Oil spill risk assessment and management for the coast of Algarve, Southern Portugal

An operational oceanography approach

By

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Supervisors' declaration

Dra. Nadia Pinardi, profesora en la Universidad de Bologna (Italia) y Dr. Flavio Martins, profesor en la Universidad del Algarve (Portugal), como sus directores,

HACEN CONSTAR: que esta Memoria, titulada *"Oil spill risk assessment and management for the coast of Algarve, Southern Portugal – an operational oceanography approach"* presentada por D. Antonio Augusto Sepp Neves, resume su trabajo de Tesis Doctoral y, considerando que reúne todos los requisitos legales, autorizan su presentación y defensa para optar al grado de Doctor en Gestión Marina y Costera/Marine and Coastal Management.

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Abstract

Oil Spill Risk Assessments (OSRAs) have been widely employed to support decision makers in managing conflicts of interests associated to the oil industry. On the one hand, oil production, transportation and storage attend a social demand but, concomitantly, represent a source of risk to the coastal and marine environment. On the other hand, it is desirable to preserve the coasts and to keep them profitable in monetary (e.g.tourism and fisheries) and non-monetary terms (e.g. nutrient cycling, gas regulation).

In the first part of this thesis, it was demonstrated that the available literature/methodologies in OSRA often fails in fulfilling basic requirements necessary to support the decision making: (1) uncertainties in the risk estimates have been neglected, (2) operational oil spills (i.e. intentional small, but frequent, spills associated to vessel operations such as tank washing) have not been addressed and (3) the risk analysis outputs are not appropriate for the their communication to the stakeholders. Relying on these conclusions, a general OSRA framework was proposed based on a critical analysis of the ISO 31000:2009 on risk management principles and guidelines, and addressing the limitations observed in the reviewed literature. The methodology, that employs ensemble numerical oil spill spill simulations to quantify the risk and its uncertainties, was applied to a real oil spill case, the explosion of the Jiyeh power station in Lebanon in 2006, being able to identify the most impacted areas and to visually communicate the risk, its components and its uncertainties.

The framework developed in the first part of the thesis was later applied to compute the oil spill risk in the Algarve, southern Portugal. Improvements in the methodology, now called Information Technology OSRA (IT OSRA), were necessary in order to address dispersed sources of risk (i.e. maritime traffic), more sources of uncertainty (i.e. where and when the spill will happen, and oil spill model configuration) and the possibility of both accidental (rare but usually involving large volumes of oil) and operational spills to occur. Over 50,000 oil spill simulations were performed and the results obtained confirmed that oil spills associated to the maritime traffic represent a risk to the Algarve in ecological and socioeconomic terms. Significant seasonal variability of the risk was observed and quantified. High frequency variability (by the order of days) of the meteo-oceanographic variables was also found to play an important role in the oil spill risk. Finally, priority areas were identified based on the risk maps and the most likely sources of potentially impacting spills were mapped. The huge number of simulations performed allowed to discover that the distribution of concentrations of oil on the coast due to marine spills follow a Poisson curve. Such finding challenges the available literature that assumed a Gaussian distribution of the variable. The discovery will demand new approaches to deal with the oil spill risk.

Resumen en español

Evaluaciones de riesgo por vertidos de petroleo (OSRAs) son amplamente empleadas para ayudar los tomadores de decisión en la gestion de conflictos de interese asociados a la industria del petroleo. Por un lado, la producción, transporte y almacenamiento de petroleo atiende a una demanda social pero también representa un riesgo al ambiente costero y marino. Por otro lado, e interesante preservar las costas y mantenerlas rentables en termines monetarios (e.g. turismo y pesca) y non monetarios (e.g. ciclo de nutrientes, regulación de gases).

En la primera parte de la tesis, fue demostrado que la literatura y las metodologías disponibles en OSRAs a menudo fallan en atender requisitos básicos necesarios para ayudar la toma de decisiones: (1) las incertidumbre en las estimativas de riesgo han estado ignoradas, (2) vertidos operacionales no son considerados y (3) los resultados de la análisis de riesgo no son apropiadas para su comunicación a las partes interesadas. Basándose en estas conclusiones, un marco para OSRA fue propuesto basado en la evaluación critica del ISO 31000:2009 para gestión del riesgo, abordando las limitaciones observadas en la literatura. La metodología, que emplea simulaciones numéricas de vertidos de petroleo *ensemble* para cuantificar el riesgo y sus incertidumbres, fue aplicada en una situación de vertido real, la explosión de la planta eléctrica de Jiyeh en Líbano (2006). Los resultados demostraron que la metodología ha sido capaz de identificar las áreas mas impactadas y comunicar visualmente el riesgo, sus componentes y sus incertidumbres.

Il marco desarrollado en la primera parte de la tesis ha sido aplicado para estimar el riesgo de un vertido de petroleo en el Algarve, sur de Portugal. Mejoras en el método, ahora nombrado IT-OSRA, fueron necesarias para abordar fuentes dispersas de riesgo (i.e. trafico marítimo), mas incertidumbres (i.e. donde y cuando ocurrirá el vertido y cual es la configuracion mas eficiente del modelo de petroleo) y la posibilidad de que tanto derrames operacionales cuanto derrames accidentales pueden ocurrir. Mas de 50000 vertidos fueron simulados y los resultados han confirmado que vertidos de petroleo operacionales y accidentales debidos al trafico marítimo representan un riesgo para el Algarve en termos ecológicos y socio-económicos. Variabilidad estacional significativa del riesgo fue observada y cuantificada. Variabilidad de alta frecuencia (del orden de días) de las variables meteo-oceanograficas también tuvieron un papel importante en el riesgo. Por ultimo, áreas prioritarias para protección fueron identificadas con base en los mapas de riesgo y las fuentes mas probables de vertidos con potencial de contaminar recursos costeros fueron mapeadas. El gran numero de simulaciones hechas permitió descubrir que la distribución estadística de las concentraciones de petroleo en la costa debido a vertidos de petroleo en el mar sigue una distribución de Poisson. La descubierta desafía la literatura actual, que habitualmente asumía una distribución normal de la propriedad, exigiendo la busca por nuevos modos para trabajar el riesgo por vertidos de petroleo.

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Prologue

Risk has been defined by Aven and Renn [6] as a variable of two dimensions described by *"the uncertainty about and severity of the consequences of an activity with respect to something humans value"*. Applying the general concept proposed by Aven and Renn [6] to the oil spill risk, we can define the possibility of a spill due to, for instance, the explosion of a coastal oil storage unit or an intentional vessel tank washing operation, as uncertainties in our system. The volume of oil observed on the coast due to the hypothetical spill would set the severity of the impacts on monetary (e.g. tourism, fisheries, recreation) and non-monetary (e.g. gas regulation, nutrient cycling) resources of the coastal environment, something we value.

Based on the previous paragraph, it is safe to state that the oil spill risk represents a conflict of interests. On the one hand, oil-related activities (e.g. production, transportation and storage) attend a social demand. On the other hand, a good environmental status is paramount to keep our coasts profitable in monetary and non-monetary terms. Oil Spill Risk Assessments (OSRAs) have been widely used as a tool to support coastal managers in managing such conflict.

In the present thesis we worked on the development of a methodology to assess the oil spill risk in the marine environment, devising a tool to support decision makers in their delicate task. The method employed ensemble oil spill numerical modelling to quantify the two dimensions of the risk (i.e. severity of the impacts and associated uncertainties) fully relying on operational oceanographic and atmospheric products. The methodology was tested in the Algarve, southern Portugal, a region where intense maritime traffic and prospective oil production sites share space with an economy and society very dependent on the marine resources.

1.1 Aims of the thesis

- to devise a general OSRA methodology capable of addressing any source of oil spill risk in any part of the global ocean;
- to employ operational oceanographic and atmospheric products to compute the impacts and the uncertainties associated to the oil spill risk through ensemble oil spill modelling;
- to adapt and apply the OSRA methodology to the Algarve.

1.2 Data and models overview

In order to fulfill the aims proposed for the thesis, the following data sets and models were used:

- International standard ISO 31000:2009 - Risk management: principles and guidelines;
- ocean currents data from the Copernicus Marine Environment Service (http://marine.copernicus.eu/);
- wind data generated by the Skiron forecasting system (http://forecast.uoa.gr/);
- MEDSLIK-II open source oil spill model (http://medslikii.bo.ingv.it/);
- cultural and ecological priority sites in the Lebanese coast defined by UNEP - ROWA [103]
- coastal vulnerability to oil for the Portuguese coastal counties developed by Frazão Santos et al. [35]

1.3 Structure of the thesis

The thesis is organized as follows:

- Chapter 2: Introduction
- Chapter 3: Towards a common oil spill risk assessment framework - Adapting ISO 31000 and addressing uncertainties
- Chapter 4: IT OSRA: applying ensemble simulations to estimate the oil spill hazard associated to operational and accidental oil spills
- Chapter 5: Results transferable to the public domain
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Chapter 2

Introduction

This thesis documents the development of an oil spill risk assessment methodology based on extensive reading, numerical experiments and validations exercises. The process initiated with defining what "risk" is, at least inside the boundaries of this thesis. Although it may seem unimportant, the outputs of this phase were rather interesting: there is no unique concept of risk and the misuses of the word occur frequently in the peer-reviewed literature. The second surprising conclusion was that the theoretical concepts of risk and risk assessment very often diverge from how they are actually approached by risk analysts.

Chapter 3 summarizes all the efforts taken in this first phase of the work, presenting a critical literature review in the field of oil spill risk assessments and comparing how the oil spill risk has been treated in reality and how it should be, in theory, assessed. Such analysis resulted in an innovative OSRA framework that tries to incorporate the actual concept of risk and the actual aims of a risk assessment. The framework, later named IT OSRA (Information Technology Oil Spill Risk Assessment), was successfully validated for a real oil spill case, the Jiyeh (Lebanon) oil spill in 2006.

In Chapter 4, the IT OSRA was improved, including limitations observed in the Chapter 3, and applied to assess the oil spill risk in the Algarve, southern Portugal. Unlike the case study carried out in Lebanon, the Algarve is exposed to a complex risk scenario where several sources of uncertainties are present and disperse sources of risk are found. The application of the IT OSRA to the Algarve represented a challenge and the results have led to interesting findings not only regarding the risk in the Algarve but also about the behavior of the oil spill hazard in the marine environment. According to the expectations, this thesis does not solve all the issues in OSRAs and, therefore, the conclusions of the thesis and the identified pending clarifications were summarized and presented in Chapter 5. The reader will find by the end of the thesis three annexes containing one article, in which an experiment undertaken in the Tuscany Archipelago, Italy, was performed in order to get acquainted with oil spill modelling, one conference abstract related to Chapter 4 and the curriculum of the PhD candidate, as recommended by the coordination of the PhD program.

In the following paragraphs, a brief presentation of some basic knowledge necessary to proceed with the thesis and even to justify our experiments is presented. It was a decision to keep the section short, since a robust literature review in OSRAs is performed in Chapter 3.

Coastal areas have a long history of attracting people by the opportunities and resources they offer. Estimates published by the European Blue Growth project [29] state that, in the European context, the seas contribute with over 150,000 million euros/year. From a broader perspective, Costanza et al. [17], in their classical work, monetized the services provided by coastal and marine areas estimating a value of US$ 20,949E9 per year. The latest updates published in Costanza et al. [18] suggest an increase in this value of US$ 0.6E12.

According to the "best estimates" of the U.S. National Research Council [104], 52% of the oil inputs to the marine environment are associated to human activities. Focusing the analysis on anthropic sources, the so called operational oil spills (i.e. typically small spills associated to intentional tank washing and leakage of lubricants), are responsible for over 70% of the anthropic share. Vessel-related accidental spills correspond to 23% of the total volume of oil. Extraction of oil correspond to only 5% of the oil inputs in the sea. Interestingly, the attention given to oil spills events by the media seems to be inversely correlated to the actual volumes of oil they add to the sea.

Every year, over 2,000 million tonnes of oil are transported by vessels [111] and, as expected, accidents and intentional spillages occur impacting not only biological but socioeconomic aspects of the coasts. Several studies were dedicated to understand the impacts [71, 78] and costs [64, 68, 106] involved in accidental oil spills. Very few initiatives have been carried out regarding operational spillages though and they have been mostly concentrated on their impacts on seabirds [12, 108, 109].

When something valued by the society is at stake due to a not well understood threat, a risky scenario is set. The coastal environment and its resources can be considered as something our society currently values. Oil-related activities carried out in the ocean (i.e. transportation, production and exploration) may represent a possible threat to the coastal environment and, in spite of all the efforts in the field, it is still not possible to predict when, where and how an oil spill will happen. An oil spill risk scenario has been therefore established. But how to deal with the risk?

2.1 Dealing with the oil spill risk

Risk assessments have been carried out in several parts of the globe in order to protect coastal resources from a wide range of risks, supporting the decision making process which, in turn, has been defined by Aven and Kõrte [4] as:

"a process with formal risk and decision analyses to provide decision support, followed by an informal managerial judgement and review process resulting in a decision."

Coasts are risky areas [57] and, currently, risk assessments due to climate-related uncertainties, multiple coastal hazards (i.e. storm-induced erosion and floods, long term erosion, jellyfish, pollution, river floods and human uses) (e.g. Lozoya et al. [66]), water eutrophication (e.g. Arhonditsis et al. [3]), pollution (e.g. Grifoll et al. [40]) or tsunamis (e.g Tucker [101]) have been documented. Oil spill risk assessments have been also extensively employed to deal with the uncertainties inherent to oil transportation, production and storage. However, as pointed out by Sepp Neves et al. [95], the ability of the available literature in OSRAs to fully support a decision making process is questionable.

In order to keep our discussion objective, we will also define what risk actually is, at least inside the limits of this thesis. Lowrance [65] proposed a very "objective" definition, depicting risk as a measure of the probability and severity of adverse effects. Thirty years later, risk was defined by the International Standardization Organization [51] as *the effect of uncertainty on objectives*. In the same year, Aven and Renn [6] delivered a philosophical discussion on the concept of risk, describing it as a two-dimensional variable defined by *"the uncertainty about and severity of the consequences of an activity with respect to something that humans value"*. Several other attempts of describing risk took place in these 30 years and new concepts will come but we can clearly see that risk has been evolving from a "measure", and therefore reliable and palpable, to "uncertainty".

Taking the general concept of risk presented by Aven and Renn [6] as a reference point, we progress reviewing how the assessment of the oil spill risk has evolved in time and identifying where there is still room for significant improvements. Stewart and Leschine [98] divided OSRA techniques into two groups: empirical approaches and simulation approaches. Empirical approaches are usually based on maritime casualties databases and consist on implementing empirical models to predict oil spill events in a given area. Although based on observations, strong limitations have been identified in this approach. The reliability of the data sets used has been questioned by Devanney [22], the small number of casualties, especially those of greater dimensions, may impact the quality of the computed probabilities [23], when it comes to maritime casualties, accident frequencies are site-specific [98], it is difficulty to propose alternative measures [5] and the difficulty in communicating the risk computations [7, 31]. In spite of the severe limitations observed, empirical approaches have been widely employed in the OSRA field and the limitations have been usually disregarded (e.g. Fowler and Sø rgård [34], Soares and Teixeira [97], Ulusçu et al. [102]).

Simulation approaches consist on modelling the main patterns observed in a given oil spill risk scenario and, within this field, some authors have focused on actually simulating the trajectory of hypothetical oil spills in the marine environment. The first work employing a simulation approach assuming the oil spill trajectory as one the main variables in the risk was performed by Smith et al. [96] for the U.S. Outer Continental Shelf (Atlantic coast, Eastern Gulf of Mexico, Southern California and Western and Northern Gulf of Alaska). Based on oil spillage data bases, the authors estimated the probability of occurrence for the points of interest. Assuming an spill to have occurred, the most likely trajectory was estimated based on a set of hypothetical trajectories under randomly sampled winds and currents from observed data. In other words, the authors assumed that simulating hypothetical spills under a a huge number of combinations of winds and currents would approximate the simulated pattern to the actual most likely trajectory. This is a very important concept and should be kept in mind for the next paragraphs.

