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NUMERICAL STUDY OF OIL SPILL IN THE PATOS LAGOON UNDER FLOOD AND EBB CONDITIONS

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Abstract. *Facing the impossibility to completely eradicate the environmental hazards caused by oil spills, mainly in areas where there are periodic oil shipments in tankers, it is crucial the establishment of action protocols against such accidents. In this context, given the potential risks involving the Southern Brazilian Shelf, the focus of this study is the harbor region of Rio Grande, Rio Grande do Sul. The ECOS (Easy Coupling Oil System) model was used to simulate oil spills under different environmental conditions simulated by the hydrodynamic model TELEMAC3D. The oil spill model ECOS uses a Lagrangian approach to simulate the behavior of oil particles subject to the three-dimensional hydrodynamics. This work sought to identify the main forces controlling the movement of the oil slicks and the simulated period consisted of an year of averaged hydrodynamic conditions from 2003 to 2015. The computational domain comprises the Patos Lagoon, the harbor area of Rio Grande and the Southern Brazilian Shelf. For the oil spill simulation eight distinct events were defined considering both flood and ebb conditions in the estuarine region of the Patos Lagoon. The starting point of the oil spills is the Transpetro harbor terminal and due to the averaging of the hydrodynamic conditions from 2003 to 2015, an attenuation of the variability of the currents and winds was observed. Also, due to the river discharge and dominance of north quadrant winds, the most common is the ebb scenario. The oil spill simulations showed that in ebb conditions, the oil slick movement is mainly ruled by the currents, moving towards the outflow. After a few hours the wind action makes the slick move towards the margins of the waterway. The flood conditions, on the other hand, show that the oil slick drifts to the interior of the estuary, following the dominant currents and the local winds.*

Keywords: *Numerical simulation, Hydrodynamics, Oil spill, Patos Lagoon and Estuarine region*

INTRODUCTION

The crescent utilization of the coastal areas for the most distinct economic purposes, promotes the occurrence of the hydrocarbons spilling and associated environmental impact (Gurjar et al., 2015). These spill events are associated with the extraction, transport, and storage of the oil in the sea and coastal regions (Lopes et al., 2007).

The petroleum and derivatives are formed by hydrocarbons composed of aliphatic and aromatic substances with the presence of dissolved metals. Their property and composition are variable, according to the origin (natural or anthropic) and refinement process (Thomas, 2004). According to Caruso e Alaburda (2008), the polycyclic aromatic hydrocarbons (PAHs), originated from fossil fuels, have toxic effects for acting as carcinogenic, mutagenic and teratogenic agents, besides having the capacity of bioaccumulate and biomagnify along the different trophic levels.

Facing the impossibility of eliminate the possibility of accidents involving oil spills, mainly in areas where occurs the transhipment of the cargo in tankers, it is important the establishment of rapid action protocols against such accidents (Stringari et al., 2013). This demands the forecast of the consequences of eventual spills and, in this way, numerical simulations that reproduce the behavior of the oil in the sea are mandatory (Sebastião e Soares, 1995).

Brazilian environmental law advocates that activities that involve the production and distribution of the petroleum and its derivatives at sea, must be substantiated by numerical simulation of oil spill scenarios. Such simulations are necessary to the definition of the indirect influence area of this activity and possible locations of contamination. Such information will compose the Individual Emergency Plan (PEI), which all the mitigation of the environmental damage is based (IBAMA, 2002).

Given the potential risks involving the Southern region of Brazil, the present study was directed to the harbor region of the Rio Grande city (Figure 1). The harbor is in the estuarine region of the Patos lagoon, and it is under influence of meteorological and oceanographic physical forcing of the Southern Brazilian Shelf (Möller et al., 2001). In 2016, The harbor of Rio Grande handled 38,223,751 tons of cargo, of which 4,602,636 tons were of liquid fuels (SUPRG, 2017). This cargo handling makes the harbor of Rio Grande susceptible to accidents involving oil spills, adding environmental importance for this region.

