure 4). The hydrodynamic patterns in coastal areas exhibit a significant variation in intensity depending on the location. In particular, the highest intensity is typically found inside the channels and river mouths, where the water flow is channeled and constrained. On the other hand, tidal flats and shallow waters exhibit a lower intensity of water currents due to their shallower depth and lower water flow. These patterns have been observed to have maximum mean values of approximately 0.5 m.s<sup>-1</sup>, which can have significant impacts on the mains direction of particle transport in addition to sediment transport, nutrient cycling, and ecological processes.

Figure 4 – Mean Current intensity (Left) and Mean Wind intensity (Right)

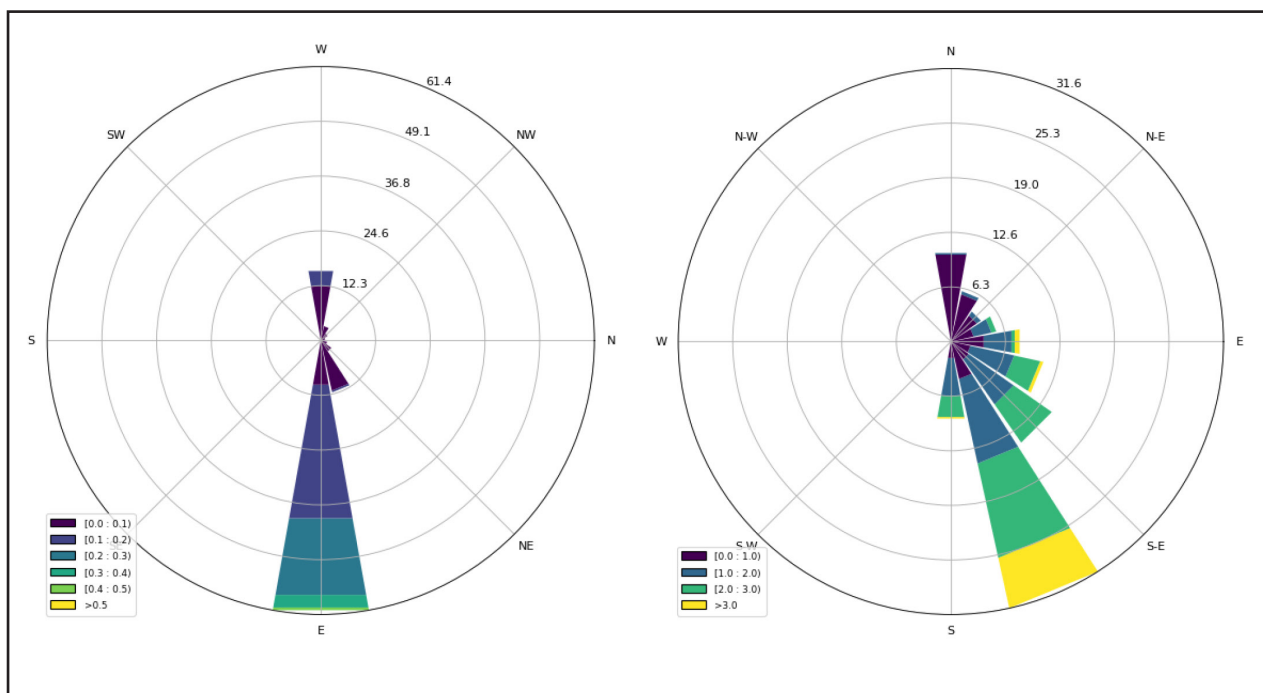


Source: Oil Spill Forecast

Another important factor that influences hydrodynamic patterns in coastal areas is wind. Wind generates waves and currents that affect the circulation of water and sediments, as well as the distribution of nutrients and pollutants. The intensity of wind varies depending on the location, with offshore areas typically experiencing higher wind intensity than continental areas. The average velocity of wind is around  $3.5 \text{ m}\cdot\text{s}^{-1}$ , which can have significant effects on the mixing of water masses and the transport of materials.

The direction of these parameters is also relevant in coastal areas for understanding its complexities. Figure 4 represents the value of currents and wind for a point in front of Paranaguá Ports ( $-25.50^{\circ}\text{S}$ ;  $-48.52^{\circ}\text{W}$ ). Ebb currents are more frequent and intense than floods, and the flow pattern is directed by the channel. Winds that blow from S-SE due to weather fronts are more frequent than others, but some winds as East winds can blow as intensely as South

Figure 5 – Current Polar Graphic (Left) and Wind Polar Graphic (Right)



