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IT-OSRA: applying ensemble simulations to estimate the oil spill risk associated to operational and accidental oil spills

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Abstract Oil Spill Risk Assessments (OSRAs) are widely employed to support decision making regarding oil spill risks. This article adapts the ISO-compliant OSRA framework developed by Sepp Neves et al. (J Environ Manag 159:158–168, 2015) to estimate risks in a complex scenario where uncertainties related to the meteo-oceanographic conditions, where and how a spill could happen exist and the risk computation methodology is not yet well established (ensemble oil spill modeling). The improved method was applied to the Algarve coast, Portugal. Over 50,000 simulations were performed in 2 ensemble experiments to estimate the risks due to operational and accidental spill scenarios associated with maritime traffic. The level of risk was found to be important for both types of scenarios, with significant seasonal variations due to the the currents and waves variability. Higher frequency variability in the meteo-oceanographic variables were also found to contribute to the level of risk. The ensemble results show that the distribution of oil concentrations found on the coast is not Gaussian, opening up new fields of research on how to deal with oil spill risks and related uncertainties.

Keywords ISO 31000, Oil spill risk assessment, Ensemble oil spill modeling, Algarve, MEDSLIK-II

1 Introduction

The U.S. National Academy of Sciences (US National Research Council (2009)) estimates that every year over 600,000 t of oil are spilled into the marine environment due to human activities. Operational discharges associated with maritime traffic (e.g., tank washing or leakage of lubricants) account for over 270,000 t/year, ranking as the main anthropic input of oil into the marine environment. Vessel-related accidental spills (e.g., collisions, explosions) account for about 100,000 t/year. Despite international efforts in reducing the oil pollution, spills still occur and it is not possible to predict when, where, or how they will happen. Oil Spill Risk Assessments (OSRAs) have been carried out in several parts of the globe to deal with such uncertainty, which can then be used to support decisions for the protection of the marine and coastal environments.

Based on a review of several OSRAs, in a previous paper (Sepp Neves et al. 2015), we proposed a new OSRA framework by tackling the main shortcomings: (1) the role of the principle cause of oil pollution in the sea, operational spills, had been neglected and therefore, remained unknown; (2) uncertainties in the risk estimations had been often disregarded or not properly addressed in the literature; and (3) no standard framework for OSRA had yet been adopted. The core of our risk computation methodology presented in Sepp Neves et al. (2015) lies in ensemble oil spill simulations covering the most likely spill scenarios for the area of interest. The outputs of the risk analysis are delivered in a probabilistic way accompanied by additional information regarding the uncertainties of the estimates.

In the present article, we take our methodology one step further by applying it to complex risk scenarios arising from operational and accidental oil spill events. Unlike previous attempts to assess the risk (e.g., Alves et al. (2014), Goldman et al. (2015), and Canu et al. (2015)), uncertainties regarding the characteristics of a possible spill and the model setup were addressed in addition to uncertainties in time and location. Our improved methodology, hereinafter referred to as Information Technology Oil Spill Risk Assessment (IT-OSRA), uses numerical model simulations to build statistically significant data sets for hazard and uncertainty estimations. Advanced techniques are used to simulate output data processing together with statistical techniques to extract the underlying general characteristics of the phenomena of interest.

IT-OSRA was applied to the Algarve coast, southern Portugal, a region with high vulnerability to oil (Frazão Santos et al. 2012) and exposed to a busy maritime route where about 200 million tonnes of oil flow through every year (ITOPF - International Tanker Owners Pollution Federation 2013). Two ensemble experiments covering accidental and operational spills, with 25,600 simulations each and 51,200 simulations in total, addressing the major sources of uncertainty were carried out in order to estimate the hazards. These were then combined with coastal vulnerability information in order to quantify the oil spill risk. Useful information to support future risk management decisions was also generated.

This article is organized as follows: the background on the meteo-oceanographic conditions in the Algarve is presented in Section 2 followed by a description of the data and models used to compute the oil spill risk in Section 3. The IT-OSRA is applied to the Algarve in Section 4. Final remarks highlighting the most important achievements of this work are presented in Section 5.

2 Meteo-oceanographic background

The average Stokes drift derived from SKIRON wind fields (see De Dominicis et al. (2013a)) and surface currents for 2013 computed by the IBI model (see Section 3.2 for further details on the ocean and atmospheric models employed in the experiment) are presented in Fig. 1. Surface currents off the west coast follow the coastline orientation, flowing southward with velocities between 10 and 20 cm/s. South of the Cape Sao Vicente, the flow splits, with one coastal branch rotating toward the Gulf of Cadiz and an offshore branch toward S-SW, as observed by García-Lafuente et al. (2006) who employed in situ current measurements. Far offshore, currents have a northward pattern in the west coast, in agreement with Relvas et al. (2007). Average Stokes drift for the same period clearly show an area of stronger southward currents off the western coast (approx. 4 cm/s). Closer to the shore, the drift deflects to SE reducing in intensity. The south coast, due to limited fetch and lower wind intensities, shows a very small drift, with values below 2 cm/s.

Winter and autumn in the Algarve are periods of high atmospheric variability. Fiúza et al. (1982) and Relvas et al. (2007) described the wind regime during these seasons as south-easterlies with episodic perturbations due to the passage of frontal systems resulting in the temporary

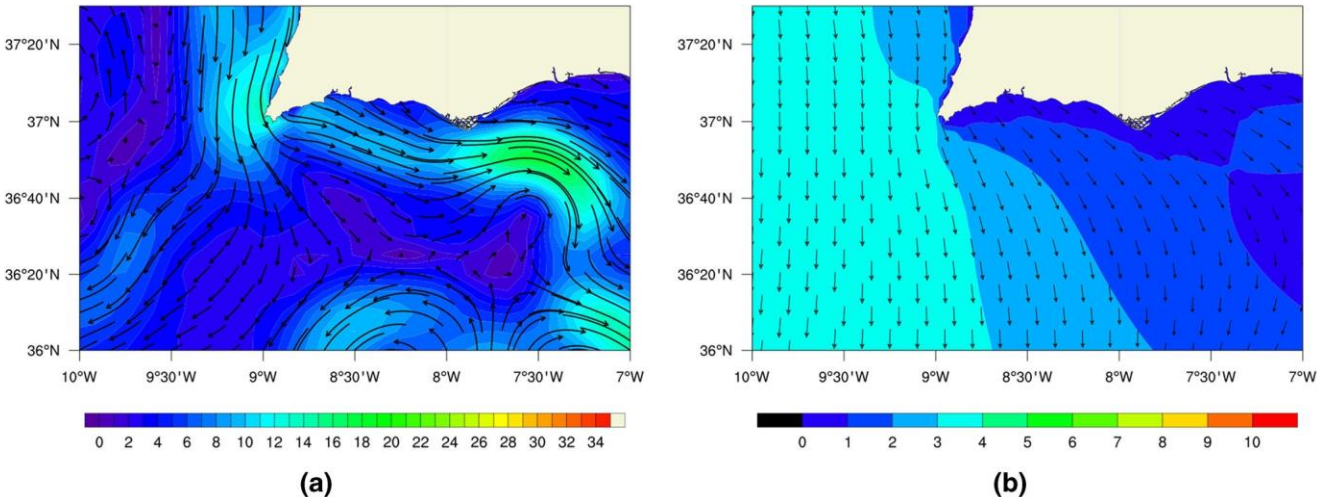


Fig. 1 Averaged (**a**) surface currents from IBI model outputs and (**b**) Stokes drift for the year of 2013 calculated by MEDSLIK-II oil spill model with SKIRON winds. In cm/s

prevalence of easterlies. During events of easterly winds, waves from SE with significant wave height between 1 and 2 m (Nunes et al. 2009) are generated in the Gulf of Cadiz mainly affecting the southern Algarve. Easterly winds also generate reversions in the average eastwards circulation in the southern Algarve shelf (Criado-Aldeanueva et al. 2006; García-Lafuente et al. 2006).

In summer, mesoscale features tend to dominate the local surface circulation in the Algarve (Relvas et al. 2007; Álvarez Salgado et al. 2003), with the development of strong upwelling events on the west coast and, less frequently, in the south coast forced by the northerly winds. Filaments associated with strong upwelling events export upwelled waters over 250 km offshore with velocities of up to 50 cm/s (Relvas 2002; Relvas et al. 2007). During periods of upwelling relaxation, a strong coastal counter-current takes place in the southern shelf, transporting warm waters from the Gulf of Cadiz eastwards in the southern shelf with velocities of up to 20 cm/s, turning northward at the Cape Sao Vicente and increasing in intensity with values of up to 30 cm/s (Fiúza et al. 1982; Relvas 2002).