This work presents a case study of eight different events of oil spill using numerical simulations. The case study is based on the coupled simulation of the three-dimensional hydrodynamic model Telemac3d, part of the open TELEMAC-MASCARET modeling suite and a Lagrangian model of transportation and weathering of oil particles.

METHODOLOGY

This work was developed using an unstructured grid, limited by the Patos lagoon and the coastline of Rio Grande do Sul. The unstructured mesh allows the representation of the computational domain using nonuniform levels of refinement to have better resolution on areas of interest (Lynch et al., 1996). The edge of the triangular elements vary from 11,000 m on deep ocean to 30 m on the location of the oil spill. The finest resolution is at the jetties of Rio Grande, with a nodal distance of 15 m. The mesh has a total of 93,050 nodes. The vertical discretization of the domain consists of 15 equally spaced sigma levels.

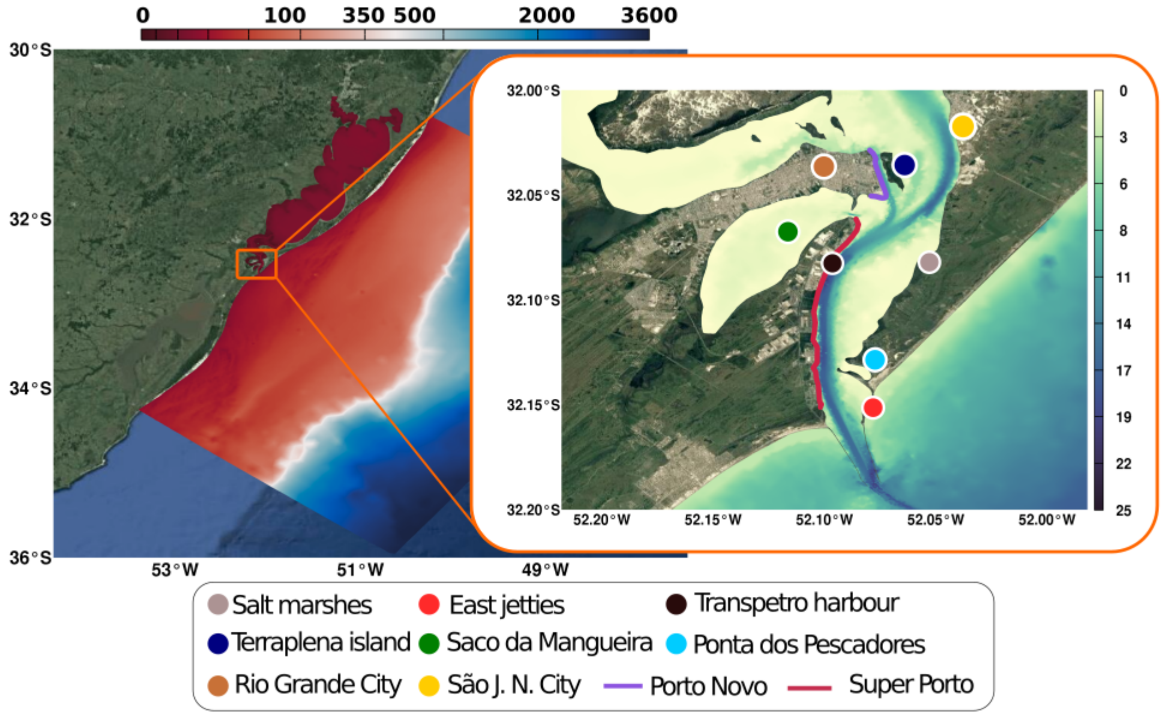

Figure 1: Representation of the computational domain. The colour scale represents the bathymetry of the study area. The points and lines are references of oil spills.

