Uncertainty Analysis in Oil spill Modelling

Sensitivity and Forcing Analysis for a spill in the Portuguese Coast and Tagus Estuary

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ABSTRACT

Oil spill modelling has evolved throughout the last decades, triggered by increased oil consumption and exploitation that have resulted in large scale accidents and in the contamination of the marine environment. This study focuses on an uncertainty analysis for oil spill modelling. Models should not only provide a “best guess” estimate for the trajectory of the spilled oil but also a quantification of its uncertainty. This will provide a greater degree of confidence in numerical models for decision makers and make response team more efficient through the “minimum regret” concept.

To test the model uncertainty three approaches were tested: (1) a sensitivity analysis of the model parameters; (2) a forcing analysis to evaluate which parameter and forcing had the most impact on the slick properties; (3) the influence on the slick trajectory was assessed by comparing the evolution of the centre of mass with time in each scenario.

The sensitivity analysis in the four scenarios studied show that variations in the API gravity and reference viscosity had the most impact on the model results. Together with wind forcing they influenced results the most. Changes in the trajectory of the slick were mostly affected by the wind coefficient and spill site.

These impacts are important for oil spill response teams to adjust their behaviour and have a more efficient plan of action, mitigating the impacts of these spills.

Keywords: Oil spill modelling; Uncertainty analysis; Sensitivity Analysis; MOHID

1 INTRODUCTION

Oil spill trajectory models have been developed for years in response to concerns for pollution in the marine environment. With increasing consumption of oil across the world promoting oil exploration, the marine environment is facing a major long term threat (Mishra et al. 2015). Major accidents in the last decade, such as the Atlantic Express (1979), ABT Summer (1991) and more recently the BP Deep Horizon (2010), have highlighted the relevance of numerical models to aid in response efforts (Afenyo et al. 2015, ITOPF 2016). Numerical models are of utmost relevance since they not only reproduce the dynamics of the system in study but also because they predict the oil spill behaviour (Mateus et al. 2008).

In order to model oil spills correctly it is fundamental to understand the mechanisms that affect oil fate and trajectory, which can be extremely complex, these are governed by transport processes and oil weathering processes. Oil transport is achieved through spreading, dispersion and sedimentation and oil weathering happens due to evaporation, emulsification and dissolution, biodegradation and photo-oxidation (Afenyo et al. 2015). These processes interact amongst each other, inhibiting or enhancing their effect, contributing to the complexity of oil spill modelling. Oil weathering modifies oil properties significantly, namely oil density and viscosity. It is also important to note that the initial conditions of the spill also influence the evolution of the slick (Mishra et al. 2015). However, there are some uncertainties when modelling oil spill trajectories, namely in prediction motion, tendency for the oil to break into smaller slicks and information about initial and discharge conditions, that are not included in most oil spill modelling software available. Environmental factors also play a major role on the fate of an oil slick, by affecting the oil weathering processes, their occurrence or significance. (Lehr 2001).

Traditional oil spill trajectory models are deterministic and provide a “best guess” of oil movement and fate; nonetheless as scientific knowledge evolves it has become evident that some indication of the model uncertainty is necessary. Uncertainty arises from input and environmental data necessary for the model (NOAA 2002) but also depends on the length and time scale of the spill (Mishra et al. 2015).

The problematic of uncertainty associated with the prediction of the dispersion of hydrocarbons is the basis for this study. Decision making by response teams in a scenario where uncertainty is unknown decreases the level of confidence in numerical models. In that scenario it is only taken into account the most likely trajectory – if that solution turns out to be different from the truth actions become unsuccessful and confidence in these models tends to decrease.

Therefore a correct quantification of model uncertainty can contribute to a more effective and prompt response by the authorities. Additionally, it supports the development of probabilistic modelling. Afterwards contamination probability maps can be generated, these maps are very significant for authorities, allowing them to identify areas of “least regret” (areas where the probability of contamination is high enough to justify mitigation or response actions).

This paper starts by giving an overview of the methodology used, explaining the software used, the study area and analysis performed. Then the main results are presented and discussed. Final conclusions are presented at the end of this paper.