3 Experimental framework

In IT-OSRA, the risk and its uncertainties are quantitatively estimated based on oil spill ensemble experiments. A range of spill scenarios (ensemble members) were simulated using numerical oil spill modeling fed with operational meteo-oceanographic inputs (winds and currents) to predict the likely trajectory of eventual spills. In the following subsections, information regarding the data set employed to carry out the ensemble experiments in the Algarve and a the setup of the experiment itself are presented.

3.1 Oil spill model

MEDSLIK-II is an open source three-dimensional Lagrangian oil spill model that predicts time changes in the state of the slick and in the volume and position of particles. Changes in the slick state are controlled by weathering processes, namely emulsification, spreading, dispersion, and evaporation. The particles that reach coastal segments are considered as beached with the possibility of being washed back depending on the coastal type. A complete description of MEDSLIK-II model is presented in De Dominicis et al. (2013a).

Prior to the experiment, MEDSLIK-II was set up based on the best tuning defined by De Dominicis et al. (2013b). As recommended by the authors, winds were not included in the analysis as a correction coefficient but as an input for the analytic computation of the Stokes drift implemented in MEDSLIK-II.

3.2 Eulerian wind and current models

One year (2013) of daily three-dimensional current and hourly 10-m wind analyses (covering the area 11° E to 6° E/35° N to 39° N) were used as input for MEDSLIK-II in the ensemble experiments. Two operational ocean circulation models, freely available on the Marine Copernicus portal (*marine.copernicus.eu*), were employed to deliver current data. The MERCATOR system, based on the NEMO v2.4 model, delivers global daily fields of the main oceanographic fields in 50 vertical levels and with a 1/12 of a degree spatial resolution. The system assimilates sea surface temperature, sea level anomalies observations, temperature and salinity profiles, and sea ice concentration (Lellouche et al. 2013). The IBI system, also based on the NEMO model, receives initial and boundary conditions from the MERCATOR system and covers the Iberia-Biscay-Ireland regional seas with a 1/36 of a degree spatial resolution and 50 vertical levels. No data assimilation is performed by the IBI system (Cailleau et al. 2012).

Hourly winds with a 0.05° spatial resolution were obtained from the SKIRON/Eta system (Kallos et al. 1997). The model covers the whole Mediterranean basin and surroundings and receives initial and boundary conditions from the NCEP/GFS system. The SKIRON wind fields were used to compute the Stokes drift in the Algarve using the formulation implemented by De Dominicis et al. (2013a).

A 1-year meteo-oceanographic data set may not be long enough to sample all the current variability frequencies. However, this does not invalidate the experiment, which focus on improving the methodology to compute the oil spill risk mapping for a limited time frame, i.e., 2013.

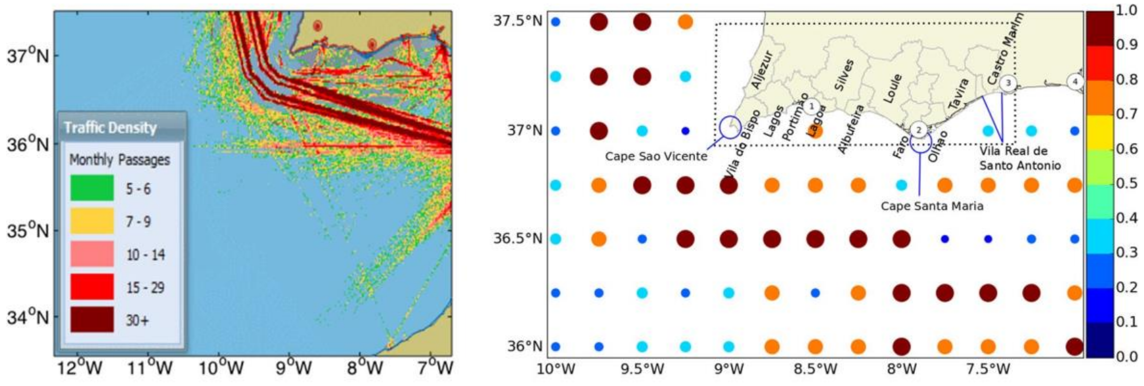
3.3 Traffic density map

The maritime traffic density map for the Algarve was made available by the Portuguese Institute of Maritime Transportation and Ports and it is based on one month AIS data for all vessel types. There are four main ports in the Algarve and surrounding area (Portimao, Faro, Huelva, and Ayamonte), and these ports thus increase the maritime traffic density in the coastal areas (Fig. 2a).

Based on the maritime traffic density data, five density levels were applied in terms of the number of passages per month: 5–6, 7–9, 10–14, 15–29, and 30 or more. The five levels proposed were translated into a traffic indicator that represents the probability of a vessel being at a given coordinate in the area, P_t, and is defined by:

$$P_t = \frac{N}{M} \tag{1}$$

where N is the number of passages in the sampled period (March 2013) and M is the number of sampled days (i.e.,



(a) (b)

Fig. 2 **a** AIS maritime traffic density map for March, 2013 in number of passages per month and (**b**) P_t index for each release point. In (**b**), the size and the color of the circles represent the maritime traffic density. The four main harbours in the study area—Portimao (1), Olhao (2), Ayamonte (3), and Huelva (4)—were signed with *white circles*. Two reference points, Cape Sao Vicente and Cape Santa Maria, were circled in the map. *Black rectangle* highlights the Algarve region

31). When N was given as a range (e.g., 10–12), the "mean" was employed (i.e., 11). P_t was calculated for 70 points in the study area that later corresponded to oil release sites for the ensemble experiments employed to compute the oil spill risk. The maritime traffic density map and the assigned weights are presented in Fig. 2. The main ports and reference points in the area are indicated in the maps.

3.4 Coastal vulnerability

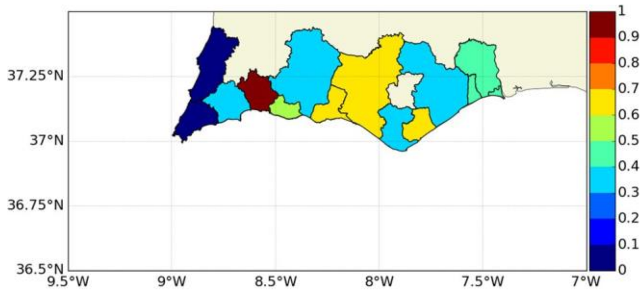
The vulnerability of the Portuguese coast to oil spills was quantified by Frazão Santos et al. (2012) at the municipality level (Fig. 3), and was defined as a composite indicator with ecological and socioeconomic dimensions. The relatively coarse spatial resolution of the indicator is mainly due to the availability of social-economic data. Three variables were considered in the ecological dimension: shoreline type, length of the shoreline considered as national protected areas, and extension of the shoreline considered as NATURA 2000 network site. Six variables were considered in the socioeconomic dimension: population living in coastal settlements, land used for tourism, accommodation capacity per thousand inhabitants, berths for recreational boating, number of fishing vessels, and number of registered fishermen. For each dimension, the coastal municipalities are scored in a relative scale ranging from 0 to 1, where 0 is the lowest vulnerability level and 1 is the maximum observed. Further discussions regarding the weighting criteria can be found in Frazão Santos et al. (2012).

As stated by Frazão Santos et al. (2012), the vulnerability index was created to show spatial relative differences among the municipalities. Therefore, prior to the calculation of the risk in the Algarve, the vulnerability dimensions were normalized by the maximum values found in the area.

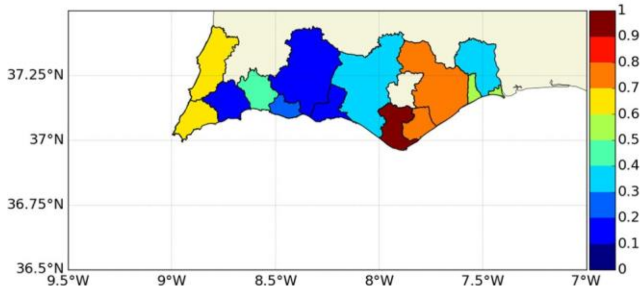
3.5 Ensemble experiment setup

The ensemble experiments and their members were designed to encompass the main sources of uncertainties identified in oil spill events:

1. Where the spill would happen.
2. The meteo-oceanographic conditions at the moment of the spill.
3. Oil spill characteristics/oil spill model setup.