Back in 1982, meteo-oceanographic data (e.g. winds, currents, waves) were restricted to observational time series and approximating the simulated "most likely spill trajectory" to the "truth" meant dealing with enormous sources of uncertainties. In 2003, Price et al. developed the OSRAM model following the insight first proposed by Smith et al. [96]. Based on a 12-year long modelled hindcast of winds and currents for the U.S. portion of the Gulf of Mexico, Price et al. [83] simulated the most likely trajectories of hypothetical oil spills originated at the recently leased oil fields and the respective impacted coastal resources. In 2003, although still restricted to some regions, ocean circulation and atmospheric models were already operationally predicting meteo-oceanographic variables in real time. This represents a change in paradigm compared to the scenario Smith et al. [96] had to face back then. Data bases describing real conditions in the oceans and in the atmosphere were becoming available with sufficient spatial and temporal resolutions and the actual issue became how to take full advantage from them.

2.2 Operational oceanographic systems

Since the first operational atmospheric forecast carried out by the Joint Numerical Weather Prediction Unit [43] and of oceanographic fields carried out by Robinson et al. [89] and Robinson et al. [90], our forecasting capabilities have substantially increased [33, 61, 80, 81, 91]. Operational forecasting became a common ground and, at present, global ocean and atmospheric forecasts covering the whole globe with few kilometers spatial and hourly temporal resolution are freely available to any user (http://marine.copernicus.eu). This "revolution" allowed the methodology proposed by Smith et al. [96] and later reworked by Price et al. [83] to be applied in many parts of the globe by, for instance, Olita et al. [75] and Canu et al. [13], which fully relied on available operational products.

Empirical OSRA approaches based on maritime casualties or simplified approaches like Smith et al. [96] did make sense in a data poor scenario. However, oceanography and meteorology have gone through an extraordinary development and this should be assimilated into a new way to perform OSRAs. This new way of performing OSRA brings new challenges though. Models are simplifications of the reality and uncertainties are inherent to their estimates, how could we address it in an OSRA?

2.3 Uncertainties in modelling

Lorenz [63] demonstrated that slight differences between initial conditions of an atmospheric forecast model may evolve into significantly different atmospheric states after a couple of days of computation. Our limited observational capacity of the atmosphere in terms of temporal and spatial resolution, and errors inherent to our modelling of the relevant atmospheric processes limit our predictability horizon. Thus, according to Lorenz's conclusions, small differences between computed initial conditions and the actual "truth" are expected to turn into considerable differences between observed and forecasted states.

The findings obtained by Lorenz [63] have evolved into a robust methodology, so called ensemble modelling, employed to address uncertainties in weather [38] and ocean [79] forecasting. Uncertainties due to the incomplete knowledge of the characteristics of oil spill events or even on oil weathering and advection processes, extrapolating Lorenz's conclusions, are also expect to significantly impact the final oil spill scenario. This insight will guide most of the steps taken in this thesis and it should be also bore in mind to quantify the uncertainty in oil spill hazard and risk mapping.

2.4 Why an OSRA in the Algarve?

Every year, about 200 million tonnes of oil flow through the main shipping corridor off the coast of Algarve, southern Portugal, transported by tanker vessels [53]. According to the Portuguese Institute of Ports, the Algarve was crossed 68,896 times by cargo vessels in 2013, from which 3,785 counts were due to tankers. Coincidentally, according to the last report devised by the Portuguese Institute of Statistics [48], the Algarve is strongly linked to the sea with over 50% of its economy relying on sea-related resources like tourism and fisheries. A conflict of interests and a coastal management issue is identified here.

In order to validate the IT OSRA as tool capable not only of quantifying the risk but also of supporting the risk management, the last step of this thesis consisted on the application of the methodology to the Algarve.

Chapter 3

Towards a common oil spill risk assessment framework - Adapting ISO 31000 and addressing uncertainties

This chapter shows the steps taken towards the proposal of a general Oil Spill Risk Assessment framework. The process consisted on reviewing the prominent literature available in the field, identifying its weak and strong points for later, in addition to the ISO 31000:2009 standard in risk assessment, incorporate it into a new OSRA framework. The developed methodology was later validated for a real oil spill case. The main output of this chapter, the OSRA framework, set the basis for the assessment of the risk in the Algarve, one of the objectives of this thesis.

The results of the experiment were communicated in the *Journal of Environmental Management* with the following referencing:

Sepp Neves, A.A., Pinardi, N., Martins, F., Janeiro, J., Samaras, A., Zodiatis, G., De Dominicis, M., 2015. Towards a common oil spill risk assessment framework – Adapting ISO 31000 and addressing uncertainties. *Journal of Environmental Management* 159, 158–168.

and in the recent MEDSLIK-II meeting of the Steering Committee from the 29th to the 30th of July, 2015, in Bologna, Italy.

Abstract

Oil spills are a transnational problem, and establishing a common standard methodology for Oil Spill Risk Assessments (OSRAs) is thus paramount in order to protect marine environments and coastal communities. In this study we firstly identified the strengths and weaknesses of the OSRAs carried out in various parts of the globe. We then searched for a generic and recognized standard, i.e. ISO 31000, in order to design a method to perform OSRAs in a scientific and standard way. The new framework was tested for the Lebanon oil spill that occurred in 2006 employing ensemble oil spill modeling to quantify the risks and uncertainties due to unknown spill characteristics. The application of the framework generated valuable visual instruments for the transparent communication of the risks, replacing the use of risk tolerance levels, and thus highlighting the priority areas to protect in case of an oil spill.

3.1 Introduction

According to the Oil Tanker Statistics published by the International Tanker Owners Pollution Federation (ITOPF) [53], the number of oil spills in the sea and the volume of oil added to the marine environment has decreased over the last 44 years. However, there are still uncertainties regarding the origin of these spills. Vessel-related oil pollution is usually grouped into accidental or operational events. Accidental oil spills are associated with maritime casualties, e.g. grounding or collision, ranging from small (less than 7 tons) to very high volumes (it is claimed that 63,000 tons of oil were spilled during the Prestige crisis). Operational events are small, but frequent, intentional or inadvertent spillages in the sea due to ship operations (e.g. tank washing). Accidental oil spills and their impacts have been addressed by several studies [41, 56, 64, 93], however, little attention has been paid to operational events. The Committee on Oil in the Sea of the US National Research Council [105] estimates that 270,000 tonnes per year are discharged due to ship operations, corresponding to 21% of the total volume of oil spilled into the sea including natural and land-based sources. The operational share reaches 51% if natural and land-based sources are not considered.

Ship-borne transportation and the size of tankers have been increasing and this trend is likely to persist [77]. Accordingly, oil spills will continue to represent an environmental threat to marine and coastal areas. At present, there is no commonly accepted method to assess the environmental impacts of oil spills, and Oil Spill Risk Assessments (OSRAs) need to be scientifically and operationally tested.

Literature has demonstrated that oil spills are usually a transnational problem (e.g. Coppini et al. [16], Höfer [45]) which makes the reporting and the response to oil pollution an international contingency regulation problem [67]. This concern is of political importance and the European Directive on the Safety of Offshore Oil and Gas Operations recommends that the activity should follow international regulations on environmental impact assessments since accidents in one

Member State may impact on other Member States, thus stressing the importance of risk assessments on the decision-making process [28]. In order to improve the preparedness for oil spill accidents and operational releases at an international level, it is necessary to define a common methodology for an OSRA.

Some key points need to be addressed by a general oil spill risk-mapping methodology. It should be based on a solid theoretical basis, which must be robust and generic enough to be replicated in different coastal environments and hazard scenarios. Finally it should rely on easy-to-access datasets, unlike previous attempts which relied on expensive and site-specific accident statistics and environmental data. In 2009, the International Standardization Organization (ISO) published the ISO 31000 defining principles and guidelines for risk management [51]. The standard was developed with the contribution of experts from different backgrounds [84] providing guidelines for risk management in any field with the aim of furnishing a common basis to tackle the lack of standards. Given the robustness of the ISO approach and its wide acceptance, we believe the adoption of the ISO as the backbone and guideline of an OSRA framework is the first step towards a standard methodology. Thus in our study we developed an ISO compliant OSRA framework and applied it to the Lebanon oil spill crisis occurred in 2006, showing the potential of the new methodology.

The paper is organized as follows. In Section 2 we review and classify existing OSRA papers using the Landquist et al. [59] items. In Section 3, we map the ISO 31000 standard to OSRA principles and propose a new framework . In Section 4 we carry out a case study. Finally, the discussion and conclusions are presented in Section 5.

3.2 Reviewing the present OSRA literature

Six fundamental papers were chosen as examples of risk mapping methodologies. The report drafted by the Queensland Transport in association with the Great Barrier Reef Marine Park Authority [85], hereafter A, was the first to implement a standard for an oil spill risk assessment. The Risk of Vessel Accidents and Spills in the Aleutian Islands [100], B, is the compilation of guidelines and insights for a future risk assessment in the archipelago. Two studies, Olita et al. [75], hereafter C, and BOEM [9] (in association with Price et al. [83] and Price et al. [82]), D, were included because of their innovative methods to compute the oil spill hazard. Transport Canada [99], E, provides an innovative approach for a quantitative estimation of risk. Martini and Patruno [69], F, was included for an OSRA in the Eastern Mediterranean Sea, one of the busiest maritime routes worldwide. The list of papers and their corresponding letters are presented in Table 3.1.

Paper	Corresponding letter
QT&GBRMA [85]	A
Transportation Research Board [100]	B
Olita et al. [75]	C
BOEM [9]	D
Transport Canada [99]	E
Martini and Patruno [69]	F

Table 3.1: Reviewed documents and their corresponding letters.

The papers were analyzed using the methodology proposed by Landquist et al. [59]. The first step consists of listing the items to be included in the Risk Assessment, namely *Establishing the Context, Risk Identification, Risk Analysis* and *Risk Evaluation* according to ISO 31000. Each item is subdivided into elements, as described in Figure 3.1. In total, twenty one elements and sub-elements were searched for in each reviewed paper, and a final mark was attributed based on the percentage of elements considered. The results obtained are shown in Table 3.2.

Landquist et al. [59] items	Paper A (%)	Paper B (%)	Paper C (%)	Paper D (%)	Paper E (%)	Paper F (%)
Establishing the context	90	100	60	60	70	50
Risk identification	100	100	50	75	75	50
Risk analysis	80	80	60	80	80	0
Risk evaluation	100	100	0	0	50	50
Overall score	90	95	57	62	76	38

Table 3.2: Reviewed documents and their respective scores.

By far the most complete methodologies were those proposed in documents *A, B* and *E*, considering more than 75% of the parameters listed by Landquist et al. [59]. *C* and *D* scored intermediately followed by F which fulfilled only 38% of the required items.

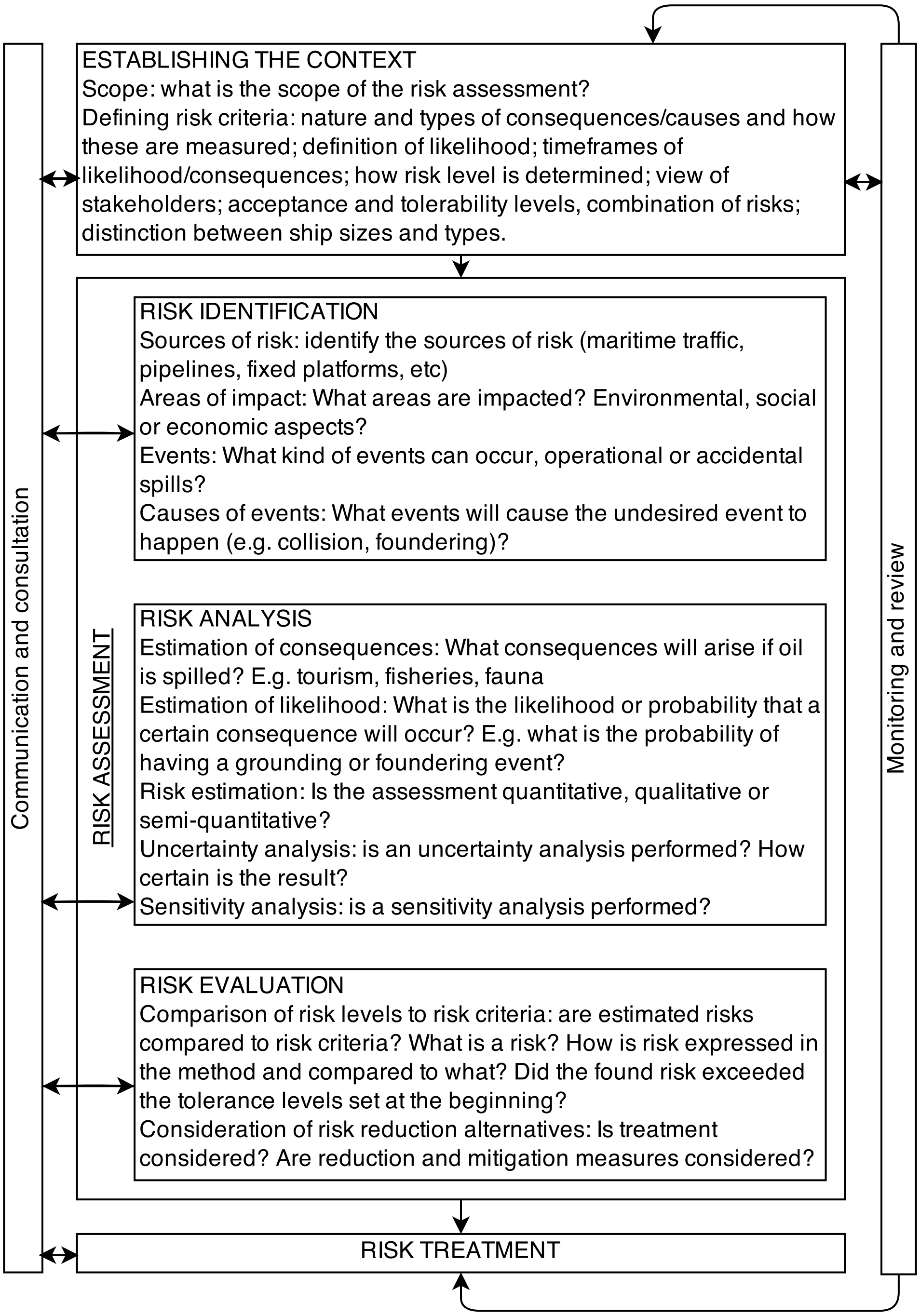


Figure 3.1: ISO-based risk management framework from Landquist et al. [59] adapted to OSRA. Items are in capital letters inside the horizontal boxes with their respective elements in lower case.

The link between maritime accidents and oil spills is clear which was covered by all the documents reviewed. However, the majority (*C,D,E* and *F*) did not consider the different accident types separately together with their respective consequences. *A* implicitly regarded the difference between accidents by narrowing the analysis to collision and grounding accidents. Initially focused on shipwreck risks, Landquist et al. [59] included an item addressing the ship size. Half of the studies (*A, D* and *E*) did not take variations in ship size into consideration.

A dichotomy was observed in the papers regarding the estimation of the oil spill hazard. *A, B* and *E* fully relied on accident frequencies based on both global and local databases. *C* and *D* heavily relied on simulations of oil spill trajectories, estimating hazards based on the probabilities of a given spill in a given spot reaching the coastline. *F* did not clearly describe how the oil spill hazard was defined.

All the papers clarified the sources of risk. *A,B* and *E* considered both bunker and cargo oil as a potential hazard. *E* only took into account crude oil transported by tankers, while *D* also included fixed platforms and pipelines. None of the reviewed OSRAs included operational oil spills as a potential source of risk.

There was considerable variety in the methodologies used to estimate consequences during the *Risk Analysis* process. *A, B, D* and *E*, at first glance, all considered the environmental, social and economic impacts of oil spills. However, *A* estimated the severity of the consequences with three vulnerability levels by integrating the three areas. On the other hand, *E* performed two separate analyses: one socioeconomic and one environmental. The OSRA *D* adopted a "binary" approach, in which a given coastal sector can be considered as important or not. Finally, *C* only considered coastal vulnerability with respect to two indicators: coastal geomorphology and protection level. In spite of the evident differences in consequences between big and small spills, only *B, D* and *E* used spill size as a factor affecting the consequences.

E adopted a quantitative approach to estimate the risk, computing the socioeconomic consequences using the concept of "statistical losses" and the environmental component in terms of estimated mortality rates for key bird species. *C* used a semi-quantitative approach, combining probabilities of oil reaching the coast with vulnerability indicators in order to generate a risk index ranging from 0 to 1. No comments were presented in terms of weighting indicators. Conversely, *A* opted for a qualitative approach using a risk matrix with three levels of likelihood and three levels of impacts. Finally, *B* proposes a two-phased strategy in which first a semi-quantitative approach is employed for the identification of the main sources of risk, which are further quantitatively estimated in the following phase. Despite using the "binary" approach to estimate impacts, *D*, did not present the methodology applied to estimate risk levels. *F* did not cover this topic.