2 METHODS

2.1 OVERVIEW

A sensitivity and a forcing analysis were carried out to comprehend in greater detail the MOHID oil spill model used and its sensitivity to parameters and forcing. For that purpose, an oil spill was modelled in two settings, first in the Portuguese coast and then on the Tagus estuary, each with two scenarios: upwelling and western wind and neap tide and spring tide scenarios, respectively. Changes in the wind coefficient and spill site were also performed to assess the model behaviour. The forcing analysis and changes in wind coefficient and spill site were carried out in the first scenario and setting, only where the oil slick does not reach the coastline and therefore where its movement is not influenced by the shoreline, facilitating the interpretation of the results.

Regarding model outputs the evolution of selected oil properties was analysed, in combination with the evolution of the centre of mass, for the sensitivity analysis an index was calculated to quantify the impact of the parameters in the output variables, when this index was not possible to calculate a simple difference was computed and compared with results obtained previously.

2.2 MOHID

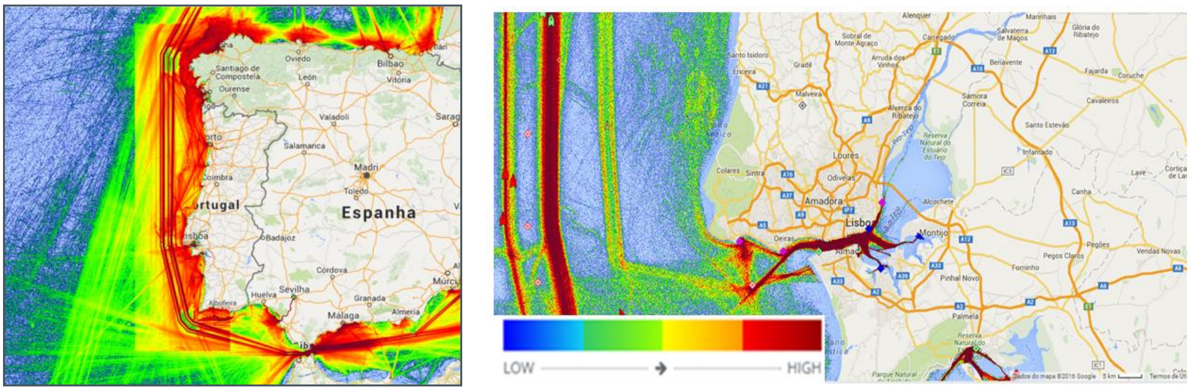
MOHID was used to perform simulations of oil spreading and weathering, it is an open-source geo-physical circulation model bases at MARETEC, a research group at IST. It is a free-surface baroclinic model that uses the hydrostatic approximations and a rotating Cartesian reference frame with angular rotation rate following the seminal primitive ocean equations. MOHID provides solution for the advection-diffusion of temperature, salinity and horizontal momentum equations. It also solves the continuity equations to determine vertical velocity, water elevation; density is calculated using the UNESCO state equation as a function of salinity, temperature and pressure (Mateus et al. 2012).

This model is written in ANSI-FORTRAN 95 and is more then sixty modules and over 300 000 lines of code. Each module has a specific task and belongs to one of four main groups: modules related with the description of the computational grid; modules that manage data input and output; modules responsible for boundary conditions; modules that change the models state variables. This software has a baroclinic hydrodynamic module for the water column and a 3D module for the sediments and corresponding eulerian transport and lagrangian transport modules. Other parameters and processes have specific modules such as turbulence, water content, ecology or transformation module.

To study the trajectory of the spilled oil is assumed that oil can be considered a large set of small particles, which implies the use of a tracer's model. These particles move by advection, diffusion and spreading specific to oil slicks. The MOHID oil spreading feature is based mainly in three sub-models: one for the evolution of properties and oil specific properties; a hydrodynamic module to calculate wind or wave induced velocity fields; lagrangian module that computes the oil particles spatial evolution based on currents velocity, wind drift, oil spreading and also the random velocity that represents diffusive transport.

2.3 STUDY AREA

For this study two settings were defined, the western part of the Portuguese coastal zone and the Tagus estuary. Both areas were selected for their relevance, namely economic, social and environmental importance. The first setting has an average of 55 000 commercial vessels per year crossing this zone, which is a mandatory passage point between the Mediterranean Sea and Northern Europe or the American Continent (Fernandes et al. 2016). The Tagus Estuary had almost 3 000 ships dock in the Port of Lisbon in 2012, which represents more than 10 000 million tonnes of cargo and 500 000 passengers (Sá Pereira et al. 2014). Figure 1 (A) and (B) shows the average ship densities in the first and second setting respectively and confirms that these areas have an intense ship traffic.