(a) Socioeconomic dimension



(b) Ecological dimension

Fig. 3 Socioeconomic (**a**) and ecological (**b**) dimensions of the coastal vulnerability to oil of the Algarve

Based on a qualitative evaluation of the current field variability in the area, a 1/4 of a degree resolution grid with 70 release points (RPs), r_n, covering the main shipping corridors in the Algarve (Fig. 2b) was created to address (1). The relatively coarse resolution of the release grid respects the spatial resolution of the current fields used in the experiment, thus safeguarding the independence of the simulations. For each RP, 300h-long oil spill simulations were carried out every 10 days throughout 2013. The duration was set based on the worst case scenario where a spill occurs at the eastern part of the domain and is transported along the coastline by an overall westward flow crossing the whole study area. It was assumed that most of the possible combinations of currents and winds were covered, thus addressing (2).

Finally, ten ensemble members covering different oil spill characteristics and model setups were run at each RP every 10 days addressing (3). In total, 51,200 oil spill simulations were performed. The ensemble members were chosen to include the major uncertainty in the model parametrizations. Although this choice is not exhaustive, it nevertheless covers a reasonable range of scenarios in the literature (see references below). The proposed members in the accidental experiment covered:

- Two volumes of oil spilled: 10,000 t, representing the most frequent spills (Huijer 2005), and 50,000 for a worst case scenario, covering about 90 % of the accidents (Burgherr 2007). The number of simulated parcels in MEDSLIK-II (i.e., 90,000) remained unchanged according to De Dominicis et al. (2013b) thus guaranteeing the "smoothness and consistency" of the simulated spills.
- Two types of oil: API (relative density of the oil compared to the water) 38 and API 12 representing lighter/heavier oil spills and covering a wide range of oil densities.
- Two spill duration: 48 h, giving that explosions and foundering are the most common accidents in open sea (e.g., Erika accident, Khark 5) (International Atomic Energy Agency 2001) and the spill would be therefore "instantaneous," and 7 days representing some of the accidents observed in the NE Atlantic (e.g., Prestige accident);
- Two MEDSLIK-II configurations: accounting and neglecting the Stokes drift component of the oil transport.
- Every item was run using ocean currents from both IBI (higher spatial resolution) and MERCATOR (coarser spatial resolution) systems.

The ensemble members for the operational experiment also cover the major sources of uncertainties in operational pollution events:

- Two volumes of oil spilled: 1 t, representing the typical volume according to the observations of Volckaert and Kayens (2000), and 46 t representing a "worst case scenario" (Hampton et al. 2003).
- Two types of oil: API 22 and API 29 representing tank washing (fuel oil) events and engine leakages (lubricant oils), respectively.
- Two durations of the spill: 6 and 14 h. Since operational spills are not documented, it is difficult to find reliable information on spill durations. According to Hampton et al. (2003), operational events, especially tank washing, are short since they require personnel. The upper threshold of 14 h was defined based on the time needed by a vessel to cross the Algarve at cruise speed.
- Two MEDSLIK-II configurations: accounting and neglecting the Stokes drift component of the oil transport.
- Every item was run using ocean currents from both IBI and MERCATOR systems.

An equal number of runs and weights were assigned to each simulation in the risk mapping. This decision may be simplistic but uncertainties in oil spill reports are high and assigning different weights to members with, for instance, different oil densities would be ad hoc since there are no data available. A summary of the members is presented in Table 1.

The experiment setup has its limitations. The 1/4 degree resolution may not cover all the possible spill locations, the time interval between consecutive simulations may not be sufficient to address the local meteo-oceanographic variability and the distribution of RPs may be limited to coastal areas. However, the experiment set up should agree with the spatial-temporal resolution and characteristics of the current fields employed, major component of the oil transport, and the maritime traffic distribution. Moreover, the aim of this study is to present a method rather than providing the final word regarding the oil spill risk in the Algarve.

3.6 IT−OSRA

The IT-OSRA framework consists in a table with 35 ISO-compliant elements that support decision making in oil spill risk assessments. The theoretical basis of the framework is presented in Sepp Neves et al. (2015). A brief explanation of the IT-OSRA elements and a summary of its application to the Algarve are presented in Tables S1 and S2 (supplementary material), respectively, and the rationale behind each of its elements is described in the present subsection (Table S2 items *Establishing the context* and *Risk identification*) and in Section 4 (Table S2 items *Risk analysis* and *Risk evaluation*). As in our previous work (Sepp Neves et al. 2015),

Table 1 Configuration of the ten ensemble members for the accidental and operational experiments

Configuration	Member 1	Member 2	Member 3	Member 4	Member 5	Member 6	Member 7	Member 8	Member 9	Member 10
Accidental spills										
Volume of oil (tonnes)	10,000	50,000	10,000	10,000	10,000	10,000	50,000	10,000	10,000	10,000
Type of oil (API)	38	38	12	38	38	38	38	12	38	38
Duration of the spill (h)	48	48	48	168	48	48	48	48	168	48
Stokes drift	MEDSLIK-II formulation	MEDSLIK-II formulation	MEDSLIK-II formulation	MEDSLIK-II formulation	Neglected	MEDSLIK-II formulation	MEDSLIK-II formulation	MEDSLIK-II formulation	MEDSLIK-II formulation	Neglected
Currents	IBI	IBI	IBI	IBI	IBI	MERCATOR	MERCATOR	MERCATOR	MERCATOR	MERCATOR
Winds	SKIRON	SKIRON	SKIRON	SKIRON	SKIRON	SKIRON	SKIRON	SKIRON	SKIRON	SKIRON
Operational spills										
Volume of oil (tonnes)	1	46	1	1	1	1	46	1	1	1
Type of oil (API)	22	22	29	22	22	22	22	29	22	22
Duration of the spill (h)	6	6	6	14	6	6	6	6	14	6
Stokes drift	MEDSLIK-II formulation	MEDSLIK-II formulation	MEDSLIK-II formulation	MEDSLIK-II formulation	Neglected	MEDSLIK-II formulation	MEDSLIK-II formulation	MEDSLIK-II formulation	MEDSLIK-II formulation	Neglected
Currents	IBI	IBI	IBI	IBI	IBI	MERCATOR	MERCATOR	MERCATOR	MERCATOR	MERCATOR
Winds	SKIRON	SKIRON	SKIRON	SKIRON	SKIRON	SKIRON	SKIRON	SKIRON	SKIRON	SKIRON

the *Risk Analysis* and *Risk Evaluation* items were performed separately for operational and accidental spills.

In accordance with the European Marine Strategy Framework Directive (MSFD), the present OSRA aimed to improve the environmental status of the Algarve. This was achieved by mapping the oil spill risk due to maritime transportation, which is the only source of risk identified in the region (elements 5, 9, 11, and 12 in Table S2. Hereinafter, only the number of the elements will be presented).

Recent publications have reported a global increase in the volume of oil transported by sea (e.g., Musk (2012)). In Europe, an increase in 20 % of the seaborne transportation of goods in European waters is expected by 2050 (European Commission 2011). However, in spite of the apparent increase in the oil spill hazard, studies highlight a negative trend in the number of illegal spills in Europe (2) (Carpenter 2007; Lagring et al. 2012).

Portugal is a signatory of the main global agreements in oil spill pollution (i.e., MARPOL 73/78, OPRC 90, and CLC) and two regional agreements, the Lisbon agreement and the European Community Task Force. In Portugal itself, oil pollution is regulated by a national oil contingency plan, the *Plano Mar Limpo* (PML) (1), which assigns the national responsibility for fighting oil spills to the Maritime Authority and the regional responsibility to the regional maritime departments (4, 7) . In the case of the Algarve, the Southern Maritime Department is in charge of fighting oil pollution (10).

According to the ITOPF (ITOPF 2011), the Portuguese Navy counts on one vessel for response operations in open waters and equipment for oil dispersion and removal from water and shore. European support is provided through the European Maritime Safety Agency (EMSA) which maintains an operational oil spill detection system (6). As far as the authors are aware, the Southern Maritime Department does not count on operational monitoring of meteo-oceanographic conditions or oil spill forecasting (8).