Risk assessments should include an appraisal of uncertainties. Among the reviewed papers, only *A,B,D* and *E* considered uncertainties in their analyses. *A* tackled uncertainties using a conservative approach in the definition of the risk index. *E* identified the estimation of accident frequencies as the main source of uncertainties. *D* performed thousands of oil spill simulations, addressing uncertainties in meteo-oceanographic conditions, however it was limited to the hazard component of the risk equation. In general, no OSRA paper carried out a proper combined analysis of uncertainties in the hazard and vulnerability components of the risk assessment problem.

3.3 Adapting the ISO 31000 to oil spill risk assessments

The ISO standard was designed to be applied to a wide range of topics. Therefore, mapping it to the topic of interest prior to its application is of primary importance. The methodology proposed by Landquist et al. [59] is suitable for shipwrecks but oversimplified for cases in which maritime traffic and oil production are both likely sources of oil spills. The International Oil and Gas Producers Association (OGP) also developed an ISO-compliant framework to give support to offshore oil production companies, aimed at exploration/production facilities from an operator perspective. In this section, the ISO items are interpreted as OSRA items and compared to what has been previously proposed by Landquist et al. [59] and the OGP. The results are summarized in the Table 3.3.

	ISO 31000	Landquist et al. (2013)	OGP	New OSRA
Establishing the context				
1	The social and cultural, political, legal, regulatory, financial, technological, economic, natural and competitive environment, whether international, national, regional or local			International and domestic legislation on oil spill pollution (e.g. MARPOL, MSFD)
2	Key drivers and trends impacting on the objectives of the organization			Drivers and trends impacting on the oil spill hazards (e.g. increase in maritime traffic or ship size, changes in oil type)
3	Relationships with, perceptions and values of external stakeholders			Perceptions of stakeholders (e.g. fishermen, tourism-related entrepreneurs, NGOs) regarding the oil spill hazard
4	Governance, organizational structure, roles and accountabilities			Governance, roles and accountabilities on oil spill prevention, detection and combat
5	Policies, objectives, and the strategies that are in place to achieve them			Environmental standards, policies and objectives to be achieved (e.g. MSFD)
6	Capabilities		Risk mitigation measures (oil spill prevention, preparedness and response)	Capabilities on oil spill prevention, detection and combat (e.g. aerial surveillance, contingency resources available)
7	The relationships with and perceptions and values of internal stakeholders and the organization's culture			
8	Information systems, information flows and decision making processes			Oil spill contingency plan (accident reporting-detection-combat)
9	Standards, guidelines and models adopted by the organization			Standards, guidelines and models adopted by the organization
10	Form and extent of contractual relationships			
11	Defining the goals and objectives of the risk management activities		Implicit (the document is focused on risk assessment and response planning for offshore installations)	Goals and objectives of the oil spill risk management
12	Defining responsibilities for and within the risk management process		Responsibilities related to planning and execution	Responsibilities in the risk management process
13	Scope, depth and breadth of the risk management activities, including specific inclusions and exclusions	Scope and distinction between ship sizes and types	Scope, boundaries and basis for the OSRA and level of detail	Scope and depth of the OSRA, including specific inclusions and exclusions
14	Activity, process, function, project, product, service or asset in terms of time and location			Geographical coverage and life span of the OSRA
15	Relationships between a particular project, process or activity and other projects, processes or activities of the organization			
16	Risk assessment methodologies		Establish methods, models and tools	Establish methods, models and tools
17	Performance and effectiveness measurement strategies			Define the way performance and effectiveness are evaluated in the management of risk
18	Identifying and specifying the decisions that have to be made			
19	Identifying, scoping or framing studies needed, their extent and objectives, and the resources required for such studies			Identifying information/instruments needed for a better risk management

continued on the next page

	ISO 31000	Landquist et al. [59]	OGP	New OSRA
Risk identification				
20	The nature and types of causes and consequences that can occur and how they will be measured	Nature and types of consequences/causes and how these are measured	Establishing methods, models and tools to be used in the process	Accident types, their causes and consequences, and how they will be measured
21	How likelihood will be defined	Definition of likelihood	How likelihood will be defined	How likelihood will be defined
22	How the level of risk is to be determined	How risk level is determined	How the level of risk is to be determined	How the level of risk is determined
23	The time frame(s) of the likelihood and/or consequences(s)	Time frames of likelihood/consequences		Time frame of the likelihood and consequences
24	The view of stakeholders	The view of stakeholders	View of stakeholders	View of the stakeholders regarding hazards, impacts and risk determination method
25	The level at which risk becomes acceptable and tolerable	Acceptance and tolerability levels	Risk tolerance criteria	
26	Whether combinations of multiple risks should be taken into account and, if so, how and which combinations should be considered	Combinations of risks		Combination with other risks and how this will be considered
27	Sources of risk	Sources of risk	Identify hazards associated with the facilities and operations being studied	Potential sources of oil pollution
28			Potential volumes of hydrocarbons discharged/type of hydrocarbon released	Variables affecting the oil spill hazard and impacts and how they will be measured
29	Areas of impacts	Areas of impacts	Areas of impacts (environmental, social and, economic)	Areas of impacts (environmental, social and economic)
30	Events	Events	Identify the potential characteristics of hazardous events	Pollution events considered (operational and/or accidental oil spills)
31	Causes of events	Causes of events	Identify circumstances which may trigger hazardous events	Causes of events
Risk analysis				
32	Consequences of events	Estimation of consequences	Consequence of events	Estimated environmental, social and economic impacts in the area
33	Likelihood of consequences	Estimation of likelihood	Likelihood of the identified hazardous events	Likelihood of actually polluting vulnerable areas
34	Existing controls and their effectiveness/efficiency		Identify potential preventive measures	Effectiveness and efficiency of the available oil spill prevention, detection and combat instruments
35	How risk levels are estimated and expressed	How risk levels are estimated and expressed	How risk levels are estimated and expressed	How risk levels are estimated and expressed
36	Uncertainty analysis	Uncertainty analysis	Uncertainty analysis	Uncertainty analysis
37	Sensitivity analysis	Sensitivity analysis	Sensitivity analysis	Sensitivity analysis
Risk evaluation				
38	Comparison of risk levels to risk criteria	Comparison of risk levels to risk criteria	Comparison of risk levels to risk criteria	
39				Risk communication tools and information dissemination
40	Identifying risks that need treatment		Identification of main factors contributing to risk	
41	Prioritization for risk treatment		Prioritization for risk treatment	Prioritization for risk treatment
42	Consideration of risk reduction alternatives	Consideration of risk reduction alternatives	Consideration of risk reduction alternatives	Consideration of risk reduction alternatives

Table 3.3: Comparisons among the available OSRAs methodologies and presentation of the new ISO-based OSRA framework.

In the *Establishing the Context* ISO step of Table 3.3, objectives, scope, strategies, responsibilities and accountabilities should be stated, followed by a description of the criteria used to define risk and the methodology employed to estimate it. In the OSRA case, the first step should be to define the character of the analysis (qualitative, quantitative or a combination), limit the geographical area and define the specific hazards and impacts to be considered. It should also contain the relevant legislative regulations related to oil pollution and environmental quality standards. Institutions working on oil spill reporting, such as the European Maritime Safety Agency (EMSA), and response (e.g. Coast Guard) should be identified and taken into consideration. Clearly, the actual needs of the institution implementing the risk management should also be stated.

OGP and Landquist et al. [59] failed to carry out a comprehensive review of the legislation on environmental standards and oil pollution, and of the interactions among institutions. For example, environmental standards are mainly regulated by the Marine Strategy Framework Directive (MSFD) in the context of the European Union, which requires the establishment of environmental targets and the implementation of monitoring indicators. In this way, the MSFD is expected to impact, for instance, the way oil spill consequences are estimated and the indicators adopted for risk monitoring. Where a risk tolerance level is proposed, it should take into account the general guidelines and the standards of good environmental status proposed by the Directive. Based on the ISO guidelines, elements regarding the *"International and domestic legislation on oil spill pollution"* (Element 1 in Table 3.3. Hereinafter only numbers will be presented.), *"Governance, roles and accountabilities on oil spill prevention, detection and combat"* (4) and *"Environmental standards, policies and objectives to be achieved"* (5) were included in our framework.

Trends in both hazards (e.g. increase in maritime traffic or oil production) and impacts (e.g. increase in population in coastal areas or in the share of the sea related economy) were addressed in our framework through the element *"Drivers and trends impacting oil spill hazard"* (2). OGP and Landquist et al. [59] did not consider long-term variations in oil spill risks and OGP did not address the possible combination of risks.

One of the recommendations of ISO 31000, followed by Landquist et al. [59] and OGP, is the definition of risk tolerance levels during the establishment of the context. This may not be applicable for OSRAs ([31], [5], [4], [7]) and was disregarded in our framework. The element *"Risk tolerance criteria"* (25) was thus removed.

Establishing the Context is followed by a *Risk Identification* step (Table 3.3). According to ISO 31000, the organization must "*identify sources of risk, areas of impacts, events (including changes in circumstances) and their causes, and their potential consequences*". When mapping it to OSRA, it is important to bear in mind that both operational and accidental oil spills represent hazards to the marine environment. The decision to address one or both risk sources will depend on the scope of the OSRA, however, to assume negligible impacts of operational oil spills in the environment is a mistake. In agreement with Landquist et al. [59], the element *Events* was rewritten as *"Pollution events considered - operational and/or accidental spills"* (30), given the growing awareness on the role operational discharges of oil play on marine pollution. The OGP framework does not take operational pollution events into consideration.

Variations in the oil spill risk have been identified by previous studies as being due to, for instance, sea conditions [8, 27], and maritime traffic distributions [75]. In our framework, the risk was considered as a dynamic index, in which short-term spatial and temporal variations were tackled including the element *"Variables modulating the oil spill hazard and impacts and how they will be measured"* (28), which may include, for instance, changes in meteo-oceanographic conditions and their respective impacts on oil trajectories and accident probabilities, or seasonality in maritime traffic.

Studies such as Grigalunas et al. [41], O'Rourke and Connolly [77], McCay et al. [71] and García Negro et al. [37] determined the multiple impacts associated with the oil industry. They demonstrate that impacts are not restricted to the biota, but also include the economy and society. Thus, coastal vulnerability should be considered as a composite index, covering environmental, social and economic aspects, as recommended in item (29). This is a common practice in OSRA, however some analysts still neglect it. A description of the process behind the construction of the vulnerability index is rarely presented. It is advisable that the inclusion/exclusion of variables in an index and their respective weighting should represent the priorities of the local stakeholders.

Once risks are identified, a *Risk Analysis* process must be undertaken, where the identified risks are quantified. Firstly, operational and accidental oil spills should be treated separately since the former can be considered as a high frequency/low impact hazard, while the latter is characterized by low probabilities/high impacts. This approach is recommended by the ISO and by the Organisation for Economic Co-operation and Development [76] and prevents the inappropriate combination of the two components in the risk analysis.

Assessments of uncertainties should play a major role in the *Risk Analysis* and, in accordance with ISO 31000, we added them to the OSRA framework (36). Concerning marine OSRA, oil spill characteristics (e.g. oil type, moment of spillage, spill rate, spilled volume) and meteo-oceanographic conditions affect the oil trajectory and, therefore, the coastal segments impacted. It is difficult to get precise oil spill characteristics either for accidental or operational events, and meteo-oceanographic fields have large uncertainties especially for long-term forecast, thus making those two components the dominant sources of uncertainty in OSRA. An innovative method to address uncertainties will be part of the *Risk Analysis* step in the Lebanon case study that will follow.

Assuming the *Risk Identification* process has considered oil spill risks as significantly variable in the area of interest, this should be quantified. Although seldom considered, existing controls (e.g. early warning systems, response plans, etc) should be taken into consideration. Therefore, the item *"Effectiveness and efficiency of the available oil spill prevention, detection and combat* *instruments"* (34) was included in our OSRA framework, complementing the *"Identify potential preventive measures"* proposed by the OGP. Landquist et al. [59] does not consider control measures.

The final step recommended by ISO 31000 is to undertake a *Risk Evaluation* process. It is argued that risks estimated during the *Risk Analysis* step should be compared to the previously defined tolerance levels in the *Establishing the Context* step, thereby identifying and prioritizing those that actually need treatment. We propose replacing it by the development of *Risk communication tools and information dissemination* (39) to inform the *Risk Analysis* outputs, expressing risk magnitude, spatial-temporal variations of risk, uncertainties and risk interactions, and comparing alternatives [62]. In addition, we removed the element *"Identifying risks that need treatment"* (40) proposed by the ISO 31000 on the basis that any risk should be kept as low as reasonably practicable.

In conclusion, Table 3.3 contains the 35 final elements of the OSRA for accidental and operational oil spills. In the next section this methodology is applied to the Lebanon case study.

3.4 The OSRA case Study: 2006 Lebanon crisis

Between the 14th and 15th of July, 2006, two oil depots of the Jiyeh power station, located in Lebanon, were shelled during the Israel-Lebanon hostilities, spilling between 10,000 and 20,000 tonnes of oil. The OSRA framework proposed in Section 3 was applied to the Lebanon oil spill crisis and the results are presented in Table 4.1. The assumptions made for each of its elements are described below.

It is clear that our case study covered only one source of risk, i.e. a power plant explosion, and that an OSRA should be carried out for many other sources of risk, however this is outside the scope of this case study.

Establishing the context		
1	International and domestic legislation on oil spill pollution	International agreements signed by the Lebanese government: Barcelona Convention, Emergency Protocol '76, MARPOL, CLC '69 [69]. Domestic regulation: Law on the Protection of Environment 444/02 [70]
2	Drivers and trends impacting oil spill hazard	The energy policy scenario in Lebanon was described by Houri [46] as an increasing share of oil-related energy production, depicting a positive trend in the oil spill hazard. By July, 2006, the hostilities with Israel were growing, modulating the main driver (for the present assessment) of the oil spill hazard
3	Perceptions of stakeholders regarding the oil hazard	Djoundourian [25] states that the environmental awareness of the Lebanese society was little before the Jiyeh event and going through a downward trend.
4	Governance, roles and accountabilities on oil spill prevention, detection and combat	Ministry of the Environment (government)/ Directorate General for Ports and Port Authorities (operational responsibility)
5	Environmental standards, policies and objectives to be achieved	Law 690/2005 entrusts the Ministry of Environment as the institution responsible for setting the environmental standards [72]. By the time of the accident, no standard had been proposed [15].
6	Capabilities on oil spill prevention, detection and combat	Government and private response equipment to tackle minor oil spillages [69]
7	Oil spill contingency plan	By 2006 Lebanon had no National Contingency Plan [69]. Neighboring countries (i.e. Egypt, Israel and Cyprus) developed an international contingency plan within the Barcelona Convention.
8	Standards, guidelines and models adopted by the organization	The Lebanon Government requested through REMPEC oil spill modeling predictions but the Lebanese Government was not yet organized to use such information as a risk reduction policy in case of oil spills.
9	Goal and objectives of the oil spill risk management	To improve the environmental status of the marine and coastal areas surrounding the Jiyeh power station.
10	Responsibilities in the risk management process	Jiyeh power station
11	Scope and depth of the OSRA, including specific inclusions and exclusions	To evaluate a posteriori the probability of oil beaching due to a single source of risk: the shelling of an oil storage unit at the Jiyeh power station.
12	Geographical coverage and life span of the OSRA	Lebanese coast during the month of July 2006
13	Establish methods, models and tools	Ensemble oil spill simulations will be combined with a coastal vulnerability index map
14	Define the way performance and effectiveness are evaluated in the management of risk	e.g. accident simulations, risk acceptance by the local community.
15	Identifying information/instruments needed for a better risk management	The World Bank [110] identified that, in addition to the engagement of the stakeholders, valid information about tourism, biodiversity and fisheries was lacking prior to the Jiyeh oil spill, thus compromising the ecosystem management.
16	Accident types, their causes and consequences and how they will be measured	Complete rupture of an oil storage unit due to explosion resulting in a catastrophic spill.
17	How likelihood will be defined	Likelihood is defined as the probability of the oil reaching the coast based on oil spill simulations.
18	How the level of risk is determined	Quantitatively.
19	Time frame of the likelihood and consequences	Valid for July 2006. Longer ensemble simulation should be carried out for longer time frame.
20	View of the stakeholders regarding hazards, impacts and risk determination method	Not applicable for the case study. Such analysis should have been undertaken prior to the accident since an accident in the past may change the view of the stakeholders.
21	Combination with other risks and how this will be considered	Assumed as negligible for the case study.
Risk identification		
22	Potential sources of oil pollution	Jiyeh oil storage units
23	Variables affecting the oil spill hazard/impacts and how they will be measured	Variations in meteo-oceanographic conditions and oil spill characteristics (volume, spill rate and type of oil) and their respective impacts on the oil spill hazard will be measured through ensemble oil spill simulations.
24	Areas of impacts (environmental, social and economic)	Cultural and ecological aspects proposed by UNEP - ROWA [103].
25	Pollution events considered	Accidental oil spill
26	Causes of events	Intentional attack on the oil storage unit
		continued on the next page