(A)

(B)

FIGURE 1 – AVERAGE SHIP DENSITY IN 2014 IN (A) THE PORTUGUESE COAST (B) THE TAGUS ESTUARY (WWW.MARINETRAFFIC.COM)

2.4 LAGRANGIAN TRANSPORT MODEL

This study was developed using the MOHID software described in section 2.2, the simulations were made through the oil spill fate and behaviour component integrated with the lagrangian transport model. This model has the ability to run integrated with the hydrodynamic solution or coupled with metocean models. The latter option was selected to optimize computational efficiency, taking advantages of models previously run.

The models used to obtain current and water properties and atmospheric conditions where the PCOMS-MOHID (Mateus et al. 2012) model, a 3D hydro-geochemical model for the Iberian western Atlantic region, and the MM5 model, which is used as atmospheric forcing of the PCOMS (Payne et al. 1984). The wave parameters necessary for the first setting were obtained from the Portuguese wave forecasting system implemented at MARETEC, the WaveWatch III.

2.5 SENSITIVITY ANALYSIS

Sensitivity analysis (S.A.) is a common approach to identify parameters which have a greater influence on the model behaviour. First a reference simulation was modelled to have a benchmark to compare model results. Then each parameter listed in Table 1 was varied by $\pm 10\%$, as suggested by (Stiver et al. 1984, Fingas et al. 1993), sequentially in separate runs, while holding all other terms constant. To evaluate the sensitivity of the model some variables were selected (Table 1) based mainly in two factors: The first relates to trajectory analysis and second with the usefulness to emergency responders in clean-up strategies.

TABLE 1 – MODEL PARAMETERS CHOSEN FOR THE S.A. AND MODEL OUTPUTS EVALUATED IN THE S.A.

Parameters	Variables	
API gravity [-]	Slick Area [m^2]	Trajectory [-]
Pour Point [^oC]	Slick Volume [m^3]	Tracers Position [-]
Reference Viscosity [cP]	Oil Volume [m^3]	Mass Dispersed [kg]
Resin Content [%]	Oil thickness [mm]	Mass Evaporated [kg]
Saturate Content [%]	Density [kg/m^3]	Mass Water Content [%]
Asphaltenes Content [%]	Viscosity [cP]	

A sensitivity index was used to quantify the changes in the model results; the criteria to select the index were simplicity and ability to quantify normalized sensitivity and also the nature of the variation. The normalized sensitivity index proposed by Mateus (2015) is defined as the relative change in model output divided by the relative change in the parameter value (Equation [1]):

$$S_{(p)} = \frac{\left(V_{(p)} - V_s\right)/V_s}{(p - p_s)/p_s}, \qquad [1]$$

where V stands for the value of the variable; p is the parameters value. The lower index s represents the standard case value.

The index computes a positive or negative result that according to the parameter variation indicate either a negative impact on the model results, lower values are obtained when compared with the reference run, or a positive impact on the model results (Table 2). If the result obtained is greater then 0.1 means that the model is sensitive, and a variation of more then 1% in the model results; if it is larger then 1 the model is highly sensitive and has a variation of more than 10%; if is larger than 10 the model is extremely sensitive and results change more than 100% when compared with the reference.

TABLE 2 – SENSITIVITY INDEX INTERPRETATION

	Positive index Value	**Negative Index Value**
Negative Variation (-10%)	Negative Impact Lower value then reference	Positive Impact Larger value then reference
Positive Variation (+10%)	Positive Impact Larger value then reference	Negative Impact Lower value then reference

2.6 WIND COEFFICIENT AND DISCHARGE LOCATION

Wind coefficient and spill location are relevant parameters for oil spill modelling and have large uncertainties associated with them. Therefore a similar analysis as the one explained earlier was carried out, varying one parameter at the time keeping all other values constant and comparing the results with the reference run. The wind coefficient was varied to 0.02 and 0.04 and the spill site was changed to 1 km north, south, east and west.

2.7 FORCING ANALYSIS

To perform this analysis the input meteorological files were modified and multiplied by factors to induce a $\pm 20\%$ change in the components found to be more relevant. This percentage was selected since it is an error common for the meteorological and wave models, even though the latter usually has larger errors, it is assumed that they have the same magnitude of error in this study. Changes were done one component at the time, keeping all other model parameters unchanged. Table 3 lists wind and wave components that were changed.