Risk was computed quantitatively (18) by combining the oil spill hazard, estimated through oil spill ensemble simulations (17), and the social-economic and ecological coastal vulnerabilities to oil (13). Two ensemble experiments were set up for operational and accidental events, with 25,600 simulations each. The ensemble experiments were carried out in order to address the possible scenarios in the case of an offshore maritime accident (i.e., vessel explosion, foundering) resulting in a catastrophic oil spill, as well as for typical operational discharges for accidental and operational events, respectively (16, 21).

Environmental risks rank as the second major concern of Portuguese citizens regarding risks (Delicado and Gonçalves 2007). In the same study, Portuguese citizens declared that they were "very concerned" regarding the oil spill risk. In spite of the relatively high importance given to environmental issues by Portuguese citizens, their involvement in environmental causes historically has been low (3). Delicado and Gonçalves (2007) also observed that 88 % of the Portuguese believe that the participation of scientists in environmental issues is important or very important and 80 % declared that they believed in the recommendations by scientists (20).

The OSRA performed covers the year 2013, bound by the meteo-oceanographic conditions used as inputs for the ensemble experiments (19). In order to extend the timeframe of the analysis, it is necessary to perform ensemble experiments based on a longer meteo-oceanographic time series, enabling the "climatological" risk to be calculated, and on longer-term traffic density data to identify temporal variations in the maritime traffic (15).

The strategy for the evaluation of risk management decisions should take into consideration the inputs from stakeholders. However, one of the most important contributions of the ensemble experiments is to compare the present hazard and risks with the analogous indicators obtained under alternative scenarios (14) (Aven and Vinnem 2005).

Vessels were considered to be the only potential source of pollution (22). The oil spill hazard is modulated by variations in meteo-oceanographic conditions, the spatial distribution of maritime traffic and characteristics of the oil spill (i.e., volume spilled, type of oil and duration) and such variability was addressed through ensemble oil spill simulations. Variations in the hazard due to the maritime traffic were disregarded due to the lack of data (23). Coastal vulnerability was assumed to be constant in time (24).

The risk analysis was carried out for operational and accidental events separately (25). Regarding operational events, the members were related to potential tank washing and the leakage of lubricants. For accidental events, the members were designed to cover open-sea accidents (26). Detailed information on each member and the reasoning behind them is presented in Section 4.1.3.

4 The Algarve risk analysis and evaluation

This section is divided into subsections covering the framework items *Risk analysis* and *Risk evaluation* and presents the actual improvements in IT-OSRA addressing the aim of our paper.

4.1 Risk analysis

No controls due to oil spill prevention, detection, and combat instruments were employed in the risk analysis (29). As described in element (6), Portugal has only one vessel to fight oil pollution and an Exclusive Economic Zone (EEZ) area of over 1,700,000 km^2. Therefore, the effectiveness of the available resources was assumed to be negligible. In order to illustrate the assumption, the journey between the Azores, one of the Portuguese archipelagos, and the Algarve in a straight line would take at least five days.

4.1.1 Hazard and risk equations

In IT-OSRA, risk is defined for each coastal section (30), s, by:

$$R_s = H_s * I_s \tag{2}$$

where H is the oil spill hazard and I is the vulnerability of the coastal segment, as defined by Frazão Santos et al. (2012). Socioeconomic and ecological risks were treated separately. In the present experiment, the hazard, originally calculated for each coastal segment, was integrated at the level of municipality. Our original hazard equation (Sepp Neves et al. 2015) was adapted in order to fit the more complex risk scenario found in the Algarve. Following Price et al. (2003), the hazard for each coastal segment was thus defined as:

$$H_s = (P_t)_r * (P_b)_s * C_s \tag{3}$$

which combines the conditional probability of a coastal segment being hit by oil, $(P_b)_s$, and the probability of a spill taking place at the source point, $(P_t)_r$. Unlike Price et al. (2003), $(P_t)_r$ was not defined as the probability of an accident happening but as the probability of finding a vessel at the RP r based on the AIS-based maritime traffic density map for March 2013 (Fig. 2b). $(P_b)_s$ was computed as the ratio between the number of simulations in which the coastal segment was hit by oil divided by the total number of simulations of the ensemble experiment. C_s is the concentration index, defined as the ensemble mean concentration of beached oil at each coastal site normalized by the maximum mean concentration value found in the domain. In agreement with Schmidt-Etkin (2015), concentrations below 1 g/m^2, which is the minimum threshold needed to observe tarballs on the shore and thus the social impacts of an oil spill, were considered as negligible and removed from the analysis.

Three main questions were proposed in order to depict the oil spill risk in the Algarve:

1. Which areas are more likely to be affected by an oil spill and how much oil should be expected?
2. Does the spatial distribution of the risk change with time?
3. Which areas present more risk to the coast?

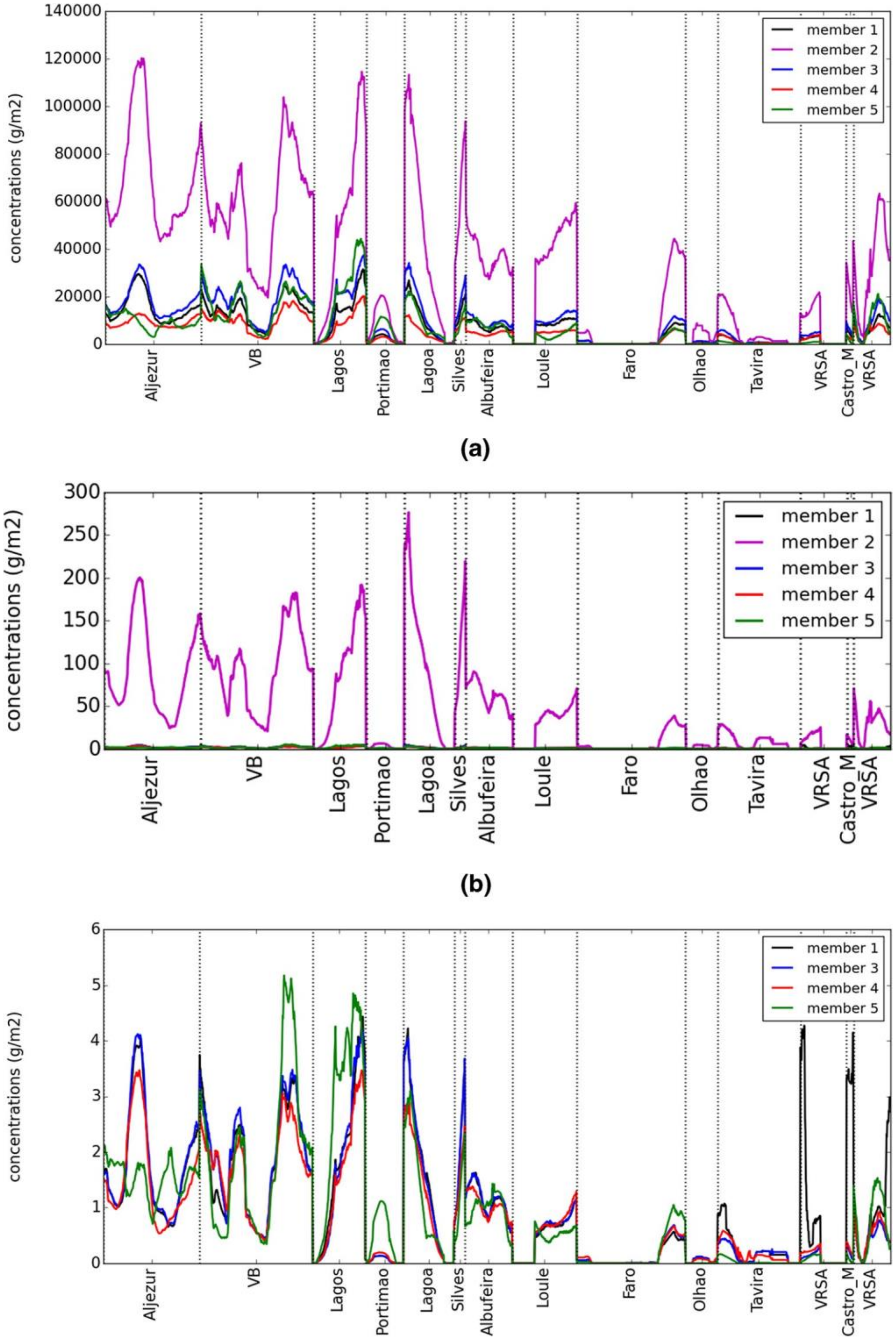
The integration of the risk index in time, among the release points (RPs) and all members was carried out in order to answer (1). The variability of the risk in time was analyzed in a seasonal scale to answer (2). In order to answer (3), the product $(P_b)_s * C_s$ was integrated over time and for all the members to estimate the share corresponding to each RP in the oil spill hazard.