Risk analysis		
27	Estimated environmental, social and economic impacts in the area	From our analysis, 9 out 15 of the high priority and 13 out the 20 medium priority coastal sites were impacted by the spill with different volumes (Figure 3.6a) and uncertainties (Figure 3.6b)
28	Likelihood of actually polluting vulnerable areas	Presented in Figure 3.7a
29	Effectiveness and efficiency of the available oil spill prevention, detection and combat instruments.	Spill detection system unavailable and combat instruments unable to tackle large spills
30	How risk levels are estimated and expressed	Risk levels are calculated in a quantitative manner through Equation 1 and expressed in relative levels between 0 and 1.
31	Uncertainty analysis	Sources of uncertainty are: meteo-oceanographic inputs for the oil spill model, oil spill model setup as volume of oil spilled, time of spillage and duration of the spill (Figure 3.7b)
32	Sensitivity analysis	The ensemble simulation demonstrated that among the evaluated variables (i.e. oil type, spilled volume, spill time and duration of the spill) the duration of the spill and oil type were the main variables controlling the distribution of oil on the coast (Figures 3.4 and 3.5)
Risk evaluation		
33	Risk communication tools and information dissemination	Visual representation of cultural-ecological priority sites (Figure 3.2), modeled oil spill beaching (Figure 3.6a) and its variability (Figure 3.6b), probability of coastal contact (Figure 3.7a), total risk (Figure 3.9) and its uncertainties (Figure 3.7b).
34	Prioritization for risk treatment	Priority areas for treatment are defined based on Figure 3.9.
35	Consideration of risk reduction alternatives	According to the International Convention on Oil Pollution Preparedness, Response and Cooperation [50], some key points should be covered in order to reduce the risk: (1) local oil pollution emergency plan, (2) oil spill reporting system, (3) definition of national/regional competent authorities, (4) national contingency plan, (5) minimum response equipment available and (6) international cooperation.

Table 3.4: OSRA framework applied to the Lebanon crisis, 2006.

3.4.1 Establishing the Context

The main goal of the OSRA was to improve the environmental status of the marine and coastal areas surrounding the Jiyeh power station regarding accidental oil pollution (element 9 in Table 4.1. Hereinafter only element numbers will be presented). The Jiyeh power station was the only source of risk addressed and therefore, for the purposes of our case study, it was considered as the main entity responsible for the risk management (10). Secondly, only one type of event was considered: the intentional explosion of the oil storage units (11, 16, 21).

Although Lebanon is a signatory of international agreements on marine oil spill control (1), the country had no national contingency plan when the spill occurred (7), no related standards/guidelines/models (8) and only limited capacity to respond to large-scale oil spills (6). The implementation of domestic environmental legislation was still ongoing (5), designating the Ministry of the Environment as the reference point at the governmental level regarding oil spills, and the Directorate General for Ports and Port Authorities at the operational level (4). Environmental awareness of the stakeholders was limited (3). Two main drivers contributed to an overall increase in the oil spill risks: hostilities with Israel were growing and the energy policy in Lebanon was moving towards increasing oil-derived energy production (2).

The geographical coverage of the OSRA should not be restricted to Lebanese waters. Satellite images analyzed by Coppini et al. [16] during the crisis and the UNEP-Regional Office for West

Asia report [103] showed that parcels of oil also reached the Syrian coast transported by currents and waves. However, in order to keep the analysis concise, the risk assessment was limited to the Lebanese coast (12).

The likelihood was estimated through oil spill simulations (17), which were later combined with coastal vulnerability data to produce the quantitative risk scenario for a catastrophic spill (13, 18). The time frame of the assessment was restricted to July 2006 due to the inputs used to run the oil spill simulations (19).

According to the report devised by the World Bank [110], more information on tourism, biodiversity and fisheries was necessary to better estimate the impacts of the Jiyeh oil spill (15). The report also highlighted the importance of stakeholder involvement for a better risk management (15, 20). Finally, the effectiveness of the OSRA could be improved, for example, via accident simulations and risk acceptance surveys, although public participation in defining performance indicators is paramount (14).

3.4.2 Risk Identification

As previously discussed, the only potential source of risk in the OSRA was the power station oil storage facilities (22). Thus changes in risk were modulated by changes in meteo-oceanographic conditions and characteristics of the oil spill (23). After the crisis in 2006, the UNEP - ROWA [103] identified fifteen high priority and twenty medium priority sites in terms of ecological and cultural aspects (Figure 3.2) (24). Unfortunately, the report does not include accurate estimates of the socioeconomic aspects of the coastal sites. Events triggering oil pollution were restricted to an accidental oil spill (25) caused by the explosion of an oil depot (26).

a b

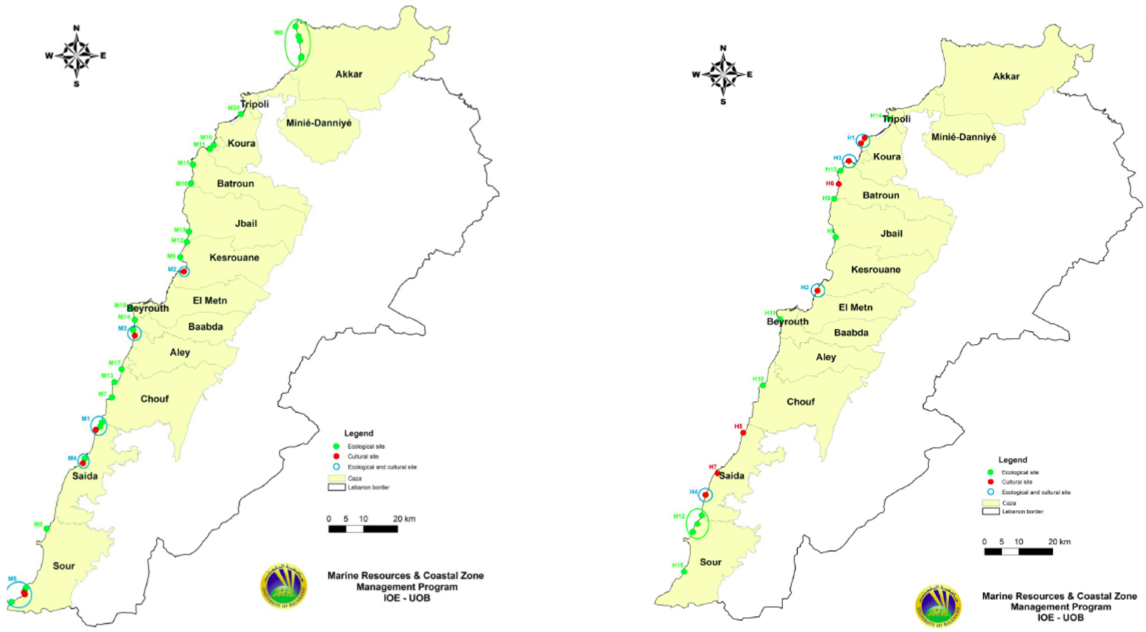


Figure 3.2: Clustered (cultural and ecological) (a) medium and (b) high priority sites for the Lebanese coast. Extracted from UNEP - ROWA [103].

3.4.3 Risk Analysis

From a quantitative perspective, the risk was estimated for each coastal sector n of the Lebanese coast using the following equation:

$$R_n = (P_{cc})_n \cdot I_n \tag{3.1}$$

where $(P_{cc})_n$ is the probability of oil beaching for the segment n and I_n are the impacts (30). I was defined for each coastal segment by adopting a vulnerability index with a value of 1 for high priority sites, 0.5 for medium priority, and 0.25 for undefined areas. Since no prevention, detection and combat instruments were identified, no controls were applied to the risk equation (29).

The ability of oil spill modeling to generate reliable predictions of the trajectory of a spill and impacted coastal segments have been successfully demonstrated by, for instance, Abascal et al. [1] for the Prestige accident off the Spanish coast and Coppini et al. [16] for the Jiyeh event. Errors related to the oil spill model were discussed at length by Coppini et al. [16] and Lardner et al. [60] with the conclusion that precise knowledge of the initial spilling event and high resolution currents were essential to reduce uncertainties. In addition, Samaras et al. [92] demonstrated the impact of uncertainties due to the definition of coastal types and in the beaching algorithm. Information on the volume spilled, spill rate and type of oil also diverged significantly, adding uncertainty to the model parameters.

Ensemble oil spill simulations were used to calculate P_{cc} and its uncertainties. A reference simulation was performed using the best model setup tested by Coppini et al. [16], forced by SKIRON high resolution winds [55] and CYCOFOS high resolution currents [112, 113] (Figure 3.3). Together with the reference simulation, eight other runs were carried out, changing one single variable at a time, covering the different information on the oil spill characteristics identified in the literature (Table 4.2). All the experiments were performed using the latest version of MEDSLIK-II oil spill model [20], including the developments proposed by Samaras et al. [92]. The results are presented in Figures 3.4 and 3.5. In order to remove spurious small scale variability in the beached oil volumes, the coastal segments were aggregated into 2km long sectors.

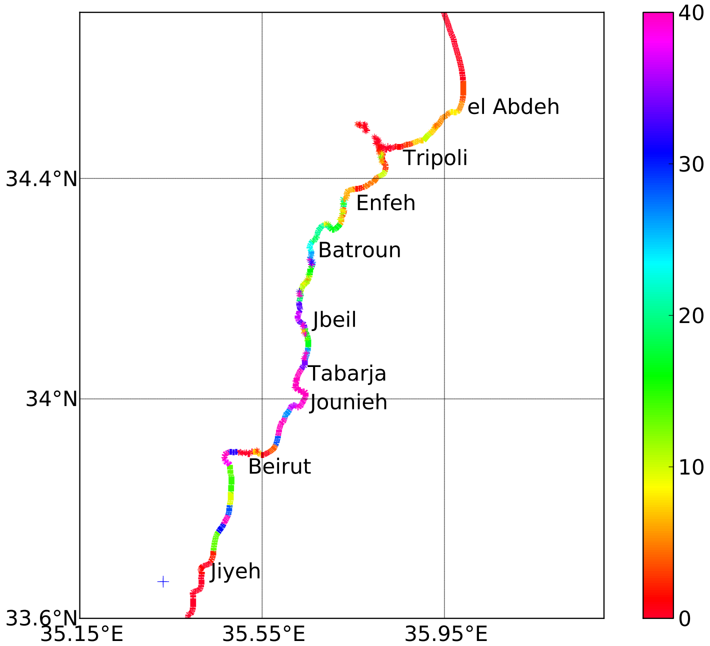


Figure 3.3: Beached oil for the 10/08/2006 - 06:00 estimated with the reference simulation based on Coppini et al. [16] (tonnes/km). Blues cross in this and in the following figures represents the initial position of the spill.

Comparisons among ensemble members and to the reference simulation, shown in Figure 3.3, suggest that the output was particularly sensitive to the duration of the spill, as demonstrated by members 7 (Figure 3.5c) and 8 (Figure 3.5d). Both show smaller or absent oil beaching south of

Configuration	Oil API	Spilled volume (tonnes)	Spill time	Spill duration (h)	Spill position
Member 1	14	18770	13/07 08:00	144	33.75N 35.33E
Member 2	26	18770	13/07 08:00	144	33.75N 35.33E
Member 3	20	10000	13/07 08:00	144	33.75N 35.33E
Member 4	20	20000	13/07 08:00	144	33.75N 35.33E
Member 5	20	18770	13/07 20:00	144	33.75N 35.33E
Member 6	20	18770	14/07 08:00	144	33.75N 35.33E
Member 7	20	18770	13/07 08:00	48	33.75N 35.33E
Member 8	20	18770	13/07 08:00	100	33.75N 35.33E
Member 9	20	18770	13/07 08:00	144	33.75N 35.33E

Table 3.5: Setup of the nine ensemble simulation members. The 9th member corresponds to the setup proposed by Coppini et al. [16].

33.8°N and the shorter duration of member 7 restricted the area of high oil concentration (> 20 tonnes/km) between the Beirut peninsula and Jbeil. Increased oil density in member 1 (Figure 3.4a) resulted in higher concentrations of oil on the coast for the whole domain. A lower volume of spilled oil led to lower concentrations on the coast, as demonstrated by member 3 (Figure 3.4c). Differences in the moment of spillage did not affect the final scenario as much as the other variables (32).

Figure 3.6 presents the ensemble mean concentration of oil on the coast and its standard deviation. In total, 9 out 15 of the high priority sites and 13 out 20 of the medium priority sites were impacted by the spill with different volumes and uncertainty. The most affected areas were the Beirut peninsula and the coastal segment from south Jounieh to Batroun. A greater uncertainty was found between Jiyeh and the Beirut peninsula, essentially due to members 7 and 8. The Enfeh and south Tripoli areas also presented considerable uncertainty compared to the mean value, primarily due to members 7 and 3 (31).

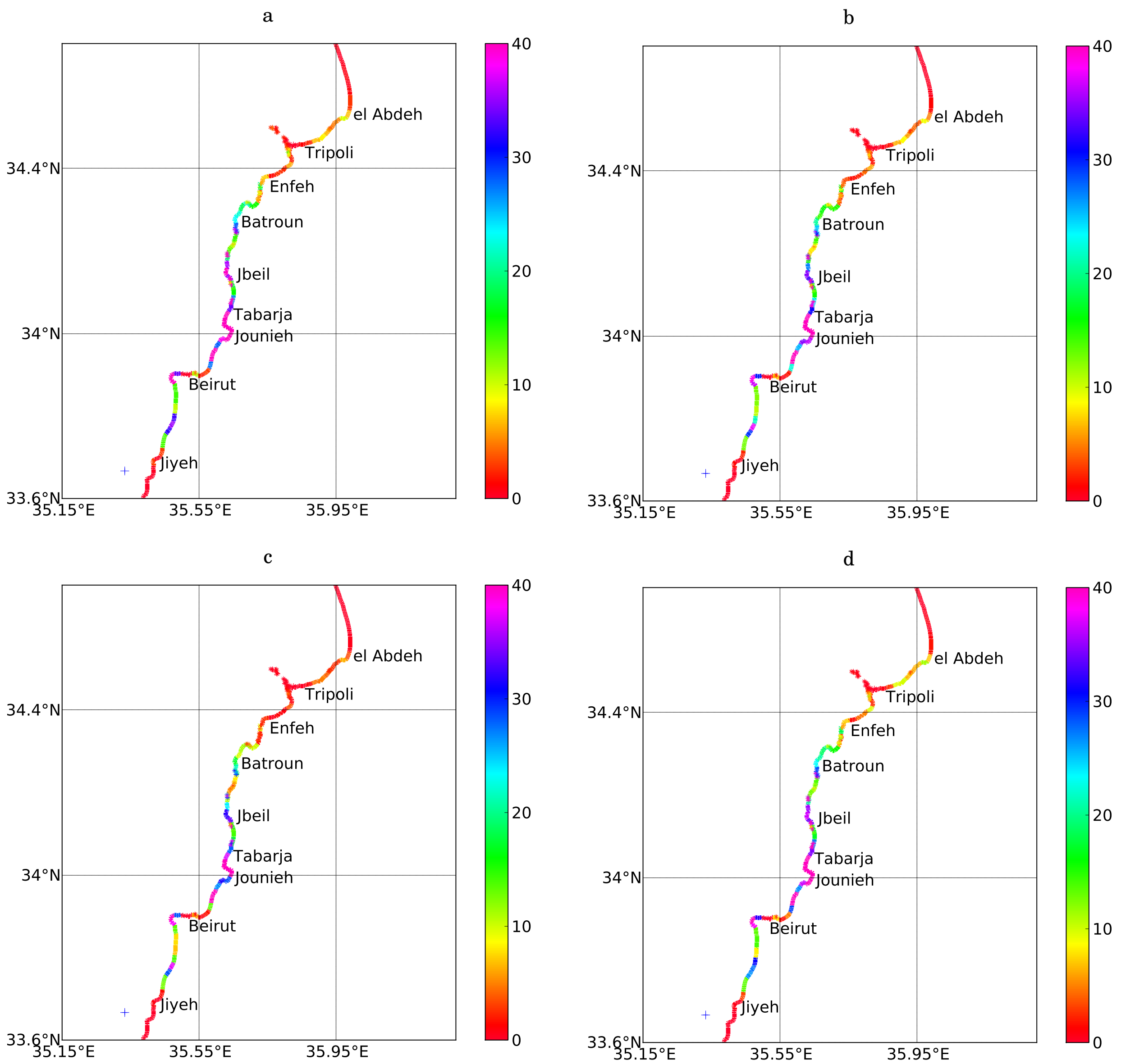


Figure 3.4: Beached oil for the 10/08/2006 - 06:00 computed by the ensemble members 1-4 (tonnes/km).