TABLE 3 – COMPONENTS EVALUATED WITH THE FORCING ANALYSIS

Wind components	**Wave Components**
Wind velocity, x component	Wave height
Wind velocity, y component	Wave period

3 RESULTS AND DISCUSSION

In the Portuguese coast two scenarios were used, the first in an upwelling event and second in a westerly wind, both with a 7-day duration. On the Tagus estuary two scenarios were also proposed, first a neap tide scenario then a spring tide scenario.

3.1 SENSITIVITY ANALYSIS

For the Portuguese coast in an upwelling event Table 4 shows the model sensitivity to those variations. Variations in the API parameter resulted in a variation of more than 1% for most variables (green) and more than 10% for viscosity. Reference viscosity impacted a fewer number of variables, but resulted in changes of more then 10% in the models results for mass dispersed and viscosity.

TABLE 4 – SENSITIVITY INDEX FOR THE PORTUGUESE COAST IN AN UPWELLING SCENARIO (GREEN – SENSITIVE MODEL; ORANGE – HIGHLY SENSITIVE MODEL | + – POSITIVE SENSITIVITY INDEX; - – NEGATIVE SENSITIVITY INDEX)

	API gravity		Pour Point		Reference Viscosity		Resin Content		Saturate Content		Asphaltenes Content	
	+10%	-10%	+10%	-10%	+10%	-10%	+10%	-10%	+10%	-10%	+10%	-10%
MassOil	🟩 -	🟩 +			+	-						
VolumeOil	🟩 -	🟩 +			+	-						
Volume	🟩 -	🟩 +			+	-						
Area	🟩 +	🟧 -										
Thickness	🟧 -	🟧 +			+	-						
MEvaporated	🟩 +	🟩 -										
MDispersed	🟩 -	🟩 +			🟧 -	🟧 +						
MWaterContent	+	-										
Density	-	+										
Viscosity	🟧 +	🟧 -			🟧 +	🟧 -						

Table 5 shows that for a western wind scenario the model was found to be sensitive to most changes of the API parameter, apart from viscosity, and mass dispersed and volumes for positive variations of the API gravity. Changes in the reference viscosity had the same results as the previous scenario, highly sensitive model with regards to mass dispersed and viscosity.

TABLE 5 - SENSITIVITY INDEX FOR THE PORTUGUESE COAST IN A WESTERN WIND SCENARIO

	API gravity		Pour Point		Reference Viscosity		Resin Content		Saturate Content		Asphaltenes Content	
	+10%	-10%	+10%	-10%	+10%	-10%	+10%	-10%	+10%	-10%	+10%	-10%
MassOil	🟩 -	🟩 +			+	-						
VolumeOil	🟧 -	🟩 -			+	-						
Volume	🟧 -	🟩 -			+	-						
Area	🟩 +	🟩 -										
Thickness	🟧 -	+			+	-						
MEvaporated	🟩 +	🟩 -										
MDispersed	🟧 -	🟩 +			🟧 -	🟧 +						
MWaterContent	+	-										
Density	-	+										
Viscosity	🟧 +	🟧 -			🟧 +	🟧 -						

The perturbations on the oil parameters presented above even though had an impact on the slick properties showed no impact on the trajectory of the spilled oil.

Table 6 and shows similar results for the Tagus estuary in a neap tide scenario, API gravity resulting in 1% to 10% changes in model results for most variables and reference viscosity showing that the mass dispersed and viscosity had a change of more than 10% in the final result, oil volume and volume had changes of more then 10% and 100% for positive and negative perturbation of the reference viscosity, respectively.