The bathymetric data used was obtained from nautical charts (Patos Lagoon - N°2140, Pinhal to Rio Grande - N°2350, Rio Gande and Arroio Chuí - N°2112) and coastal data from bathymetric surveys of the Brazilian Navy (LEPLAC). The numerical model used to simulate the hydrodynamics was TELEMAC3D. This model is used for three-dimensional hydrodynamic studies of free-surface flows in rivers, estuaries, and coastal and oceanic regions (Hervouet, 2007). TELEMAC3D solves the Navier-Stokes and the mass conservation equations considering the Boussinesq approximation to solve the system.

Following the methodology of Marques et al. (2017), the hydrodynamic simulation used a time step of 90 seconds and the horizontal turbulent processes were simulated using the k-ϵ turbulence model. To describe the oil drift processes the ECOS model was used. This model is being developed at the Universidade Federal do Rio Grande (FURG) and since 2010 has been incorporated several improvements (Marques et al., 2013).

ECOS represents the oil slick as a number of discrete particles that move independently in the water while still acting on each other to compute the processes of advection, scattering, and oil turbulence. The following section explain these processes.

Advection

The advection of the oil particles takes into account the transportation of the oil under the influence of the currents and the winds. The particles are also transported by process of spreading and turbulent diffusion. The meridional, zonal, and vertical components of the advective velocities of the i^{th} particle are calculated by the equations 1, 2 and 3:

$$U_i = k_c U_c + k_w U_w \quad (1)$$

$$V_i = k_c V_c + k_w V_w \tag{2}$$

$$W_i = k_c W_c + w_i \tag{3}$$

where U_c, V_c, and W_c are the three orthogonal current components, U_w and V_w, the wind components, and k_c and k_w are the drag coefficients of the currents and the winds, respectively. ECOS uses the Stokes law to compute the sink velocity of the oil particles (French-McCay (2004)):

$$w_i = \frac{d_i^2 g(1 - \frac{\rho_o}{\rho_w})}{18 \upsilon_w} \tag{4}$$

where d_i is the diameter of the oil particle, g is the acceleration of gravity, ρ_o the oil density, ρ_w the water density, and υ_w, the dynamic viscosity of the sea water.

Spreading

The spreading is the horizontal expansion of the oil slick due to differential surface tensions acting on the water-oil interface. Thus, the spreading process represents the balance between the gravitational, inertial, and viscous forces, and the surface tension. Currently, ECOS uses the classical formulation proposed by Fay (1969) to calculate the scattering velocities. The final formulation of the process was stated by Proctor et al. (1994), using the coefficients by Sebastião e Soares (1995) and Flores et al. (1998).

The phenomenon is calculated in three stages. Firstly, the spreading coefficients D_x and D_y are calculated using equation 5:

$$D_x = D_y = \frac{\pi k_2^2}{16} \left(\frac{\Delta g V^2}{\upsilon_w^2} \right)^{\frac{1}{3}} . \frac{1}{\sqrt{t}} \tag{5}$$

where V is the volume of the oil slick, t is the time since the start of the spill, and k_2 is a coefficient with value of 0.725 (Flores et al., 1998). The next step is to calculate the action radius of the scattering, U_r and V_r, using equations 6 and 7, respectively:

$$U_r = \sqrt{\frac{2D_x}{\Delta t}} \tag{6}$$

$$V_r = \sqrt{\frac{2D_y}{\Delta t}} \tag{7}$$

Finally, the spreading velocities Us_i and Vs_i are calculated using the equations 8 e 9, respectively:

$$Us_i = R_1 \cos(2\pi R_2).U_r \tag{8}$$

$$Vs_i = R_1 \sin(2\pi R_2).V_r \tag{9}$$

Turbulent Diffusion

ECOS uses a mixing length model modified for the oil as described by Al-Rabeh et al. (1989) to calculate the turbulent diffusion. Initially the maximum distance ΔS that an oil particle can move in a time interval Δt is defined (Equation 10). Thus, the velocity components Ud_i and Vd_i are calculated using equations 11 and 12, respectively.