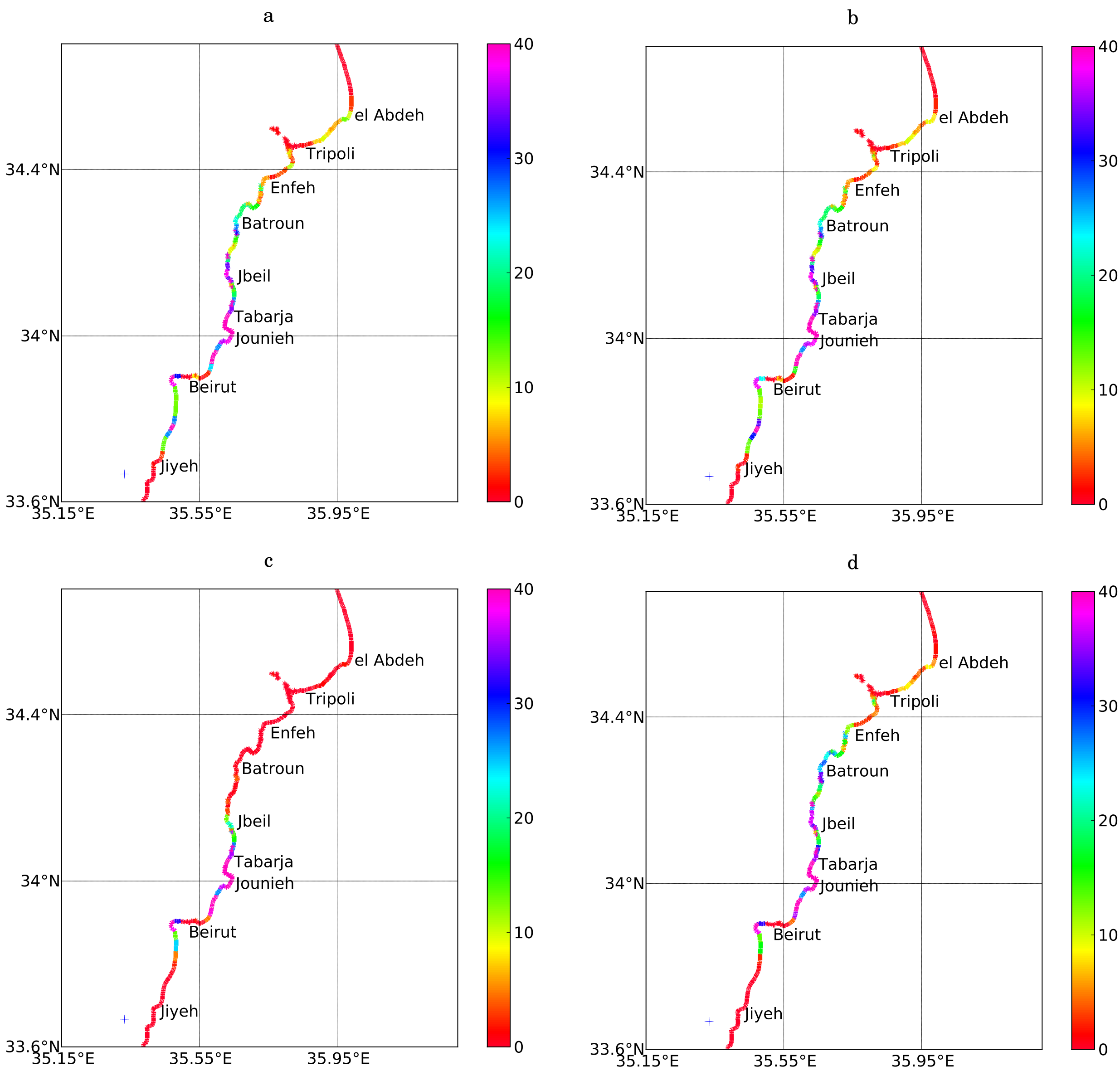


Figure 3.5: Beached oil for the 10/08/2006 - 06:00 computed by the ensemble members 5-8 (tonnes/km).

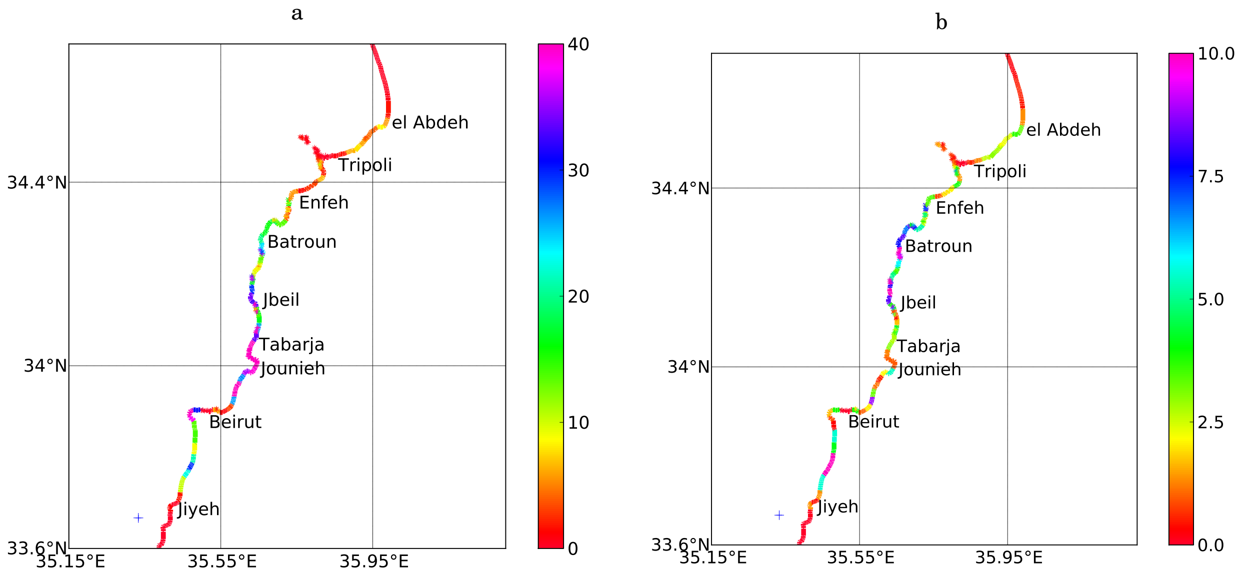


Figure 3.6: Ensemble (a) mean and (b) standard deviations of beached oil for the 10/08/2006 - 06:00 - (tonnes/km).

Based on the ensemble outputs, P_{cc} was calculated for each coastal segment as:

$$(P_{cc})_n = \frac{\overline{C_n}}{\overline{C}} \tag{3.2}$$

where $\overline{C_n}$ is the mean concentration of oil in segment n, $\overline{C}$ is the average of oil beached in all coastal segments. P_{cc} was further normalized by the maximum value of P_{cc} found in order to restrain the values along the coast between 0 and 1 (Figure 3.7a). Uncertainties in P_{cc} were calculated using the coefficient of variation, CV_n (Figure 3.7b), defined as:

$$CV_n = \frac{STD_n}{\overline{C_n}} \tag{3.3}$$

where STD_n is the ensemble standard deviation at n. The values shown were further normalized by the maximum CV on the coast.

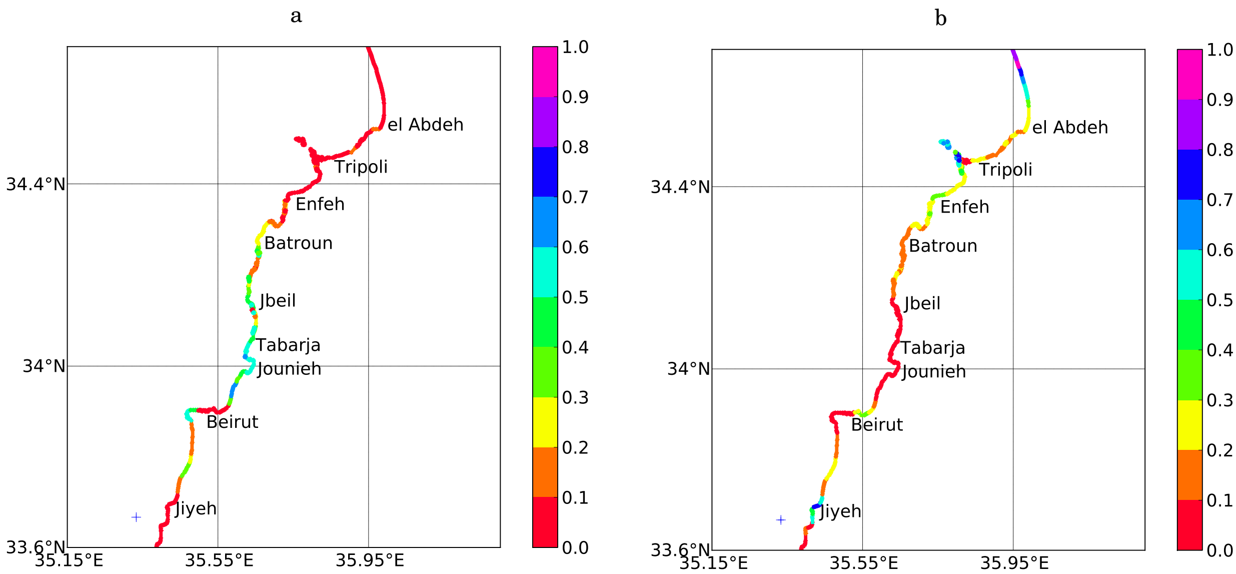


Figure 3.7: (a) Probability of oil pollution due to Jiyeh power plant accident and (b) uncertainties in the estimation.

Comparisons of P_{cc} with in-situ oil observations published by the Green Line Association [39] (Figure 3.8) show that areas with P_{cc} greater than 0.5 (Jounieh-Batroun region and Beirut peninsula) cover the majority of the areas in which oil was found after the spill. By including P_{cc} values between 0.3 and 0.5, we managed to incorporate areas between Jiyeh and Beirut. Discrepancies between observed and modeled beached oil occurred in Jounieh bay and in the area between the Jounieh bay and the Beirut peninsula. Pollution north of El Abdeh was detected by the Green Line Association [39] but the model did not reproduce that. Furthermore, pollution between Jiyeh and Beirut was underestimated. The relatively coarse spatial resolution of our input dataset (i.e. hydrodynamics, coastal types and winds) are possible contributing effects to the model failure to reproduce some of the observed features.

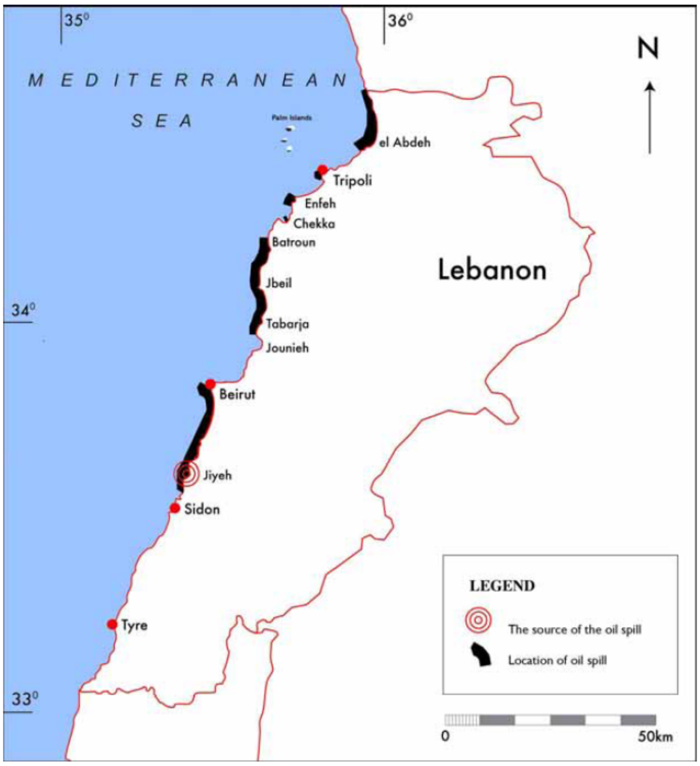


Figure 3.8: Impacted coastal sectors according to observations by Green Line Association [39].

3.4.4 Risk Evaluation

Six outputs to support the visual communication of the oil spill risk were thus generated/compiled by our framework (Figures 3.2, 3.4, 3.5, 3.6 and 3.7) (33). In Figure 3.9 we add the calculated normalized risk in which priority protection areas in the case of future spills can be identified (34). The area just south of Jounieh presented the highest risk level ($0.2 < R < 0.7$) combining $P_{cc} > 0.6$ with a high vulnerability site and $CV < 0.1$. A similar scenario was found at Jbeil with R and P_{cc} above the 0.5 threshold and medium to high vulnerability. The area of Batroun also stood out, reaching higher R and P_{cc} values than 0.4 and a high confidence level ($CV > 0.1$). Three areas (i.e. the Beirut Peninsula, Jounieh bay and Tabarja) scored intermediate risk levels (> 0.2) with high P_{cc} (> 0.5), medium vulnerability and high confidence levels ($CV < 0.1$).

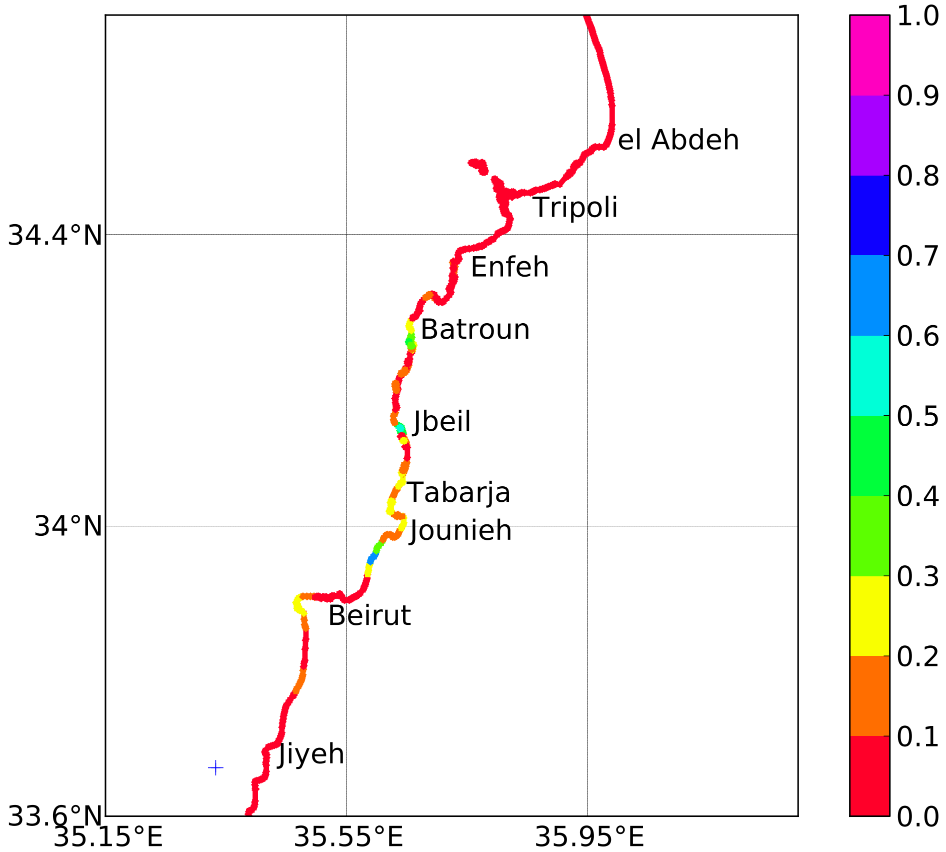


Figure 3.9: Oil spill risk evaluated by equation (1) associated with Jiyeh power station for the Lebanese coast.