4.1.2 Sensitivity analysis

Prior to answering the main questions regarding the risk in the Algarve, a sensitivity analysis (32) was performed in order to understand the impacts of the decisions taken in identifying the ensemble members. The analysis focused on identifying the role of the oil spill model setup and of the current fields (i.e., IBI and MERCATOR) in the oil beaching. Firstly, the average concentrations of beached oil generated by the five different oil spill model configurations (i.e., duration of the spill, volume of oil spilled, type of oil, and inclusion/exclusion of the Stokes drift) not differentiating between IBI and MERCATOR current inputs (Fig. 4). For the sake of simplicity, the first member of each experiment was assumed as the reference simulation. Secondly, simulations fed by IBI and MERCATOR fields were analyzed separately, grouping the five model configurations (Fig. 5).

Regarding the accidental experiment (Fig. 4a), member 1 showed high volumes of oil in Vila do Bispo (hereinafter also referred to as VB), Lagos, Lagoa, Silves, and parts of Aljezur. The increased volume of oil spilled in member 2 resulted in an overall increase in the volume of beached oil compared to the reference simulation, without changing the spatial pattern in the study area. An increase in the oil density in member 3 resulted in lower losses due to evaporation and higher losses due to oil dispersion. An analysis of the oil fate in members 1 and 3 (not shown) showed that lower evaporation rates outweighed the higher dispersion resulting in a net increase in the coastal concentrations in member 3. An increase in the duration of the spill (member 4) resulted in lower volumes of oil on the coast, changing the spatial pattern of distribution presented by members 1, 2, and 3 with higher concentration values observed in Vila do Bispo and parts of Lagos. Member 5 showed how the Stokes drift (i.e., waves) may impact on the oil spill risk. Disregarding the Stokes drift resulted in lower beaching on the western side of the coast, a small increase in the central area of the southern coast (Lagos, Portimao, Silves and part of VRSA), and a slight decrease in the concentration on the western side of the Cape Santa Maria (Loule).

In the operational experiment, the reference member showed oil concentrations on the coast ranging between 0 and 5 g/m^2 (Fig. 4b, c). The highest concentrations were found in VB and Aljezur on the west coast, Lagos, Lagoa and Silves in the area between the Cape Sao Vicente and the Cape Santa Maria, and Castro Marim and Vila Real de



(a)

(b)

(c)

Fig. 4 Ensemble average concentration (g/m^2) of oil for the year of 2013 observed along the Algarve coastal segments for the five ensemble configurations observed in the (**a**) accidental and (**b**) operational experiments. Due to the large range of concentrations observed in the operational experiment, a third plot (**c**) showing only the four members with lower values is presented. *Vertical dotted lines* mark the boundaries of each county. No minimum concentration values were applied

Santo Antonio (VRSA) in the east. The higher volume of oil spilled in member 2 produced a dramatic increase in the oil concentrations, with values reaching the 150 g/m^2 on the west coast, Lagos, Lagoa, and Silves. The relative spatial distribution observed for member 2 followed that observed for member 1. A lower oil density (member 3) did not result in dramatic differences in the beaching scenario, with small detectable changes in Castro Marim and VRSA, where a lower oil density meant lower volumes of beached oil. A longer spill duration (member 4) resulted in lower volumes

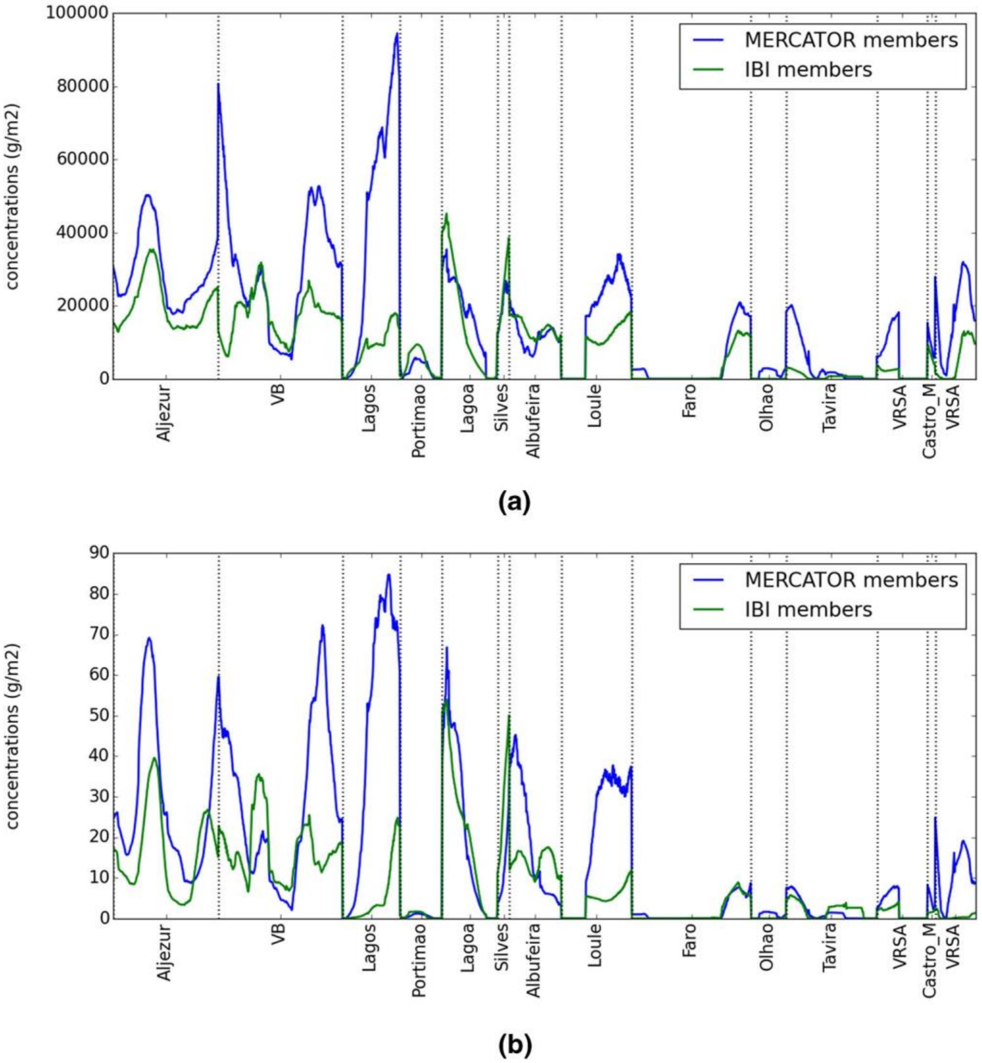


Fig. 5 Ensemble average concentration (g/m^2) of oil for the year of 2013 observed along the Algarve coastal segments for (**a**) accidental and (**b**) operational experiments. The concentrations represent the average of all the MERCATOR-fed, *blue solid line*, and IBI-fed, *green solid line*, members. *Vertical dotted lines* mark the boundaries of each county. No minimum concentration values were applied

of oil on the coast with a significant reduction in the western side of VB, part of Lagos, Castro Marim, and VRSA. The removal of the Stokes component from the calculations (member 5) led to an important reduction in the beaching process for the whole coast, with special focus on the west coast, the western end of the south coast (VB) and Castro Marim/VRSA.

Regardless of the member configuration, small-scale variations (in the order of a few kilometers) were observed in the beached concentrations (Fig. 4). This suggests that processes other than the member setup affected the results of our experiment. Embayments, capes, and promontories along the Algarve coast are expected to generate “shaded areas” where beaching is compromised under certain meteo-oceanographic conditions. Different beach types (e.g., sand beach, rocky shore, etc.) also have different retention capacities and probabilities of oil removal in MEDSLIK-II (Samaras et al. 2014).

The average of all the members using the MERCATOR results as inputs was compared to the corresponding average using IBI currents for the accidental and operational experiments (Fig. 5). In general, the MERCATOR-based members depicted a quasi-continuous sector of higher oil concentrations in the west coast, part of VB, Aljezur, and most of the southern coast (Lagos, Lagoa, Silves, Albufeira, and Loule). A similar pattern was observed in IBI, but with a significant reduction in oil concentrations, with exceptions in parts of Loule, VB, Lagos, Castro Marim, and VRSA. Since no evaluation of the actual predictive skills of the models was carried out for the study area, it is not possible to highlight whether one model outperformed another.