$$\Delta S = R_1 \sqrt{(12 D_x \Delta t)} \tag{10}$$

$$Ud_i = \Delta S \cos(2\pi R_2) \tag{11}$$

$$Vd_i = \Delta S \sin(2\pi R_2) \tag{12}$$

Initial and Boundary Conditions

The hydrodynamic model was forced by atmospheric data from NOAA (National Oceanic and Atmospheric Administration - www.noaa.org), oceanographic data from HyCOM (Hybrid Coordinate Ocean Model - www.hycom.org), tidal data from the OTIS (OSU Tidal Inversion Software - www.volkov.oce.orst.edu/tides/otis.html), and river discharge data from the ANA (Agência Nacional de Águas - www.ana.gov.br) database.

Initial conditions are the current velocity components, salinity, and temperature from HyCOM with a spatial resolution of 0.75°×0.75°. The oceanic boundaries were also forced by data from HyCOM, with temporal resolution of one day, and by tidal constituents from OTIS. The superficial boundary was forced by wind velocity, atmospheric pressure, and air temperature from NOAA, with spatial resolution of 2.5°×2.5°and temporal resolution of 6 h. The river were forced by daily time series of river discharge from ANA.

The hydrodynamic simulations were performed in two steps. Initially, four simulations with 105 days long were performed to validate TELEMAC3D. Posteriorly, one simulation with 365 days long using daily averaged boundary conditions, from 2003 to 2015, was carried out in order to choose the events of oil spill.

For the case study of oil spill simulations, eight distinct hydrodynamic events were chosen with flood and ebb conditions of the estuary of the Patos Lagoon. The oil spill started for all the simulations, at the Transpetro harbor terminal, at coordinates 32°04'37.2"S and 52°05'27.6"W, considering a spilled volume of 20 m^3 of oil.

VALIDATION OF HYDRODYNAMICS RESULTS

The hydrodynamic simulations were performed during 105 days, between 11.01.2010 and 02.15.2011. The results were compared with field observations to validate the model and tests were performed to calibrate the TELEMAC3D hydrodynamic model using four settings of the following parameters: the wind friction coefficient and the bottom friction coefficient. Table 1 shows the values used for these tests:

Table 1: Simulation parameters.

Simulation	Wind friction coefficient	Bottom friction coefficient
V1F4	$1.\,10^{-5}$	0.04
V1F5	$1.\,10^{-5}$	0.05
V5F4	$5.\,10^{-6}$	0.04
V5F5	$5.\,10^{-6}$	0.05

The current data was obtained using an Acoustic Doppler Current Profiler (ADCP) located at the navigation channel at 14 m depth. To enhance the comparison between modeled and observed series was used a Lanczos square filter to remove higher frequency oscillations (periods shorter than 12 h). Salinity data was collected using a Temperature and Conductivity sensor located at same station of the CTD, but at 3 m depth.

In order to verify the model reproducibility, the hydrodynamic simulation result was compared with field observations of current and salinity time series of the Patos Lagoon channel at Praticagem Station, between the period of 01.03.2011 and 01.25.2011.