The final step of our framework considers risk reduction alternatives (35). According to the International Convention on Oil Pollution Preparedness, Response and Co-operation [50], the reduction of oil spill risks involves various key issues: (1) a local oil pollution emergency plan, (2) an oil spill reporting system, (3) the definition of national/regional competent authorities, (4) a national contingency plan, (5) the minimum response equipment available and (6) international cooperation. As discussed in the *Establishing the Context* step, only the first (element 1 in Table 4.1) and third (element 4) points were fulfilled for the Lebanese case, thus making the remaining items possible alternatives for risk reduction.

3.5 Discussion and Conclusions

The results generated by reviewing the published OSRAs showed that, to date, no standard methodology has been followed by the oil spill risk community. Compared to the latest attempt to standardize risk assessments, the ISO 31000, none of the papers fulfilled all the required items proposed by the standard. We devised and tested a new framework with 35 items by mapping the

ISO 31000 to OSRAs, thus not simply translating the items of the standard, but also critically evaluating their applicability to the topic.

The case study carried out for the Lebanon crisis demonstrated that deterministic oil spill modeling can successfully predict the areas impacted by an oil spill. The application of ensemble simulations also showed that uncertainties can be addressed by combining the outputs of the ensemble members, and that relatively small changes in the oil spill characteristics may lead to significantly different results.

Seven figures were developed in the application of our framework, visually communicating the risks and replacing, in a more transparent way, the risk tolerance levels set a priori as proposed by the ISO 31000. The figures also helped to identify priority areas for protection in the case of future spills originating in Jiyeh.

Although the results obtained with the new OSRA framework for the Lebanon spill were positive and encouraging, further tests are still necessary. Only one source of risk was considered while in the future multiple sources of risk (e.g. maritime traffic, oil platforms) should be considered to give the most complete mapping of coastal oil pollution risks.

Chapter 4

IT OSRA: Applying ensemble simulations to estimate the oil spill hazard associated to operational and accidental oil spills

In this chapter, the OSRA framework developed in Chapter 3 was improved and applied to the compute the oil spill risk in the Algarve, Portugal. The preliminary results of the experiment were presented in the International Liege Colloquium in Marine Environmental Monitoring, Modelling and Prediction held in Liege, Belgium, in 2015. The following manuscript presents the final the results of the experiment and, after necessary work, will be submitted to the special issue in the Ocean Dynamics journal organized by the colloquium. The abstract submitted to the conference is presented in the Annex B.

Abstract

Oil Spill Risk Assessments (OSRAs) are widely employed to support the decision making regarding the oil spill risk. In this article, the OSRA framework developed by Sepp Neves et al. [95] was adapted to estimate the risk in a complex scenario where uncertainties related to when, where and how a spill will happen, and to the risk computation methodology (ensemble oil spill modeling) are present. The improved method was applied to the coast of the Algarve, Portugal. Over 50,000 simulations were performed in two ensemble experiments to estimate the risk due to operational and accidental spill associated to the maritime traffic. The risk was found to be important for both types of events, with significant seasonal variability due to variations, in the same temporal scale, of the currents and the waves. Higher frequency variability in the meteo-oceanographic variables were also found to actively modulate the risk. The ensemble results also pointed out to the fact that the distribution of concentrations of oil on the coast, key parameter in the definition of the risk, unlike stated by the literature, does not follow a Gaussian but a Poisson distribution. Such finding opens new fields of research, demanding innovative methodologies to deal with the oil spill risk and its uncertainties.

4.1 Introduction

Estimates published by the U.S. National Academy of Sciences ([105]) revealed that, every year, over 600,000 tonnes of oil are spilled in the marine environment due to human activities. Operational discharges associated to the maritime traffic (e.g. tank washing or leakage of lubricants) contribute with over 270,000 thousands of tonnes/year, ranking as the main anthropic input of oil to the marine environment. Vessel-related accidental spills (e.g. collisions, explosions, etc) contribute with about 100,000 tonnes/year. In spite of the 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 supporting decisions for the protection of the marine and coastal environments.

Based on a review of several OSRAs, Sepp Neves et al. [95] proposed a new OSRA framework tackling the major shortcomings identified: (1) the role of the main responsible for oil pollution in the seas, 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 been adopted until then. The core of the risk computation methodology proposed by Sepp Neves et al. [95] lies on 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 aimed on taking the methodology proposed by Sepp Neves et al. [95] one step ahead allowing its replication in complex risk scenarios where operational and accidental events are possible, the characteristics, the time and the place of an eventual spill are uncertain and the best oil spill model setup is unknown. The improved methodology, hereinafter referred to as IT-OSRA (Information Technology Oil Spill Risk Assessment), was applied to the coast of the Algarve, southern Portugal. The region combines high ecological value, with significant part of its coast protected by the Sudoeste Alentejano e Costa Vicentina and Ria Formosa natural parks, and an economy heavily relying on sea-related activities [48]. Concomitantly, the Algarve is exposed to a busy maritime route where about 200 million tonnes of oil flow through every year [53].

Two ensemble experiments covering accidental and operational spills, with 25,600 simulations each, covering the major sources of uncertainties were carried out to estimate the hazard and later combined with coastal vulnerability information to quantify the oil spill risk. Useful information to support future risk management decisions were also generated by the ensemble.

The article was organized as follows: a description of the data and models employed to compute the oil spill risk is presented in section 4.2. The application of the IT-OSRA to the Algarve is carried out in section 4.3. A description of the ensemble experiments performed to quantify the oil spill risk and the results are shown in section 4.4. Final remarks highlighting the most important achievements of this work are presented in section 4.5.

4.2 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 dataset employed to carry out the ensemble experiments in the Algarve is presented.

4.2.1 Oil spill model

MEDSLIK-II is an open source three dimensional Lagrangian oil spill model able to predict time changes in the slick state and in the volume and position of particles. Changes in the particle position are estimated based on the outputs of Eulerian wind and current models. 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 very didactic and complete description of MEDSLIK-II model was presented in De Dominicis et al. [20].

Prior to the experiment, MEDSLIK-II was setup based on the best tune defined by Dominicis et al. [26]. 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.

4.2.2 Eulerian wind and current models

One year of daily three dimensional current data and hourly 10-m winds were used as input for MEDSLIK-II in the ensemble experiments. Two operational ocean circulation models 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 degree spatial resolution. The system assimilates sea surface temperature, sea level anomalies observations, temperature and salinity profiles, and sea ice concentration [61]. 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 degree spatial resolution and 50 vertical levels. No data assimilation is performed by the IBI system [11].

Hourly winds with a 0.05 degree spatial resolution were obtained from the SKIRON/Eta system [55]. The model covers the whole Mediterranean basin and surroundings and receives initial and boundary conditions from the NCEP/GFS system.

It is acknowledged that a one year long meteo-oceanographic dataset may not be enough to encompass all the possible combinations of currents and winds/waves in the study area. However, such limitation does not invalidate the experiment, since it is focused on presenting a new method to compute the oil spill risk and apply it to map the risk in a limited time frame, the year of 2013.

4.2.3 Traffic density map

The maritime traffic density for the Algarve was estimated based on one month of AIS positions made available by the Portuguese Institute of Maritime Transportation and Ports. The data set included cargo and passenger vessels, corresponding to 98% and 2%, respectively, of the total number of passages. Four main ports are found in the Algarve and surroundings (Portimao, Faro, Huelva and Ayamonte), increasing the maritime traffic density in the coastal areas (Figure 4.1b).

Olita et al. [75] observed that seasonal variations in the maritime traffic density at the Strait of Bonifacio resulted in significant variation of the oil spill risk index on the coast. Similar conclusion may be valid for the Algarve but a longer data set was not made available by the Portuguese authorities.

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 thirty or more. The five levels proposed were translated into a traffic indicator that represents the probability of having a vessel at a given coordinate of the area, P_t, and is defined by:

$$P_t = \frac{numberofpassages}{numberofsampleddays} \tag{4.1}$$

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 Figure 4.1. The main ports and reference points in the area were indicated in the maps.

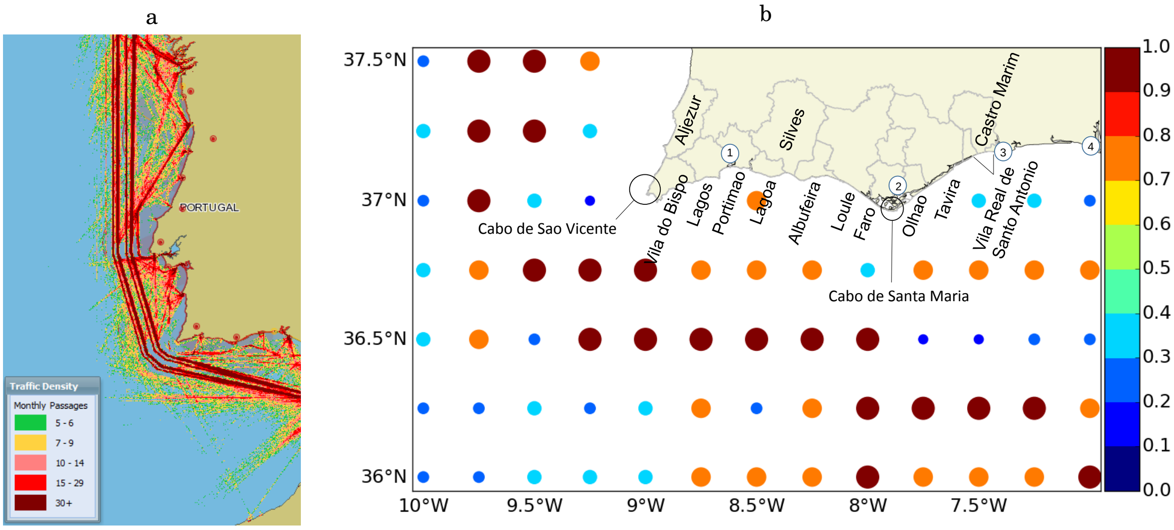


Figure 4.1: (a) AIS maritime traffic density map for March, 2013 in number of passages per month and (b) P_t index for each release point. In (b), the size and the color of the circles represent the maritime traffic density. The four main harbours in the study area - Portimao (1), Olhao (2), Ayamonte (3) and Huelva (4) - were signed with white circles. Two reference points, Cape Sao Vicente and Cape Santa Maria, were circled in the map.

4.2.4 Coastal vulnerability

The vulnerability of the Portuguese coast to oil spills was quantified by Frazão Santos et al. [35] to the county level (Figure 4.2). The coastal counties scored in a relative scale ranging from 0 to 1, where 0 is lowest risk level and 1 the maximum observed. Risk was defined as a composite indicator with ecological and socioeconomic dimensions. Three variables were considered in the ecological dimension: shoreline type, extension 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 parishes, the relative touristic land use, lodging capacity per thousand inhabitants, berths for recreational boating, number of fishing vessels and number of registered fishermen. Ecological and socioeconomic dimension received equal weights for the calculation of the risk indicator. Further discussions upon the weighting criteria can be found in Frazão Santos et al. [35].

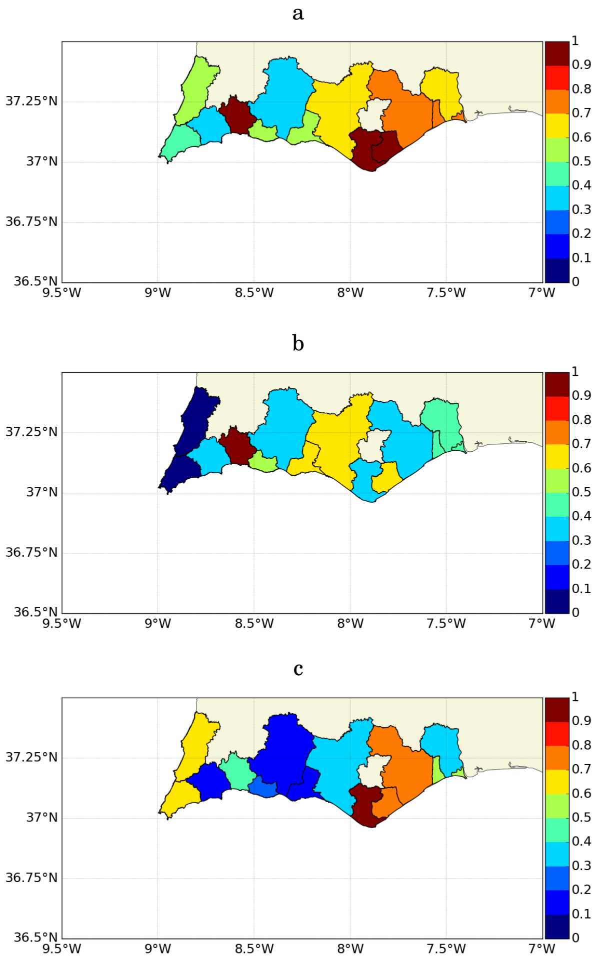


Figure 4.2: (a) Vulnerability index and its (b) socioeconomic and (c) ecological dimensions.

As stated by Frazão Santos et al. [35], the vulnerability index was created to show spatial relative differences among the counties. Therefore, prior to the calculation of the risk in the Algarve, the risk indicators were normalized by the maximum values found in the area.

4.3 The Algarve OSRA case study

Recent oil exploration initiatives carried out in the Algarve point out that considerable resources of oil and gas may lie in Portuguese deep waters. However, consistent oil production has not taken place in the area yet. No significant oil depots are found in the local ports and maritime traffic stands out as the only source of risk to the Algarve. The closest important oil storage site is found in the port of Sines, located up north the Algarve, but it has not been included in the analysis due to the fact it is outside the geographic area and scope of this study. The evaluation of the risk represented by the maritime traffic is especially challenging since the source of risk is dispersed, variable in time and both small and frequent (i.e. operational) and large and rare (i.e. accidental) events are possible.

The summary of the application of the IT-OSRA framework to the Algarve is presented on Table 4.1 and the reasoning behind each of its 35 elements is described in the following sections. As recommended by Sepp Neves et al. [95], the *Risk Analysis* and *Risk Evaluation* items were performed separately for operational and accidental spills.

Establishing the context		
1	International and domestic legislation on oil spill pollution	MARPOL 73/38 (annexes III,IV,V and VI), OPRC '90, OPRC HNS, CLC '92 (funds and supplies); Lisbon Agreement and member of the European Community Task Force. In the national level, oil pollution is regulated by the Plano Mar Limpo (PML).
2	Drivers and trends impacting oil spill hazard	A global increase in seaborne transportation was detected by Musk [73]. According to the authors, such trend is likely to persist. In a regional scale, the actual European policy on transportation is to shift significant part of the road freights to waterborne transportation by 2050. An overall increase of 20% of the later is expected European Commission [30].
3	Perceptions of stakeholders regarding the oil hazard	Environmental risks posed as the second major risk concern for the Portuguese society, which also declared to be "very concerned" regarding oil spill risk Delicado and Gonçalves [21].
4	Governance, roles and accountabilities on oil spill prevention, detection and combat	The National Maritime Authority (NMA) is responsible for the actual implementation of the national contingency plan, mainly through the Maritime Authority Directorate (MAD). The Maritime Departments and Port Authorities are responsible for the implementation of the regional and local level contingency plans, respectively. The authority in charge for oil spill monitoring and response in the Algarve is the Southern Maritime Department.
5	Environmental standards, policies and objectives to be achieved	According to the European Marine Strategy Framework Directive (MSFD), Portuguese coastal waters should reach/keep a "good environmental status" by 2020.
6	Capabilities on oil spill prevention, detection and combat	The Portuguese Navy counts on one vessel for marine pollution response operations. Dispersant, booms and skimmers, and shoreline oil removal equipment are distributed among five main ports in Portugal. In the Algarve, the available equipment is found in Faro. Concerning the detection of oil spills, Portugal is part of the CleanSeaNet, run by the European Maritime Safety Agency (EMSA), which monitors oil spills in European waters through satellite remote sensing.
7	Oil spill contingency plan	The national contingency plan is defined by the "Plano Mar Limpo". According to the national plan, regional analogues should be prepared by the regional maritime departments.
8	Standards, guidelines and models adopted by the organization	As far as the authors are aware, no operational models are adopted by the Southern Maritime Department for the monitoring of meteo-oceanographic conditions or for oil spill forecasting.
9	Goal and objectives of the oil spill risk management	To improve the environmental status of the marine and coastal areas in the Algarve area.
10	Responsibilities in the risk management process	Southern Maritime Department
11	Scope and depth of the OSRA, including specific inclusions and exclusions	To assess the oil spill risk represented by the maritime traffic in the Algarve.
12	Geographical coverage and life span of the OSRA	Algarve coast during the year of 2013.
13	Establish methods, models and tools	Maritime traffic density maps, ensemble oil spill simulations and a coastal vulnerability index maps were combined to compute the risk.
14	Define the way performance and effectiveness are evaluated in the management of risk	The performance of the risk management measures will be evaluated through the changes they generate in the hazard and vulnerability indexes.