A complementary test was performed in order to understand the differences observed in beached concentrations due the different dynamics reproduced by IBI and MERCATOR members. One release site located on the eastern side of Cape Santa Maria was picked as an example due to its

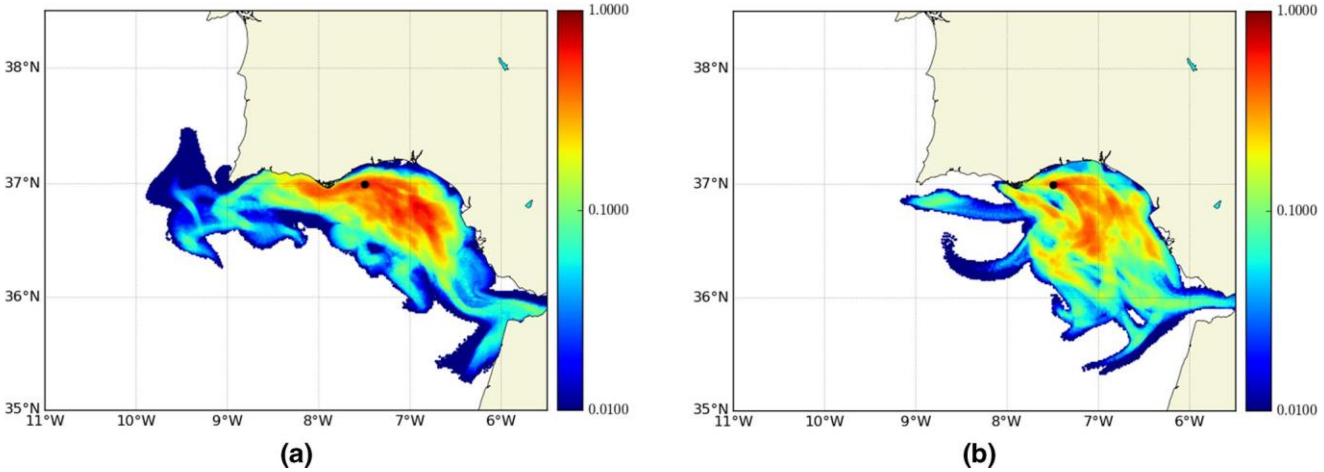


Fig. 6 Relative oil observation frequencies for all the simulations of the year of 2013 originated at one release point (*black dot*) for (**a**) IBI and (**b**) MERCATOR members. *Colors* represent the relative importance compared to the most impacted site

exposure to episodic events. The whole set of oil trajectories (i.e., 2013) covering operational events for each model was plotted on a map thus identifying the most frequent and anomalous trajectories (Fig. 6). Concentrations of oil on the surface were not evaluated but simply the number of parcels found in 1.5 km x 1.5 km cells divided by the number of parcels found in the most densely populated cell in the study area, creating a scale from 0 to 1. The procedure was carried out for MERCATOR and IBI members separately.

The test results show that the oil tends to flow southeastwards in most of the simulations for both MERCATOR and IBI, in agreement with the average surface circulation. However, it also shows that episodic reversions of the surface currents are relatively more frequent (i.e., larger areas with values close to 1 westwards of the release site) and more intense (i.e., areas subject to oil extend farther west) in the IBI members. Further analyses (not shown) indicate that the reversal of the surface currents may result in frequent but low magnitude beaching events for the coastal RPs at the eastern part of the domain.

4.1.3 Risk mapping

The ecological risk due to accidental spills in the Algarve for the year 2013 (Fig. 7b) was found to be mainly concentrated in the western municipalities of Aljezur and VB ($0.7 < R <= 1$), which have most of their coastlines protected by the Sudoeste Alentejano e Costa Vicentina natural park. The evaluation of the hazard equation terms (Fig. 8a, c) show that the hazard levels in the area were due to large volumes of oil beached (C) and high Pb values (about 1 %). Low ecological risk values ($R = 0.3$) were observed in the municipalities encompassing the Ria Formosa Natural park (Faro, Loule, and Olhao), characterized by the low hazard due to relatively low C and P_b values (27, 28). An analysis of the seasonal variation in the ecological risk associated with accidental events (Fig. S1 supplementary material) reveals that the western municipalities of Aljezur and Vila do Bispo (VB) dominated the scenario throughout the year, with VB always leading the rank ($R = 1$). The importance of Aljezur peaked in winter ($R = 1$) and reached its minimum, 0.5, in autumn.

As expected, the annual socioeconomic risk (Fig. 7a) reached the highest values along the southern Algarve, where tourism, marine sports, and fisheries play a major role in the local economy and where the most populated towns are located (I N E – Instituto Nacional de Estatistica 2012). Lagoa ranked first, followed by Albufeira ($R = 0.9$), Loule/Olhao ($R = 0.8$), Silves/Lagos ($R = 0.7$), and VB ($R = 0.5$). Intermediate values ($R = 0.4$) were observed in Aljezur and Portimao. A low risk was found in the other municipalities. Important changes in the socioeconomic risk associated with accidental events were detected at the seasonal scale (Fig. S1 supplementary material). Loule scored the highest in winter, Albufeira in spring, Lagoa in summer, and Olhao in autumn. Important risk values were observed in Lagos during winter ($R = 0.6$) and summer ($R = 0.8$) time. During summer, the meteo-oceanographic conditions contributed to a risk value of 0.8 in Portimao, which scored low values in the other seasons.

At the annual scale, the Pb and C maps (Fig. 8) generated by the operational experiment showed similar patterns to their respective pairs in the accidental experiment. Consequently, the spatial distribution of the hazard was found to be analogous except for Lagoa and Loule (Aljezur), where the hazard levels were higher (lower) in the operational experiment. Since the release grid and spill frequency were identical for both experiments, the most likely causes for this discrepancy are (i) application of the 1 g/m^2 threshold, which may have been especially efficient in removing very