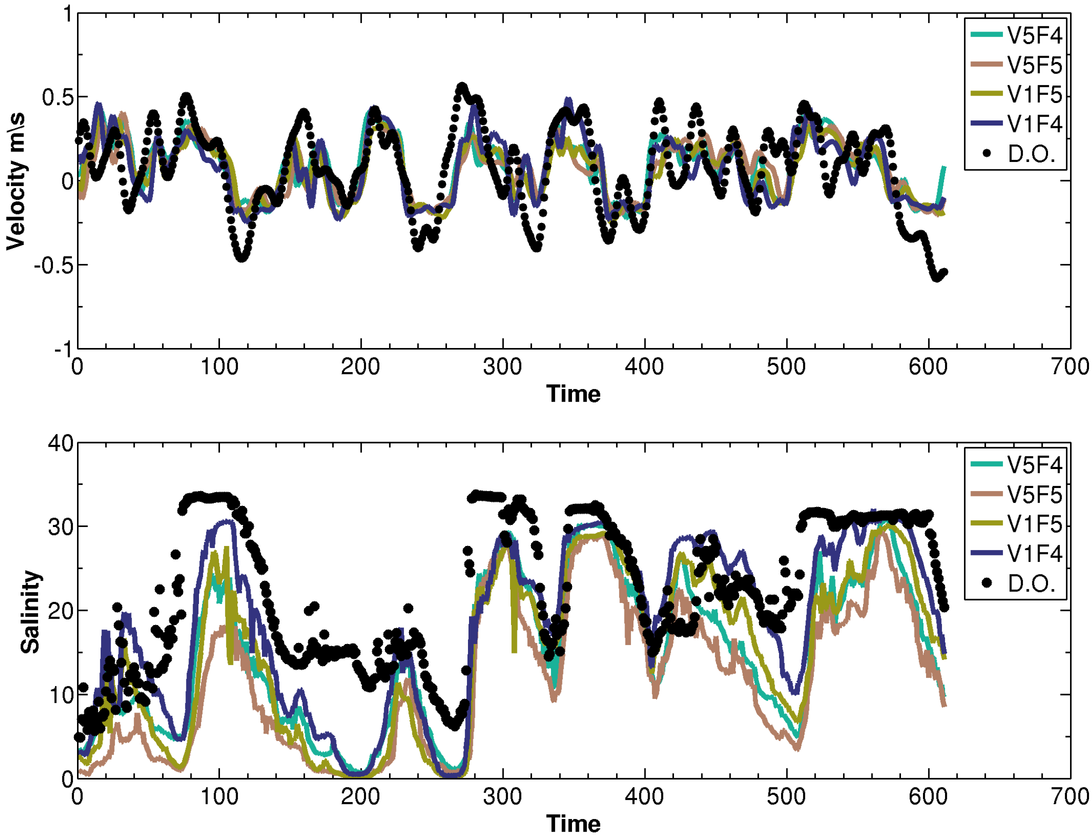

Figure 2: Comparison between observations (black dots) and model results (colored lines) for four parameters settings. The plot shows the meridional velocity above and salinity below at Praticagem Station.

Figure 2 compares observed series (black dots) with four different model settings results (colored lines). The model showed good concordance with the current and salinity observations trends. Overall the model values underestimates the observations.

The simulation performance were quantified using the methods applied by Sutherland e Wallingford (2001); Marques et al. (2017); Oleinik et al. (2017), computing the mean, absolute error, mean square error, coefficient correlation and the bias between the observations and model results. The V1F4 (blue line) simulation showed the best performance when compared to the other settings, as Table 2 shows.

The underestimated values of simulation results could be related to the use of constant coefficients of wind over the whole mesh, absence of energy generated by the wind and absence of wave-current interaction. These factors have large variability in the study area, but the im-

Table 2: Calibration Statistics.

	Parameters	V1F4	V1F5	V5F4	V5F5
Current Velocity	Mean	0.066	0.059	0.082	0.080
	Absolut Error	0.155	0.161	0.158	0.159
	Mean Square Error	0.193	0.195	0.194	0.196
	Correlation Coefficient	0.661	0.648	0.652	0.645
	Bias	-0.008	-0.014	0.008	0.007
Salinity	Mean	18.450	14.949	14.754	11.856
	Absolut Error	5.740	8.019	7.976	10.622
	Mean Square Error	7.466	9.864	9.525	12.109
	Correlation Coefficient	0.768	0.750	0.780	0.757
	Bias	-3.907	-7.408	-7.603	-10.501

plementation requires information that can not be easily obtained. Another cause could be the low resolution of the reanalysis products used, which do not reproduce the synoptic oscillations recurrent in the area.

Simionato et al. (2006) performed numerical simulations using reanalysis data at La Plata River region, observing that high intensity events were underestimated by 50% when compared with field observations. Sutherland e Wallingford (2001) attributed to the low resolution of reanalysis products as the major source of errors, when compared with wind fields analyzed at Mediterranean Basin.