Establishing the context		
15	Identifying information/instruments needed for a better risk management	A longer maritime traffic time series would allow to estimate temporal changes in the traffic density in the Algarve. Longer ensemble experiments would allow to estimate the "climatological" risk. Other sources of meteo-oceanographic data would generate a more robust risk estimate. Trust should be build in the Portuguese society towards potentially polluting companies and national government [21].
16	Accident types, their causes and consequences and how they will be measured	• Accidental events: oil spills due to offshore vessel accidents (explosion, rupture and sinking) • Operational events: oil spills due to tank washing and leakage of lubricants
17	How likelihood will be defined	See Equation 4.3
18	How the level of risk is determined	Quantitatively.
19	Time frame of the likelihood and consequences	Valid for the year of 2013.
20	View of the stakeholders regarding hazards, impacts and risk determination method	Delicado and Gonçalves [21] concluded that 88% of the Portuguese believe to be very important the participation of scientists in risk assessments. 80% of the population declared to believe in the judgment of scientists.
21	Combination with other risks and how this will be considered	The oil spill risk in the Algarve is linked to the maritime risk and their association was considered in the OSRA through weighting the oil spill hazard with the maritime traffic (P_t).
Risk identification		
22	Potential sources of oil pollution	Cargo, passenger and tanker vessels.
23	Variables affecting the oil spill hazard/impacts and how they will be measured	Variations in meteo-oceanographic conditions, oil spill characteristics (volume, spill rate and type of oil), spill location and time of spillage and their respective impacts on the oil spill hazard were quantitatively calculated through ensemble oil spill simulations. Variations in maritime traffic were disregarded due to the lack of data
24	Areas of impacts (environmental, social and economic)	Ecological, social and economic defined by Frazão Santos et al. [35]
25	Pollution events considered	Accidental and operational oil spills
26	Causes of events	Maritime accidents in the open sea and intentional operational spills.
Risk analysis		
27	Estimated environmental, social and economic impacts in the area	Impacted coastal counties due to operational and accidental spills are presented in Figure 4.5g for the year of 2013 and Figure 4.9 for the seasons of the year.
28	Likelihood of actually polluting vulnerable areas	• Accidental events: see Figure 4.5e. • Operational events: see Figure 4.5f
29	Effectiveness and efficiency of the available oil spill prevention, detection and combat instruments.	No controls were applied in the computation of the oil spill hazard since the capability of fighting spills in open seas was assumed to be negligible. Portugal counts with one single vessel to control 1,727,408 km^2 of Economic Exclusive Zone.
30	How risk levels are estimated and expressed	Risk levels were quantitatively calculated through Equation 4.2. Risk was expressed in relative levels between 0 (lowest) and 1 (highest).
31	Uncertainty analysis	Sources of uncertainty are: ocean circulation model skills, oil spill model setup (i.e. volume of the spill, duration of the spill, Stokes drift, type of oils), location of the spill and time of spillage.
32	Sensitivity analysis	For accidental and operational events: see Figure 4.3 and Figure 4.4

Risk evaluation		
33	Risk communication tools and information dissemination	The risk was communicated through visual representations of the results obtained by the ensemble experiments. The oil spill risk for the year of 2013 and the risk equation components were presented in Figure 4.5. Seasonal variations of the risk were presented in Figure 4.9. The main sources of risk and their variation throughout the seasons were presented in Figure 4.8.
34	Prioritization for risk treatment	Priority areas should be defined based on Figures 4.5 and 4.8 for accidental and operational spills.
35	Consideration of risk reduction alternatives	According to the International Convention on Oil Pollution Preparedness, Response and Cooperation [50], some key points can be covered in order to reduce the risk: (1) local oil pollution emergency plan, (2) oil spill reporting system, (3) definition of national/regional competent authorities, (4) national contingency plan, (5) minimum response equipment available and (6) international cooperation. All the items have been addressed by the Portuguese government. However, the OSRA suggests that there is still room for improvements in the national level. In the case of accidental spills, Hassler [44] advises national efforts in enforcing flat state responsibility, response equipment and Coast Guard training. In the case of operational spills, port state control and monitoring have shown to be most effective initiatives.

Table 4.1: IT-OSRA framework applied to the Algarve.

4.3.1 Establishing the context

The present OSRA aimed on improving the environmental state in the Algarve, mapping the oil spill risk due to maritime transportation, the only source of risk identified in the region (elements 9, 11 and 12 in the IT-OSRA table. Hereinafter only the number of the elements will be presented). The aim of the OSRA is in accordance with the European Marine Strategy Framework Directive (MSFD) which states that the marine environment in the European member States should reach a good environmental status by 2020 (5).

Recent publications have observed a global increase in the volume of oil transported by vessels (e.g. Musk [73]) and, in the European context, there is an official policy of shifting towards maritime transportation, increasing in 20% the seaborne transportation of goods in European waters by 2050 [30]. However, in spite of the apparent increase in the oil spill hazard, studies performed in the North sea [14, 58] point to a negative trend in the number of illegal spills due to surveying and new regulations in the EU context (2).

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. Nationally, oil pollution is regulated by the national oil contingency plan, the *Plano Mar Limpo* (PML) (1). The PML assigns to the Maritime Authority the responsibility for fighting oil spills in the national level and the regional maritime departments are the authorities responsible for the regional level (4, 7) . In the case of the Algarve, the Southern Maritime Department is the authority in charge of fighting oil pollution (10).

According to the ITOPF [52], the Portuguese Navy counts with one vessel for response operations in open waters and equipment for oil dispersion and removal from the waters and shores among the maritime departments. As a signatory of the Lisbon Agreement, Portugal may also request support from its partners (i.e. France, Spain and Morocco). Support at the European level comes through the European Maritime Safety Agency (EMSA) which maintains an operational oil spill detection system (6).

Risk was computed quantitatively (18) combining the oil spill hazard, estimated through oil spill ensemble simulations (17), and the coastal vulnerability to oil (13). Two ensemble experiments were set for operational and for accidental events, with 25,600 simulations each, and the total risk was calculated separately. The setup of the ensemble experiments was 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 and for typical operational discharges for accidental and operational events, respectively (16, 21).

Environmental risks, including water pollution, rank as the second major concern of the Portuguese society regarding risks [21]. In the same study, Portuguese citizens declared to be "very concerned" regarding oil spill risk. In spite of the relatively high importance given to environmental issues by the Portuguese citizens, their involvement in environmental causes has been historically low (3). Delicado and Gonçalves [21] also observed that 88% percent of the Portuguese believe to be important or very important the participation of scientists in environmental issues and 80% declared to believe in their judgment (20).

The OSRA performed covers the year of 2013 limited by the meteoceanographic conditions used as inputs for the ensemble experiments (19). In order to extend the timeframe of the analysis, it would be necessary to perform ensemble experiments based on a longer meteoceanographic timeseries, allowing to calculate the "climatological" risk, and on a longer traffic density data to identify temporal variations of the maritime traffic (15).

The strategy for the evaluation of risk management decisions should take into consideration the inputs from the stakeholders. Nevertheless, one of the most important contributions of the ensemble experiments is to allow comparisons between the present hazard and risk with the analogous indicators obtained under alternative scenarios (14) [7].

4.3.2 Risk identification

As stated in the *Establishing the Context* item, maritime traffic currently is the only source of oil spill risk for the Algarve and, therefore, vessels were considered to be the only potential source of pollution (22). The oil spill hazard is modulated by variations in meteo-oceanographic conditions, 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 maritime traffic are expected to impact the hazard but, for the present study, such variable has been disregarded due to the lack of data (23). The coastal vulnerability index employed to estimate the impacts of oil spills on the coast takes into consideration ecological, social and economic aspects and it was assumed to be constant in time (24).

The risk analysis was carried out for operational and accidental events separately (25).

The definition of the members for the ensemble experiment was made based on the available information about past events. Regarding operational events, the members were related to potential tank washing and leakage of lubricants. For accidental events, the members were designed to cover scenarios of open sea accidents (26). Detailed information about each member and the reasoning behind them is presented in the Section 4.4.

4.3.3 Risk analysis

The process of risk analysis is long, involving explanations regarding the design of the ensemble experiments, the calculation of the risk itself, the risk variability and its reasons. For the sake of clarity, extensive explanations regarding the ensemble experiments employed to compute the risk were presented in Section 4.4 (30,31). The conclusions of the experiments are presented here, inside the IT-OSRA application of the framework. It is highly recommended to go through Section 4.4 prior to proceed with the present section since some knowledge about what has been done in the experiments is necessary to understand the present section.

No controls due to oil spill prevention, detection and combat instruments were employed in the risk analysis (29). As described in the element (6), Portugal has only one vessel to fight oil pollution and an Exclusive Economic Zone (EEZ) area of over 1,700,000 km2. 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.

4.3.3.1 Accidental events

The ensemble members proposed for the experiment led to rather different final oil beaching scenarios (Figures 4.3 and 4.4). An increase in the spilled volume (member 2), as expected, resulted in a direct increase in the beached volume (Figure 4.3c) compared to the reference simulation, member 1 (Figure 4.3a). The spillage of heavier oils (member 3) also meant higher concentrations of oil on the shore (Figure 4.3e). Members 1, 2 and 3, although predicting different concentrations of oil on the coast, followed a similar spatial pattern regarding the relative distribution of the oil. Longer oil spills (member 4), compared to the reference simulation, generated different spatial distribution with higher concentrations on the west coast and lower concentrations in the southern counties (Figure 4.3g). Similar conclusion can be drawn for member 5, which removed the Stokes drift from the analysis, showing that the wave action can make perceptible changes in the oil spill risk in the Algarve (Figure 4.3i). MERCATOR-based members predicted more oil beaching than IBI-based members (32).

The hazard represented by accidental spills was characterized by a dominance of the west coast counties of Vila do Bispo and Aljezur (Figure 4.5e). The counties of Lagos, Silves and Lagoa scored secondary values, followed by a homogeneous distribution of low hazard values among the remaining counties (28). As expected, the distribution of the risk (Figure 4.5g) followed the distribution of the hazard, showing very high values at the west coast. Lagoa and Olhao also obtained significant risk values.

The western coast of the Algarve is characterized by low demographic density and relatively little tourism (i.e. low socioeconomic vulnerability) [48](Figure 4.2b) but stands out as an area of great ecological value (Figure 4.2c) with its coastline protected by the Sudoeste Alentejano e Costa Vicentina natural park. Olhao is among the most vulnerable counties in the Algarve (Figure 4.2a), with its coastline protected by the Ria Formosa natural park, an important fishing industry and relatively high number of people living in coastal parishes [48]. The relatively lower vulnerability of Lagoa (Figure 4.2a), due to its lower ecological and socioeconomic importance in the Algarve, was compensated by the higher hazard it was exposed to (27, 28).

The risk mapping results indicate that temporal variations in the meteoceanographic variables (i.e. currents and waves) played a major role in modulating the risk. Very important variability was found in the seasonal scale, with a more even distribution of significant risk values among the counties during summer and spring (Figures 4.9a and 4.9c) and more concentrated risk on the west coast during winter and autumn (Figures 4.9e and 4.9g). Higher frequency variability of currents, due to mesoscale events, and waves, due to the passage of atmospheric fronts, also contributed to divert the observed risk from the the expectations based on the average values (Figures 4.10).

4.3.3.2 Operational events

The operational experiment demonstrated that a "typical" operational oil spill, as described by Volckaert et al. [107], did not represent ecological risk for the Algarve in the timeframe of our experiment (Figure 4.3). However, operational spills did represent a source of socioeconomic risk (Figure 4.5h), impacting areas where tourism (Lagos, Lagoa, Silves and Albufeira) and fisheries (Olhao) stand as major sources of income and cultural heritage for the municipalities [48]. As demonstrated in the sensitivity analysis (Section 4.4.4.1), a "worst-case scenario" operational oil spill, represented by member 2 in the operational experiment, could represent a source of ecological risk for the counties of Aljezur, Vila do Bispo, Lagos, Lagoa, Silves and Olhao, with calculated concentrations on the coast above the 100 g/m2 (Figure 4.3d).

Significant seasonal risk variability was observed in the operational experiment. The risk for the western counties increased in winter (Aljezur and Vila do Bispo) and close to the Cape Santa Maria (Albufeira, Loule and Olhao). Spring meteo-oceanographic conditions produced a strong decrease in the risk for the counties on the west coast and increased importance of counties located by the CSM (Olhao, Silves and Loule) and in the central part of the domain (Lagoa and Albufeira). The higher risk levels were concentrated in the central part of the domain (Albufeira, Lagos, Silves, Lagoa and Loule) during summer. The risk in Autumn peaked in Olhao and in the center of the domain (Lagos and Lagoa).

4.3.3.3 The hazard represented by the ensemble experiment release points

The areas under the influence of the ports of Portimao, Huelva and Ayamonte represented the most important sources of risk to the Algarve combining heavier traffic and high probabilities of impacting the coast with spills of considerable volume (Figure 4.8). During most of the year, the main shipping corridor off the Algarve did not pose as a major source of risk to the Algarve. Increased contribution of the corridor to the oil spill hazard was observed in winter (Figure 4.8c), especially due to points located off the south coast.

4.3.4 Risk evaluation

A set of graphs for the visual communication of the risk was devised with the application of the IT-OSRA. Spatial and temporal variability of the risk and its components (i.e. probability of beaching, the expected concentrations on the coast, the hazard and the vulnerabilities) was represented, 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 (33).

Regarding risk reduction measures (35), the International Maritime Organization (IMO) proposed six key points to be considered for risk reduction, namely: local oil pollution emergency plan, oil spill reporting system, definition of national/regional competent authorities, national contingency plan, minimum response equipment available and international cooperation. At present, all the requirements are fulfilled by the Portuguese government. Nevertheless, as defended by Aven and Vinnem [7], Sepp Neves et al. [95], the risk should be always treated to as low as reasonably practicable levels and possible improvements in some of the IMO items can be proposed based on the available literature and on the results of IT-OSRA framework.

According to Hassler [44], action in risk governance and management in the national level have little impact when it comes to operational oil spills. Based on the HELCOM (Helsinki Commission) experience, the author advises enforcement of port state control, aerial and surface monitoring and flag state responsibility. Regarding accidental oil spills, Hassler [44] states that national measures in the enforcement, through flag state responsibility, and remediation, through investments in towing equipment, oil removal equipment and Coast Guard training, can be rather effective in the risk reduction.

4.4 The Algarve hazard and risk mapping

4.4.1 Ensemble experiment setup

The results obtained furnished the basis of the *Risk Analysis* and *Risk Evaluation* items of the Algarve OSRA case study (Section 4.3). Two ensemble experiments covering accidental and operational spills were carried out to quantify the oil spill risk in the Algarve. The accidental and operational experiments were designed in order to encompass the main sources of uncertainties identified:

1. where the spill will happen

2. when the spill will happen

3. oil spill characteristics/oil spill model setup

A release grid with 70 release points (hereinafter also referred to as RPs), r_n, covering the main shipping corridors in the Algarve (Figure 4.1b) was created to address (1). For each RP, 300h-long oil spill simulations were carried out every 10 days throughout the year of 2013, addressing the second source of uncertainty (2). Finally, 10 ensemble members covering different oil spill characteristics and model setup were run at each RP every 10 days addressing (3). The configuration of the members was based on the available literature and a description of the reasoning behind the configuration is presented below. The proposed members for the accidental experiment covered:

- two volumes of oil spilled: 10,000 tonnes, representing the most frequent spills [47], and 50,000 for a "worst case scenario", covering about 90% of the accidents [10];

- two types of oil: API 38 and API 12 representing spills of lighter and heavier oil;

- two spill duration: 48h, giving that explosions and foundering are the the most common accidents in open sea (e.g. Erika accident, Khark 5) [49] and the spill will be therefore "instantaneous", and seven days representing some of the accidents observed in the NE Atlantic (e.g. Prestige accident);

- two MEDSLIK-II configurations: with and without the Stokes drift component of the oil transport;

- every item was run using ocean currents from both IBI and MERCATOR systems.