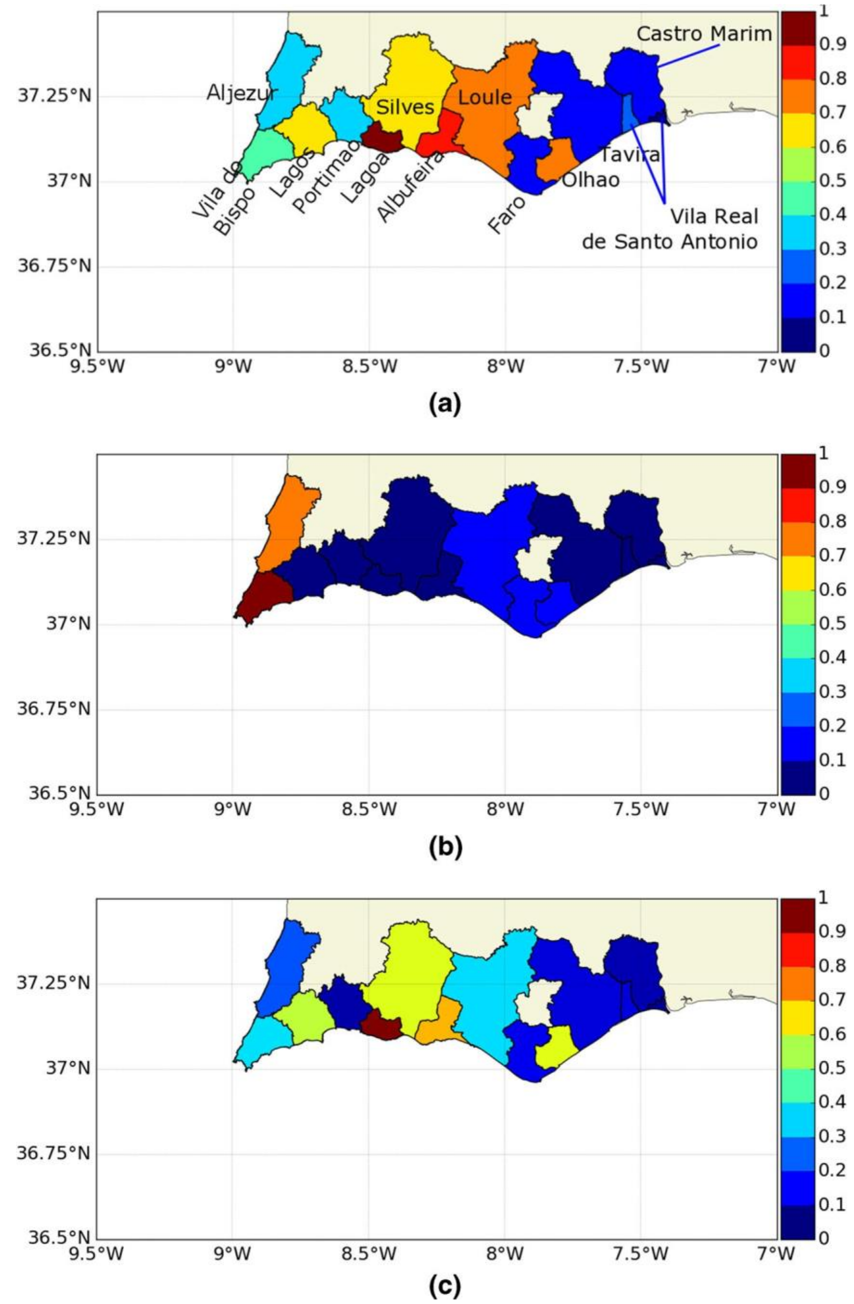


Fig. 7 (**a**) Socioeconomic and (**b**) ecological dimensions of the annual oil spill risk for the accidental experiment. In the *third row*, the (**c**) socioeconomic risk for the operational experiment

low concentration values in the operational experiment; (ii) differences in the duration of the spills (found to be important in the sensitivity analysis) between the accidental and operational scenarios; and (iii) differences in the oil type, which is expected to modulate weathering processes, thus, the concentrations observed on the coast. In a broad sense, the experiment covering operational events demonstrated that oil weathering is crucial in small spill scenarios, since it determines whether the amount of oil exceeds the lower limits proposed by Schmidt-Etkin (2015).

No concentration values above the 100 g/m^2 lower threshold proposed by Schmidt-Etkin (2015) for ecological impacts of oil spills were found in the Algarve. On the other hand, the 1 g/m^2 threshold was exceeded along most of the coastline. Since no ecological impacts are expected, the calculation of the risk for the operational experiment focused solely on the socioeconomic dimension.

The socioeconomic risk due to operational spills was mainly concentrated in the southern Algarve coast (Fig. 7c). Lagoa was the municipality with the highest risk levels for 2013 ($R = 1$), followed by Albufeira, Lagos, Silves, and Olhao ($0.4 < R <= 0.7$). Risk values below the 0.4 level were found in VB, with a low vulnerability but high hazard, and Loule, with a high vulnerability and low hazard (27, 28).

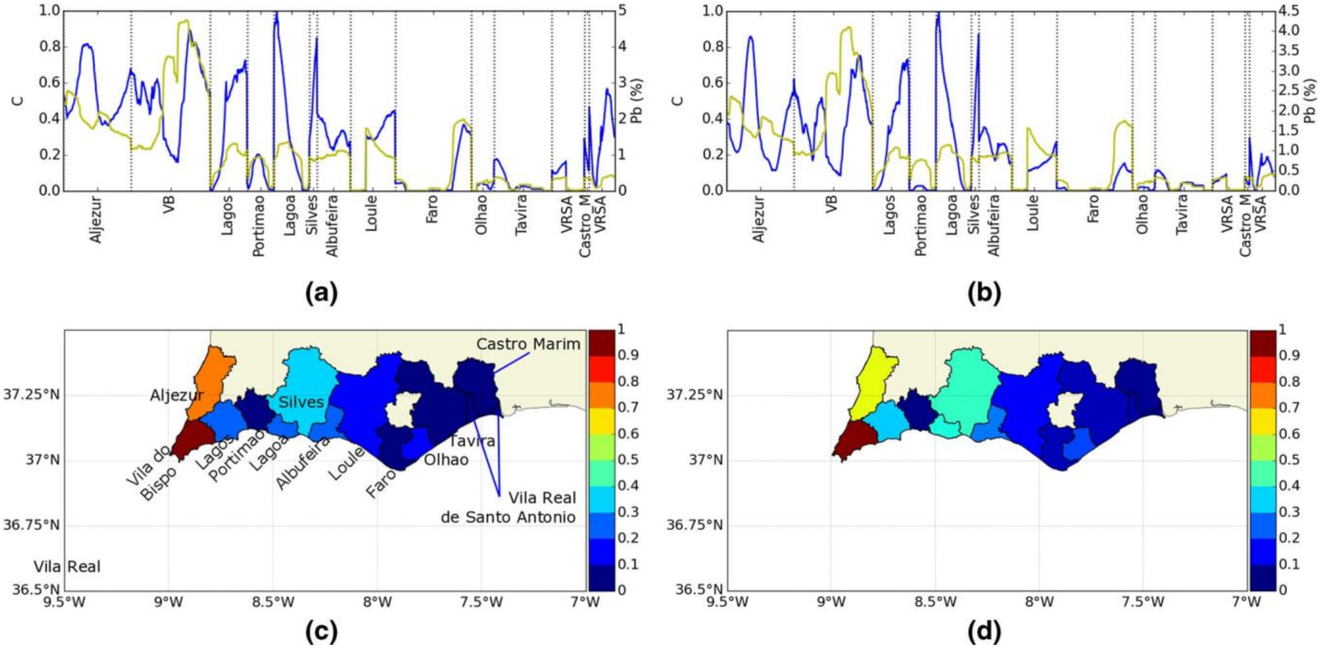


Fig. 8 In the *upper row*, annual Pb (*yellow solid line*) and C (*blue solid line*) for (**a**) accidental and (**b**) operational experiments. In the *lower row*, the annual hazard for (**c**) accidental and (**d**) operational experiments

Seasonal variations were found to be significant (Fig. S2 supplementary material). Albufeira had the highest risk scale for summer, spring, and winter seasons, followed by Lagoa and Loule, in order of importance, with values ranging from 0.4 to 1. Olhao obtained high scores in spring, winter, and autumn, with autumn having the highest risk scale. Values between 0.5 and 0.7 were assigned to Lagos during summer, winter, and autumn. VB obtained significant risk values ($0.4 < R <= 0.6$) only during winter and autumn.

In the present OSRA, the risk was assumed to be modulated by the meteo-oceanographic variables. Therefore, linking the observed risk to the surface circulation and Stokes drift patterns is fundamental in order to understand the distribution of the risk and the mechanisms behind it. The averaged meteo-oceanographic conditions for 2013 (Fig. 1) were especially favorable to oil beaching for the coastal RPs located off the western part of the Algarve which may explain the high risk values observed in the area. RPs located far offshore in the western and southern parts of the domain were subjected to currents and Stokes drift that tended to push the oil away from the coast. A similar conclusion can be drawn for the coastal RPs off the south coast. This forces us to consider that episodic events may be

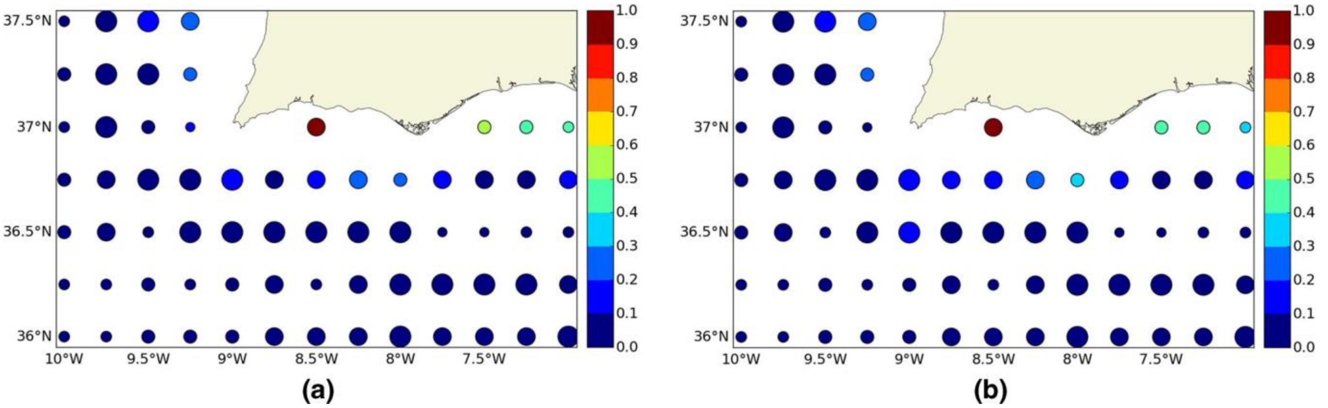


Fig. 9 Sources of risk for the year of 2013, (**a**) accidental and (**b**) operational experiments. The color inside the circles represents the computed level of hazard for the release point. The diameter of the circle represents the traffic density. The main shipping corridor is represented by the biggest circles

responsible for bringing the oil to unfavorable areas such as the southern municipalities between the Cape Sao Vicente and Cape Santa Maria.