TABLE 6 - SENSITIVITY INDEX FOR THE TAGUS ESTUARY IN AN NEAP TIDE SCENARIO (GREEN – SENSITIVE MODEL; ORANGE – HIGHLY SENSITIVE MODEL; RED – EXTREMELY SENSITIVE MODEL | + – POSITIVE SENSITIVITY INDEX; - – NEGATIVE SENSITIVITY INDEX)

	API gravity		**Pour Point**		**Reference Viscosity**		**Resin Content**		**Saturate Content**		**Asphaltenes Content**	
	+10%	-10%	+10%	-10%	+10%	-10%	+10%	-10%	+10%	-10%	+10%	-10%
MassOil	🟩 -	🟩 +			+	+						
VolumeOil	🟧 +	🟩 +			🟧 +	🟥 +						
Volume	🟧 +	🟩 +			🟧 +	🟥 +						
Area	🟩 +	+										
Thickness	🟧 +	🟩 +			🟧 +	🟥 +						
MEvaporated	🟩 +	🟩 -			+	🟩 -						
MDispersed	🟧 -	🟩 +			🟧 -	🟧 +						
MWaterContent	+	-			+	-						
Density	-	+			+	-						
Viscosity	🟧 +	🟧 -			🟧 +	🟧 -						

For the last scenario and setting it is observed that the model is sensitive for API variations for most variables and highly sensitive for mass evaporated and viscosity. Changes in reference viscosity showed a highly sensitive model with regards to oil volume and volume, as well as mass dispersed and viscosity.

TABLE 7 - SENSITIVITY INDEX FOR THE TAGUS ESTUARY IN A SPRING TIDE SCENARIO

	API gravity		**Pour Point**		**Reference Viscosity**		**Resin Content**		**Saturate Content**		**Asphaltenes Content**	
	+10%	-10%	+10%	-10%	+10%	-10%	+10%	-10%	+10%	-10%	+10%	-10%
MassOil	🟩 -	🟩 +			-	-						
VolumeOil	🟩 -	🟩 +			🟧 +	🟧 +						
Volume	🟩 -	🟩 +			🟧 +	🟧 +						
Area	🟧 +	🟩 -										
Thickness	🟧 -	🟧 +			🟧 +	🟧 +						
MEvaporated	🟧 +	🟧 -			+	+						
MDispersed	🟩 -	🟩 +			🟧 -	🟧 +						
MWaterContent	+	-			+	-						
Density	-	+			+	+						
Viscosity	🟧 +	🟧 -			🟧 +	🟩 -						

3.2 WIND COEFFICIENT AND SPILL LOCATION

The study on the impact of variation in spill site and wind coefficient was performed only in the Portuguese coast in the upwelling event since it is the only scenario where oil does not reach the shoreline, and therefore oil movement is not influenced by it.

These changes had some impact with regards to oil slick properties and weathering that are going to be compared with the results obtained for the other variations in the end of this section.

However changes in wind coefficient and spill site had a significant impact on the trajectory of the spilled oil, mainly with wind coefficient set to 0.02 and 1km north, with average changes in latitude of around 0.232 and 0.221 respectively (Figure 3). Changes in longitude were 0.139 and 0.127 for wind coefficient equal to 0.02 and 1km north changes respectively (Figure 2).

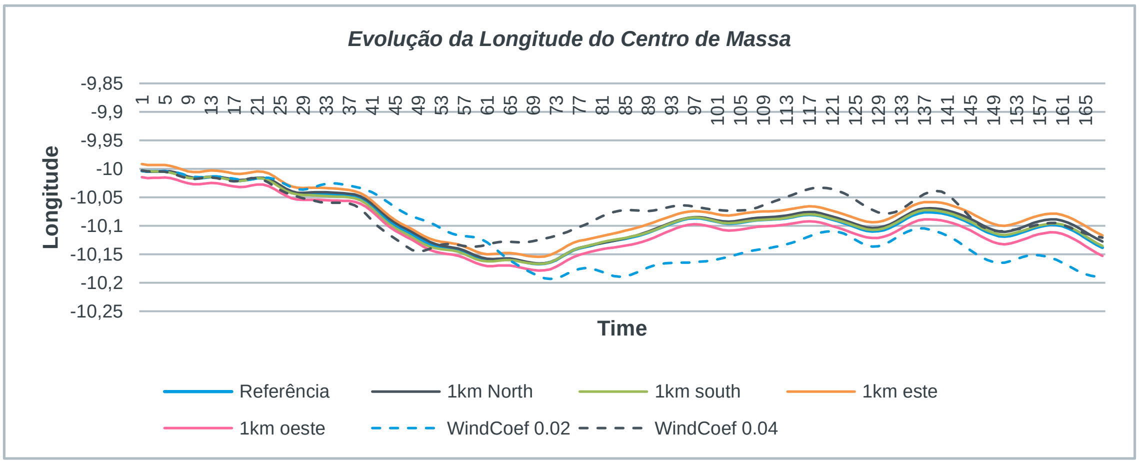


FIGURE 2 – EVOLUTION OF THE CENTRE OF MASS LONGITUDE IN THE ANALYSIS TO WIND COEFFICIENT AND SPILL SITE LOCATION.