Source: Oil Spill Forecast

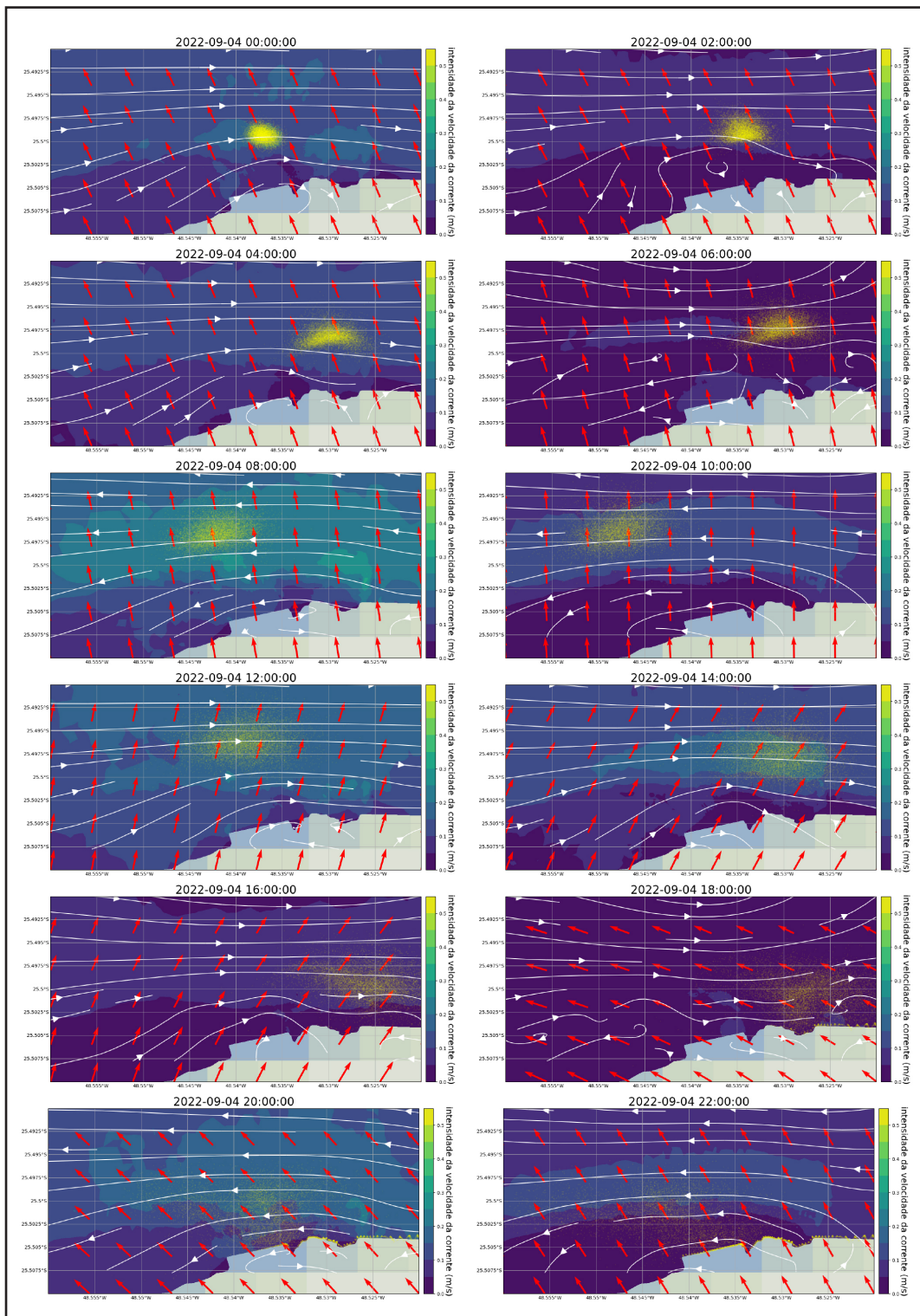
### 3.2 Forecast images output

An oil spill event can have catastrophic effects on the environment and human health, making it crucial to understand their dynamics and develop effective response strategies. For instance, in a simulation performed for the day 2022/09/04 and processed at 2022/09/03 (Figure 6), the oil can be represented as yellow particles, wind direction as red arrows, and current intensity in the background color. Moreover, the direction of the water currents can be depicted as white streams.

In the present study, we conducted a series of forecast simulations to generate an oil dispersion map, as depicted in Figure 6. The simulation images evolve over time, with each image representing a two-hour interval, starting from 04 September 2022 00h. Analysis of the oil dispersion map revealed that, during the first 12 hours of the simulation, the oil was influenced by wind direction, moving towards the middle of the bay, which was characterized by high hydrodynamic intensity. Subsequently, the oil

was carried by the currents, resulting in its dispersion in the environment. However, the spread area was not far from the initial spill, indicating the limited mobility of the oil.

Figure 6 – Forecast simulation of the day 2022/09/04



Source: Oil Spill Forecast

Moreover, it was observed that, during the simulation period, there was a cyclical pattern in the direction of the water currents, with the ebb currents occurring until 06h, followed by a change to flood until 10h, and then back to ebb again every 4-5 hours.