As described in Section 2, episodic events can dramatically change the meteo-oceanographic conditions in the Algarve. Due to their short life span, in the order of days, ocean mesoscale events and the passage of cold fronts are unlikely to have a clear impact on the seasonal average, but can contribute to oil beaching under specific situations. In Fig. 6, we could see that average meteo-oceanographic conditions played an important role in defining the oil spill trajectory (and beaching), with great part of the oil being transported southeastwards. However, current reversions associated with episodic meteo-oceanographic events transported part of the oil along the southern coast explaining the high risk values observed between Cape Santa Maria and Sao Vicente, and in Olhao.

4.1.4 Mapping the sources of risk

Figure 9 shows a map of the relative importance of each RP to the overall risk map due to accidental and operational spills calculated as:

$$H_r = (P_b)_{s,r} * C_{s,r} \tag{4}$$

where H_r is the hazard level assigned to the release point, $(P_b)_{s,r}$ is the probability of beaching at the coastal segment, and $C_{s,r}$ is the concentration index for spills occurred in r. As the reader will notice, the two maps are similar and, therefore, the following description is valid for both experiments. The RP located just off Portimao ranked as the most important source of risk to the Algarve, as it combines significant traffic density and high probabilities of a spill reaching the coast in significant volumes. This RP is located near the entrance of the port of Portimao, thus explaining its high traffic density. The influence of the traffic associated with the port was also observed in the adjacent release sites which, in turn, presented lower hazard values (0.3). Under the influence of the ports of Huelva and Ayamonte, the three release points located in front of the eastern municipalities showed hazard levels between 0.4 and 0.6 and considerable traffic. Interestingly, the main shipping corridor, represented by the larger circles in the map, presented very low hazard values along most of its extension, with values ranging from 0 to 0.2 off Aljezur and off Albufeira.

4.1.5 Uncertainties in the risk analysis

In Sepp Neves et al. (2015), we computed the uncertainty of our oil beaching estimates using the standard deviation of the oil concentrations along the coasts. A limited number of ensemble members were employed and the distribution of the results was assumed to be Gaussian.

The results obtained in the present experiment, with over 50,000 simulations, suggest that the assumption in Sepp Neves et al. (2015) may not be appropriate. Olita et al. (2012) mentioned a non-Gaussian distribution of the risk index but did not clarify whether it was due to the hazard or the vulnerability component of the risk. Figure 10 presents a histogram of the simulated beached volumes for the Algarve coast in 2013. Members 2 and 7 were deliberately removed to remove the potential effect of higher concentrations associated with larger spills. The curve indicates that observations do not fit a Gaussian distribution. In fact, most of the beaching events involve small concentrations of oil, although the range of observed values is quite wide and a significant amount of oil is found in the lower frequency tail. These conclusions suggest that the way oil spill impacts are currently dealt with may need to be adapted to the characteristics of the data set.

The definition of the most appropriate statistical distribution to describe the data set and, consequently, the strategy to compute the risk and its uncertainties will be determined by assuming a Poisson-like distribution or an exponential distribution but statistical tests are still underway to determine which one is the best case (31). This will give us the way to ascertain uncertainties, i.e., for Poisson-like distribution the standard deviation is the square root of the mean while for exponential it is equal to the mean. For the present experiment, we opted for the conservative approach of qualitatively addressing uncertainties through the application of ensemble techniques and avoiding quantifying them by employing the standard deviation.

4.2 Risk evaluation

The spatial variability of the risk and its components were graphically represented (Figs. 7 and 8), supporting the prioritization process for risk treatment (33, 34). In addition, maps of the release points and their relevance in terms of maritime traffic density and the hazard they represent were presented (Fig. 9) (33).

The International Maritime Organization (IMO) proposed six key points regarding risk reduction, namely a local oil pollution emergency plan, an oil spill reporting system, identification of national/regional competent authorities, a national contingency plan, minimum response equipment available, and international cooperation (35). All these requirements are currently covered by the Portuguese government.

As stated by Aven and Vinnem (2005) and Sepp Neves et al. (2015), the risk should be always treated as low as is reasonably practicable and possible improvements in some of the IMO items can be proposed based on the literature available and on the results of the IT-OSRA framework. Hassler (2011) advises the enforcement of port state

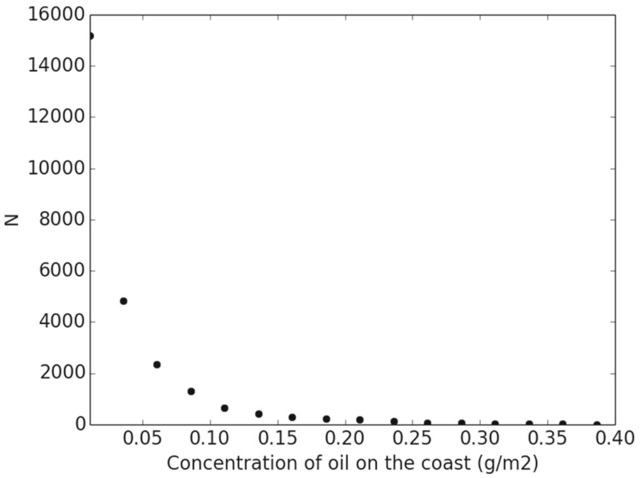


Fig. 10 Histogram of the modeled concentrations of oil on the coast in the Algarve for the year of 2013 (operational events)

control, aerial and surface monitoring, and flag state responsibility in order to reduce the risk of operational spills. Regarding accidents, risks can be reduced through national enforcement measures, through flag state responsibility, and remediation through investments in towing equipment, oil removal equipment, and coast guard training.

5 Conclusions and outlook

In the present paper, the OSRA framework originally proposed in Sepp Neves et al. (2015) was fully implemented considering various sources of uncertainties (i.e., spill location, spill time, and model configuration) for operational and accidental oil spill scenarios. The methodology was applied to the Algarve coast, and focused on accidental and operational spills associated with maritime traffic, assuming the shipping routes provided spatial information about the sampling of the source location uncertainty. The ecological and socioeconomic oil spill risks and their seasonal variability were quantified.

Accidental spills were found to represent a source of risk for both the ecological and social-economic dimensions. Operational events on the other hand, due to the smaller oil volumes released, do not represent significant risk to the coastal ecosystem mainly because the oil evaporates before it arrives near the coasts.

Seasonal variability in the oceanographic fields (i.e., ocean currents and wind-induced currents or Stokes drift), was found to generate significant changes in the spatial distribution of risk in the Algarve. High-frequency events in the ocean (i.e., mesoscale features) and in the atmosphere (i.e., easterly events) were also found to contribute to the final definition of the risk scenarios. The spatial resolution of the current fields was a significant source of uncertainty in the risk estimates.

The outputs of the IT-OSRA demonstrated that accidental spills do represent a source of ecological and socioeconomic risk to the Algarve. “Typical” operational oil spills posed a socioeconomic risk in the area and, in addition, worst-case operational spills may lead to beached oil concentrations which are sufficiently high that they impact not only on the socioeconomic aspects on the coast but also on the local biota. Our IT-OSRA generated visual outputs that reflect the current risk and its components, thus supporting decisions regarding risk reduction alternatives.

Finally, some shortcomings came to light during our experiments, which require further work. Firstly, the release point grid and timing were set subjectively and might not have fully sampled the relevant scales. Principal component analysis of the flow field will help in the future to establish the required sampling scheme. Secondly, the number of simulations performed suggests that assuming a Gaussian distribution of the modeled oil concentrations on the coast may not be appropriate. This highlights the need for further work to establish how to compute uncertainty from non-Gaussian distributions. Additionally, it is clear that in the future longer time series will be required to sample relevant ocean transport events which greatly affect the amount of oil on the coasts.

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