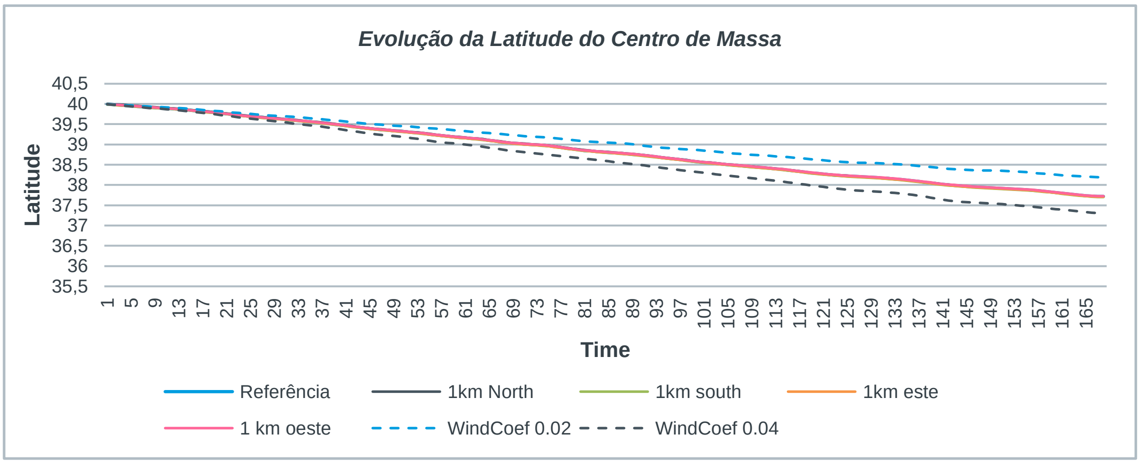


FIGURE 3 – EVOLUTION OF THE CENTRE OF MASS LATITUDE IN THE ANALYSIS TO WIND COEFFICIENT AND SPILL SITE LOCATION

3.3 FORCING ANALYSIS

Changes in components of wind and wave forcing showed some impact on the trajectory of the oil slick, but in smaller scales then in the previous section. Wind and wave forcing showed a significant impact in the model results evaluated, namely on oil mass, mass evaporated and dispersed, total volume and oil volume as well as in the area of the slick.

3.4 TRAJECTORIES

Figure 4 shows the main simulations that affected the trajectory of the oil slick, namely Wind coefficient equal to 0.02, spill site 1 Km north and wind forcing (y component of the velocity). The first image shows the reference run after the time period analysed, the following ones show the simulations that affected the slick trajectory the most, namely wind coefficient, changes in spill site, wave and wind forcing (left to right).

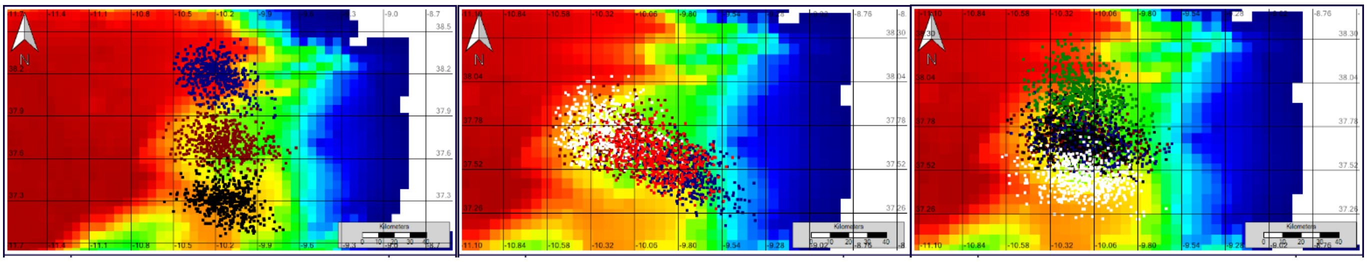


FIGURE 4 – COMPARISON OF SLICK TRAJECTORY AMONGST SIMULATIONS

4 DISCUSSION

The sensitivity analysis showed similar results for both the Portuguese coast and Tagus estuary, with variations in the API gravity and Reference viscosity resulting in the most significant impacts. API gravity perturbations showed that most variables had more than 1% change in its results when compared to the reference value, viscosity had a change of more than 10%. Reference viscosity however impacted a fewer number of variables, but resulted in most cases in changes of more than 10%.