Even with resolution limitation of the data used to force the model, our results reproduce the observations trends at Patos Lagoon Estuary accurately. So its possible to use these hydrodynamic results to evaluate likely scenarios of fate and behavior of oil spill in this area using the ECOS model.

RESULTS

The numerical results using the V1F4 setting and daily averages, between 2003 and 2015, exhibit attenuation of the wind and current components and these results represent meteorologic and oceanographic conditions of a normal year. As consequence our results differ from previous hindcast works in the Patos Lagoon Estuary, as the works of Marques et al. (2010), Marques et al. (2011), Fernandes (2001) and Fernandes et al. (2007) based on scenarios for specific years.

Comparative analysis between flood and ebb events show that ebb events are more frequent. The contribution of north quadrant winds and river discharge of the Patos Lagoon result in a estuarine flux seaward. The flood conditions are associated to the south quadrant winds which promote secondary effects, resulting in flow northward towards the estuary. Relation between ebb and flood events and their circulation patterns where studied by Möller et al. (1996), Marques (2005) and Monteiro et al. (2006) that described the estuarine circulation of the Patos Lagoon.

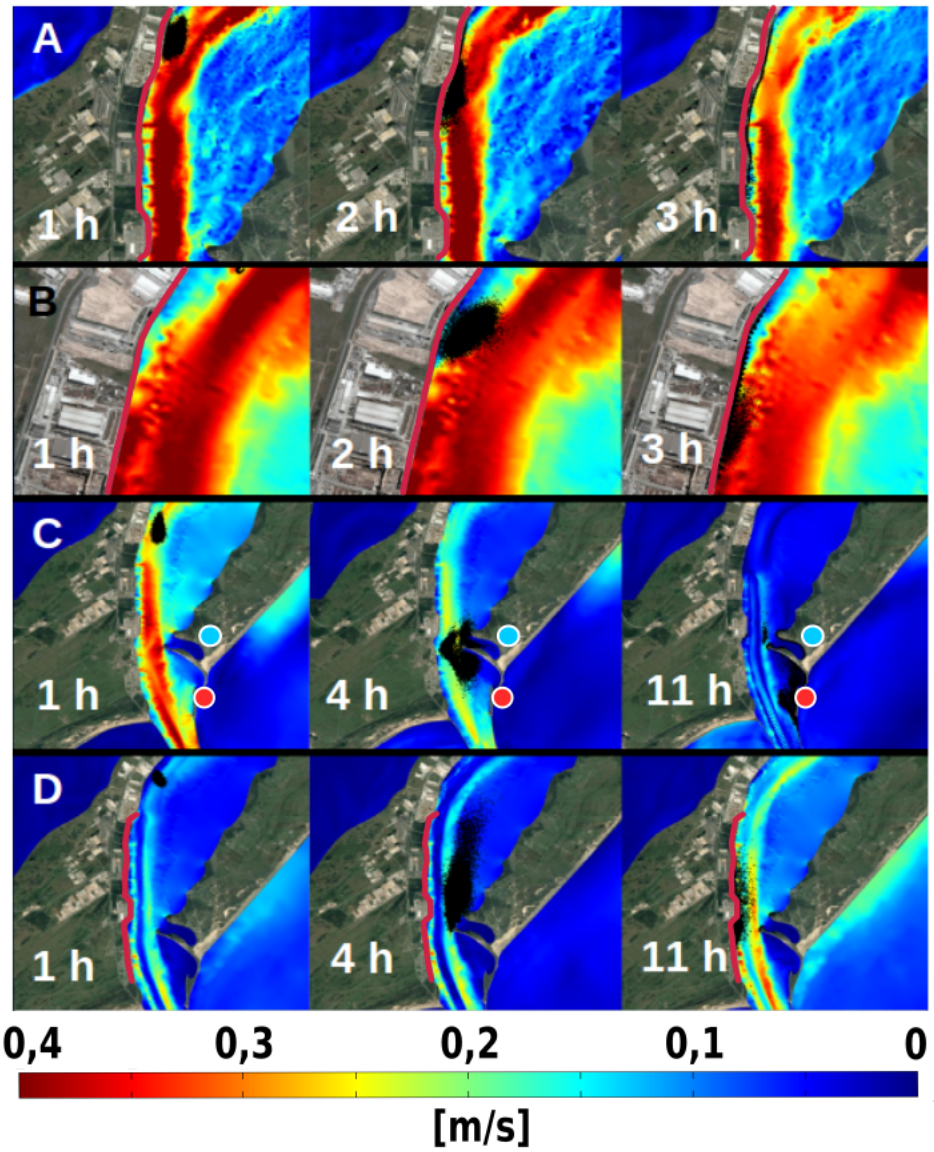

Figure 3: Simulation results of oil spill on ebb conductions A, B, C e D. The oil (black dots) is advected seaward in all events. The color scale shows the current magnitude (ms^{-1}), higher in the channel of the estuary

Figure 3 shows oil spills events (A, B, C and D) in ebb conditions, were seaward current is dominant at the starting hours of oil spill. After some hours, the wind begins to transport the oil to the channel margin. In all these events of oil spill during ebb conditions, transport to outside of the estuary was not observed.

The simulations of events A and B (Figure 3) have intense winds. This conditions cause the fast displacement of oil towards the port, reaching the margin. The impacts verified are the economic losses in the direct influence area, because the intense cargo transport or shipment in this location.

Events C and D (Figure 3) show similar characteristics, however the oil slick follows the currents by a distance of 6000 m before it is influenced by the winds. In the event C, the oil is transported to the east margin reaching the mouth at east jetties and Ponta dos Pescadores. During this event, the oil slick reaches the São José do Norte city and regions of salt marshes, that are important areas for artisanal fishing of Rio Grande city.