At 18h, the oil was found to be stranded on the shore, specifically in the Paranaguá Port area (SW of the spill site), due to its widespread distribution.

### **3.3 Oil dispersion pattern**

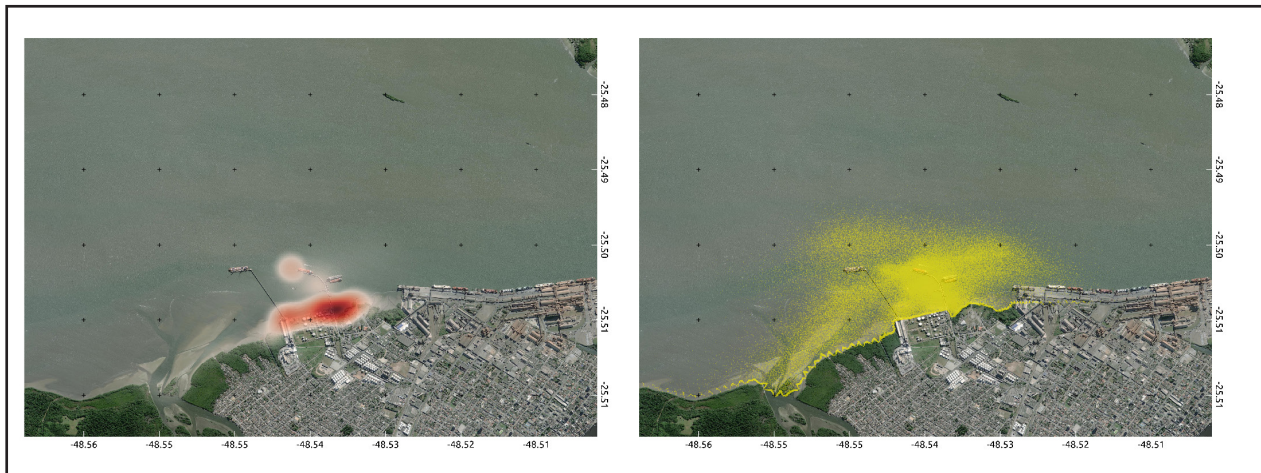
Oil dispersion maps are used to identify areas of potential oil spill impact and to help plan effective responses. They are typically created towards the usage of several database such as wind and water currents, the type and amount of oil spilled, and the geography of the affected area, in addition to modelling results. These maps can be used by emergency responders to quickly assess the potential impact of an oil spill and to plan the best course of action for containment and cleanup. They can also be used by government agencies to develop policies and regulations related to oil spills and environmental protection.

The dispersion of oil from a spill tends to be concentrated near the source and frequently results in accumulation southward from the initial trajectory. Figure 7 depicts a heatmap of the oil dispersion, represented in shades of red, indicating the main locations where the oil was carried by wind and water currents. Additionally, a scatter plot of oil particles, illustrated in yellow,

was generated from simulations conducted over several time periods.

The simulation results reveal that the tidal flat in front of the Catallini company, which is responsible for liquid bulk and where the soy oil spill originated, experienced the greatest concentration of oil. This area, unlike surrounding locations, lacks dense vegetation, which may have facilitated the accumulation of oil.

Figure 7 – Oil particles simulated (Left) and Heat map of average oil dispersion (Right)



Source: Oil Spill Forecast

## 4 CONCLUSIONS

The Paranaguá bay region is home to a significant number of mangroves and a sensitive ecosystem, which can be severely impacted in the event of an oil spill accident, causing environmental instability and long-term damage.

While the average intensity and direction of wind and water currents are important factors in determining the path of oil dispersion, the initial conditions at the time of the spill are critical in determining the trajectory of oil particles. This underscores the importance of conducting detailed forecast simulations to track the movement of oil particles and facilitate prompt environmental response activities.

In particular, hourly monitoring of oil dispersion patterns can greatly enhance the effectiveness of response efforts, enabling a more rapid and efficient recovery of oil from the environment. By leveraging advanced modeling techniques and closely monitoring conditions on the ground, we can work to minimize the negative impacts of oil spills and propose better tools for decision-makers.

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## Authorship contributions

### 1 – Luiz Gustavo Schmidt

Oceanography Student

<https://orcid.org/0009-0007-5565-1475> • [luizgschmidt@gmail.com](mailto:luizgschmidt@gmail.com)

Contribution: Conceptualization, Data curation, Formal Analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Writing - original draft, Writing - review & editing

### 2 – Eduardo de Paula Kirinus

Oceanologist, Master in Computational Modeling, PhD in Physical, Chemical and Geological Oceanography and Post-Doctorate in Ocean Engineering

<https://orcid.org/0000-0003-4754-5537> • [ekirinus@ufpr.br](mailto:ekirinus@ufpr.br)

Contribution: Conceptualization, Data curation, Formal Analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Writing - original draft, Writing - review & editing

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