Comparing the results obtained for the different analysis it can be concluded that the API gravity has the most impact on the selected variables, together with the y component of the wind velocity.

The influence of the variations of model parameters in the S.A. on the oil slick trajectory was assessed and found to be insignificant, however other parameters, such as wind coefficient had a great impact on the trajectory of the oil tracers. Wind and wave forcing also showed a significant influence in the spilled oil trajectory. The parameter that had the most effect on the spilled oil trajectory was the wind coefficient (when equal to 0.02), followed by changes in the spill site.

5 CONCLUSIONS

The objective of this research was analysing the uncertainties that arise from oil spill modelling. For that purpose, it was suggested a sensitivity analysis, which measures the responsiveness of the model outputs to variations of model parameters, that are sometimes uncertain in the first hours of spill response and may influence results. Since forcing can influence greatly an oil slick it was proposed a forcing analysis. In the two analyses mentioned the evolution of the centre of mass was presented.

It was concluded that the oils most important parameter, the one that influenced the models results the most was the API gravity. Wind forcing, namely the y component of the wind velocity, and wind coefficient, when equal to 0.02, also had a great impact on the properties of the oil slick.

The initial location of the spill can also be uncertain and simulations where performed to assess its influence as expected on the trajectory of the oil. Wind and wave forcing also showed an impact on the trajectory of the spilled oil, however the most significant changes were with wind coefficient and spill site.

The analysis suggested were successful in pointing out which parameters were more relevant even though the quantification of the models sensitivity was not possible at times. They indicate that the model prediction of the trajectory and state of the oil is fallible if uncertainty is not taken into account.

In the future oil spill modelling should be coupled with probabilistic modelling, with uncertainty measures or confidence intervals associated with the results. Probability maps can also be generated; these maps identify areas of least regret making them useful for response teams.

6 REFERENCES

Afenyo, M., B. Veitch and F. Khan (2015). "A state-of-the-art review of fate and transport of oil spills in open and ice-covered water." Ocean Engineering.

Fernandes, R., F. Braunschweig, F. Lourenço and R. Neves (2016). "Combining operational models and data into a dynamic vessel risk assessment tool for coastal regions." Ocean Science 12: 285-317.

Fingas, M. F., D. A. Kyle and E. J. Tennyson (1993). "Physical and Chemical Studies on Dispersants: The effect of Dispersant Amount and Energy." Environment Canada.

ITOPF (2016). "Oil Tanker Spill Statistics 2015."

Lehr, W. J. (2001). Review of modeling procedures for oil spill weathering behavior. Advances in Ecological Sciences. 9: 51-90.

Mateus, M. and R. Fernandes (2008). Modelling Pollution: Oil spills and faecal contamination. I. Press: 89-102.

Mateus, M., G. Riflet, P. Chambel, L. Fernandes, R. Fernandes, M. Juliano, F. Campuzano, H. de Pablo and R. Neves (2012). "An operational model for the West Iberian coast: products and services." Ocean Science 8(4): 713-732.

Mishra, A. K. and G. S. Kumar (2015). "Weathering of Oil Spill: Modeling and Analysis." Aquatic Procedia 4: 435-442.

NOAA (2002). Trajectory Analysis Handbook. N. O. Service.

Payne, J. R., B. E. Kirstein, G. D. McNabb, J. L. Lambach, R. Redding, R. E. Jordan, W. Hom, C. de Oliveira, G. S. Smith, D. M. Baxter and G. R. (1984). "Multivariate analysis of petroleum weathering in the marine environment." Sub arctic. Environment Assessment of the Alaska Continental Shelf 22.

Sá Pereira, M. T. and A. R. Silveira Ramos (2014). "The port of Lisbon, Portugal: Maintenance dredging in a sensitive environment." Terra et Aqua 134.

Stiver, W. and D. Mackay (1984). "Evaporation rate of spills of hydrocarbons and petroleum mixtures." Environmental Science & Tecnhology 18(11): 834-840.