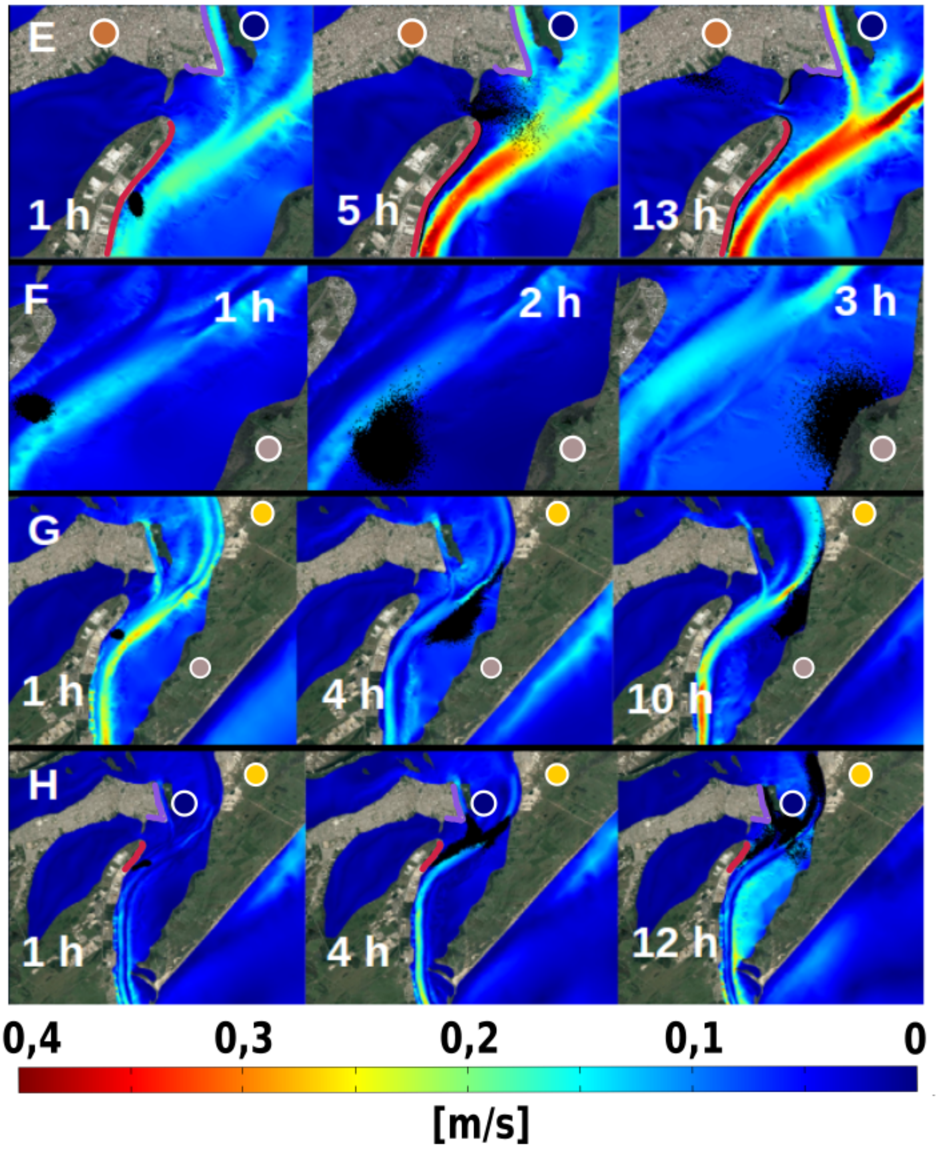

Figure 4: Simulation results of oil spill events on flood conductions E, F, G and H.

The salt marsh area was identified by Nogueira e Costa (2003) as more or less vulnerable to oil spilling, they are closely related to the point reached by the oil in the simulations for events C and D. In the event D, the oil is transported to the lower part of the Super Porto of Rio Grande city. Afterwards, the oil reaches the west margin. Direct impact and chronic contamination by the oil would influence the fishery and human health of the users of the estuary.

Figure 3 shows events (E, F, G and H) in flood conditions, where is observed the oil being transported towards the interior of the estuary following the current. Some hours after the oil spill, the south winds contribute to the transportation of the oil to the north side of the estuary.

Simulation E shows the oil reaching part of the Porto Novo of Rio Grande with the oil slick being transported by the dominant currents inside of Saco da Mangueira inlet. In the Saco da Mangueira, several economic activities are carried out as the suport to the industrial park of the Rio Grande city, shrimp fishing and leisure activities (Monteiro et al., 2006).

Simulations of events G and H shows similar behaviors, the oil is transported towards the estuarine region of the Patos Lagoon, reaching the Terraplena island, Porto Novo of Rio Grande and the urban zone of the São José do Norte. Direct impacts of the oil in this points would cause damages to the environment and to the human health through the consumption of fish.

As mentioned previously, the dangers of oil spill are diverse because the toxic effects of the oil composition. These results show several areas of the estuary reached by the oil, where the pattern of circulation promotes the permanence of the oil in the system.

CONCLUSION

The TELEMAC3D model showed capacity to simulate the pattern of currents and salinity in the Patos Lagoon estuary. The behavior of the oil spill simulated by the ECOS model could be used as a tool for environmental management and decision making in case of incidents involving oil spill in the Patos Lagoon.

The fate of oil slick in ebb scenarios investigated in this work have as major points the channel margin of the Super Porto of Rio Grande, the coastline parallel to the Ponta dos Pescadores area and in the mouth at east jetties, adjacent to São José do Norte city. In the flood scenarios investigated, the transport of the oil slick had a higher variability, being the Porto Novo of Rio Grande, the coastline of Rio Grande city, Terrapleno island and the São José do Norte city as the most frequent fate of the oil.

Once the pattern of ebb and flood are characterized, as the wind and currents effects over the oil trajectory, this article brought information about the fate of the oil reliable to orientation of response procedures in case of oil spill on transshipment area of the Porto of Rio Grande.

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