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

- two volumes of oil spilled: 1 ton, representing the typical volume according to the observations of Volckaert et al. [107], and 46 tonnes representing a "worst case scenario" [42]

- 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: 6h and 14h. Since operational spills are not documented, it is rather difficult to find reliable information about the spill durations. According to Hampton et al. [42], operational events, especially when it comes to tank washing, are short since they demand personnel. The upper threshold of 14h was defined based on the time needed by a vessel to cross the Algarve in cruise speed.

- two MEDSLIK-II configurations: with and without the Stokes drift component of the oil transport.

- every item was run using ocean currents from both IBI and MERCATOR systems.

The summary of the members is presented in table 4.2.

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

Table 4.2: Configuration of the ten ensemble members for the accidental and operational experiments

4.4.2 Hazard and risk equations

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

$$R_s = H_s * I_s \tag{4.2}$$

where H is the oil spill hazard and I is the vulnerability of the coastal segment, as defined by Frazão Santos et al. [35]. The original hazard equation employed by Sepp Neves et al. [95] was adapted in order to fit the more complex risk scenario found in the Algarve. Following Price et al. [83], the hazard for each coastal segment was thus defined as:

$$H_s = (P_t)_r * (P_b)_s * C_s \tag{4.3}$$

which combines the conditional probability of a coastal segment to be hit by oil, $(P_b)_s$, and the probability of a spill to happen at the source point, $(P_t)_r$. Unlike Price et al. [83], $(P_t)_r$ was not defined as the probability of an accident to happen but as the probability of finding a vessel at the RP r based on the AIS-based maritime traffic density map for March, 2013 (Figure 4.1b). $(P_b)_s$ 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 [94], concentrations below 1 g/m2, minimum threshold to observe social impacts of an oil spill at the coast, 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 prone to be affect 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 offer more risk to the coast?

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

4.4.3 Sensitivity analysis - accidental experiment

Prior to answering the main questions regarding the risk in the Algarve, a sensitivity analysis was performed in order to understand the impacts of the decisions made in the definition of the ensemble members. For the Algarve case study, the average concentrations of beached oil for each of the 10 members proposed for the ensemble experiments were analyzed in order to evaluate their respective contributions to the total hazard and, therefore, risk. For the sake of simplicity, the first member of each experiment was assumed as the reference simulation.

In what concerns the accidental experiment, member 1 showed high volumes of oil in Vila do Bispo (hereinafter also referred to as VB), Lagos, Lagoa, Silves, and parts of Aljezur, Albufeira and Olhao (Figure 4.3a). The increased volume of oil spilled in member 2 resulted in an overall increment in the volume of beached oil compared to the reference simulation, not changing the spatial pattern in the study area (Figure 4.3c). An increase in the oil density in member 3 also reproduced a slight increase in the volume of beached oil due to smaller losses associated to weathering (Figure 4.3e). 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 Loule (Figure 4.3g). Member 5 showed how the Stokes drift (i.e. waves) may impact the oil spill risk. Disregarding the Stokes drift resulted in lower beaching on the western side of the coast, small increase at the central part of the Southern coast (Lagoa and Silves), and slight decrease in the concentration on the western side of the CSM (Loule) (Figure 4.3i).

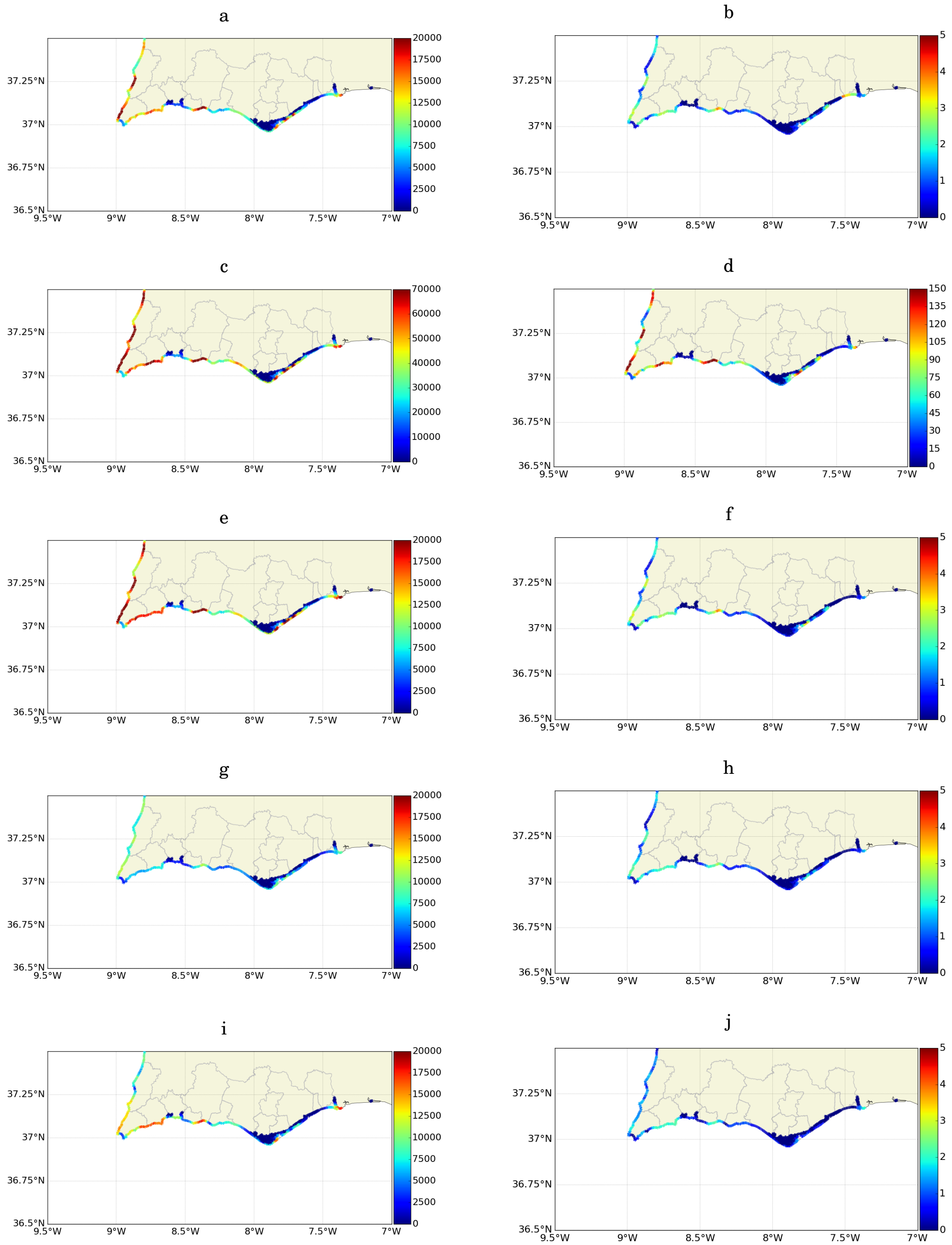


Figure 4.3: Ensemble annual mean concentration calculated for each of the five spill scenarios proposed (all ocean circulation models) (g/m2). Left column corresponds to the accidental experiment. Right column corresponds to operational experiment.

The average of all the members using the MERCATOR results as inputs was compared to the correspondent average using IBI currents (Figure 4.4). In general, the members based on MERCATOR depicted a quasi-continuous sector of oil concentrations of over 20,000 g/m2 for the whole west coast, southern part of VB and Lagos (Figure 4.4c). High concentrations were also found in Lagoa, Loule, Olhao and in the eastern limit of the Algarve. Similar pattern was observed in IBI but with significant reduction in the oil concentrations (Figure 4.4a). Since no evaluation of the skills of the models was carried out for the study area, it is not possible to point out whether one outperformed another.

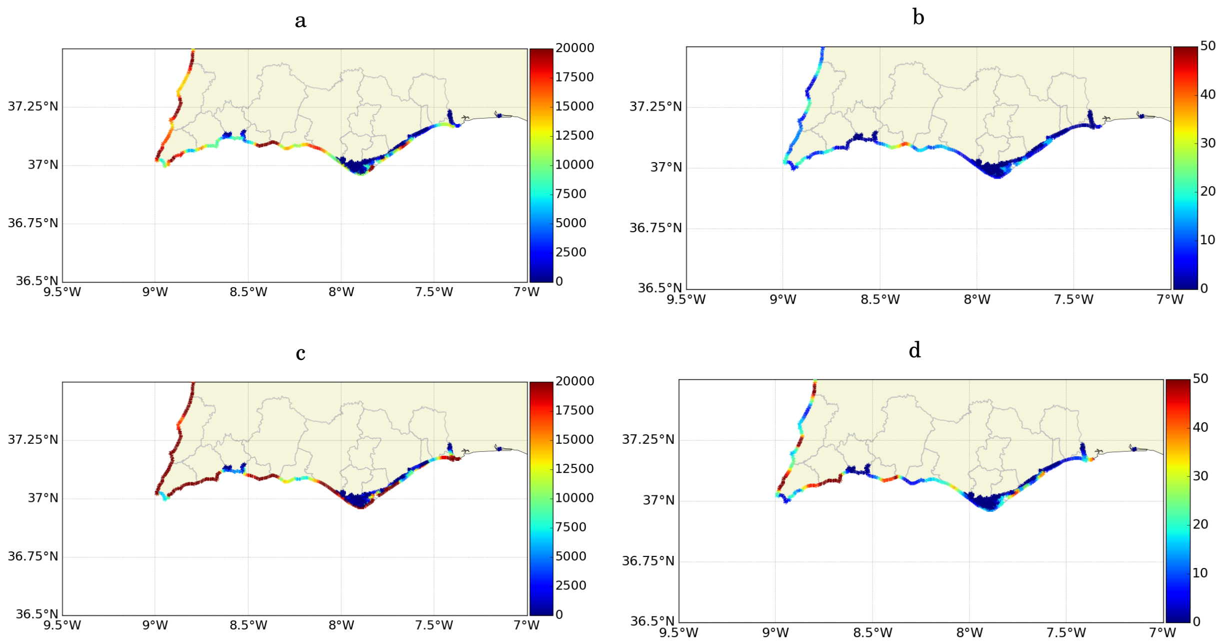


Figure 4.4: Ensemble annual mean concentration calculated for each ocean circulation model (all scenarios) (g/m2). Left column corresponds to the accidental experiment. Right column corresponds to operational experiment.

4.4.4 Risk mapping - accidental spills

Figure 4.5g depicts the oil spill risk for the year of 2013 due to accidental events. The risk was found to be more important on the west coast, in VB ($R < 1$) and Aljezur ($R < 0.8$), as a result of considerable hazard levels (between 0.3 and 0.4) (Figure 4.5e) combined with a high vulnerability to oil (between 0.3 and 0.4). The evaluation of the hazard equation terms (Figures 4.5a and 4.5c) show that the hazard levels in the area were due to large volumes of oil beached (C) and high Pb values (about 1%).

Considerable risk, by the order of 0.4, was found in Olhao, on the eastern side of the Cape Santa Maria (CSM), and Lagoa, situated in the central part of the domain. Olhao was characterized by the low hazard (< 0.1), due to low C and high P_b, and high vulnerability (about 0.7).

Similar conditions were found in Lagoa, with a hazard index close to (0.1) and vulnerability index of approximately 0.4. Most of the counties located between the Cape Sao Vicente and Caspe Santa Maria (Loule, Albufeira, Silves and Lagos) obtained lower risk values ($R < 0.3$), followed by very low risk counties like Portimao, Faro, Tavira, Vila Real de Santo Antonio (VRSA) and Castro Marim.

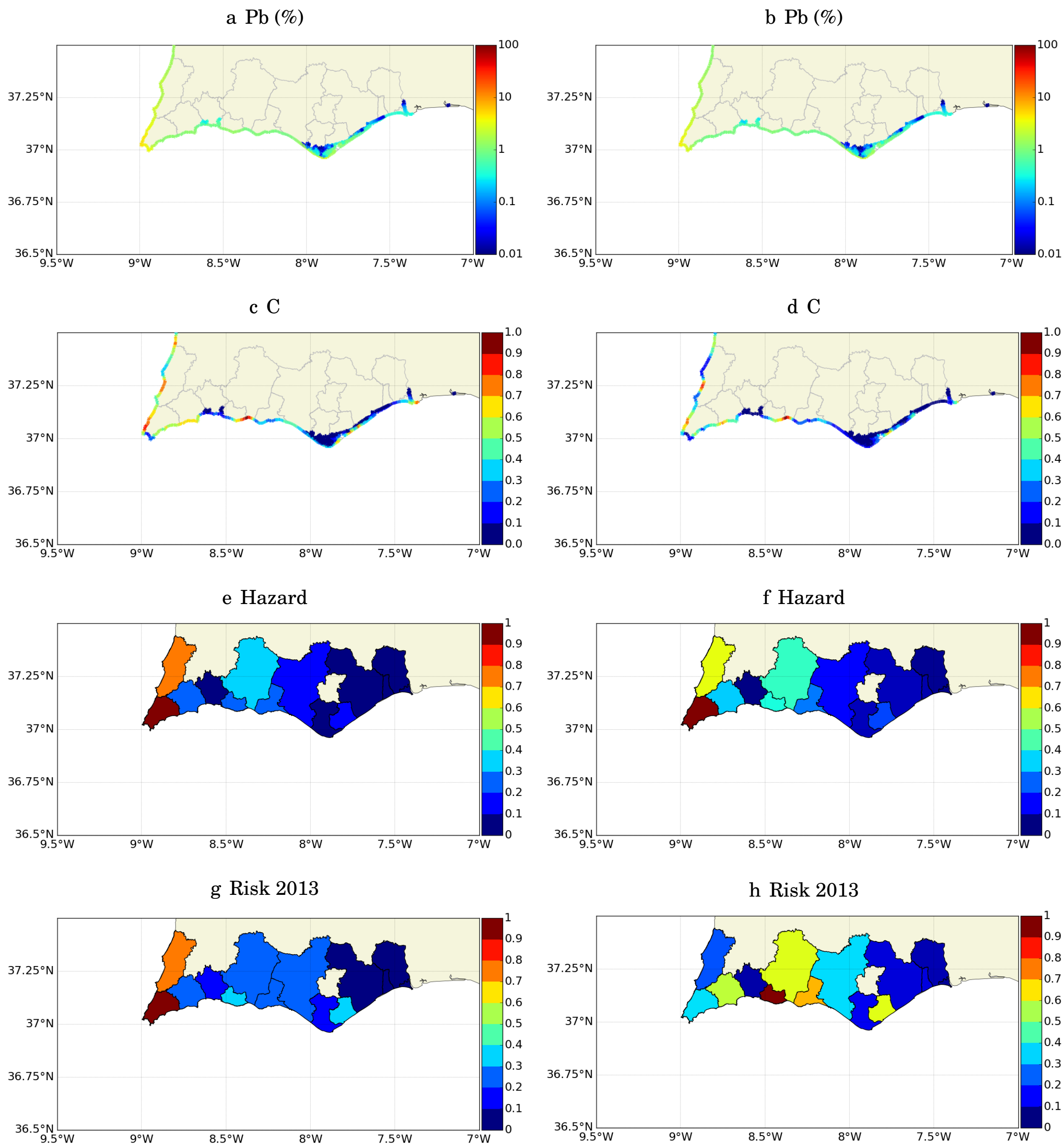


Figure 4.5: Risk and its components for the year of 2013. Results for the accidental experiment are presented on the left column and results for the operational experiment on the left.

In the following paragraphs, currents, from IBI forecasts, and Stokes drift, derived from SKIRON forecasts, maps for the year of 2013 and its seasons were discussed in order to answer whether average meteo-oceanographic conditions are enough to predict the oil spill risk in the Algarve or episodic events play an important role in modulating oil spill trajectories and, therefore, the risk.

The average Stokes drift and surface currents for the year of 2013 are presented in Figures 4.6e and 4.7e, respectively. Surface currents off the west coast followed the coastline orientation, flowing equatorwards with velocities between 10 and 20 cm/s. After the CSV, the flow divided with one coastal branch rotating towards the Gulf of Cadiz and and offshore branch towards S-SW. Far offshore, currents described a poleward pattern in the west coast, in agreement with the observations of Relvas et al. [88].

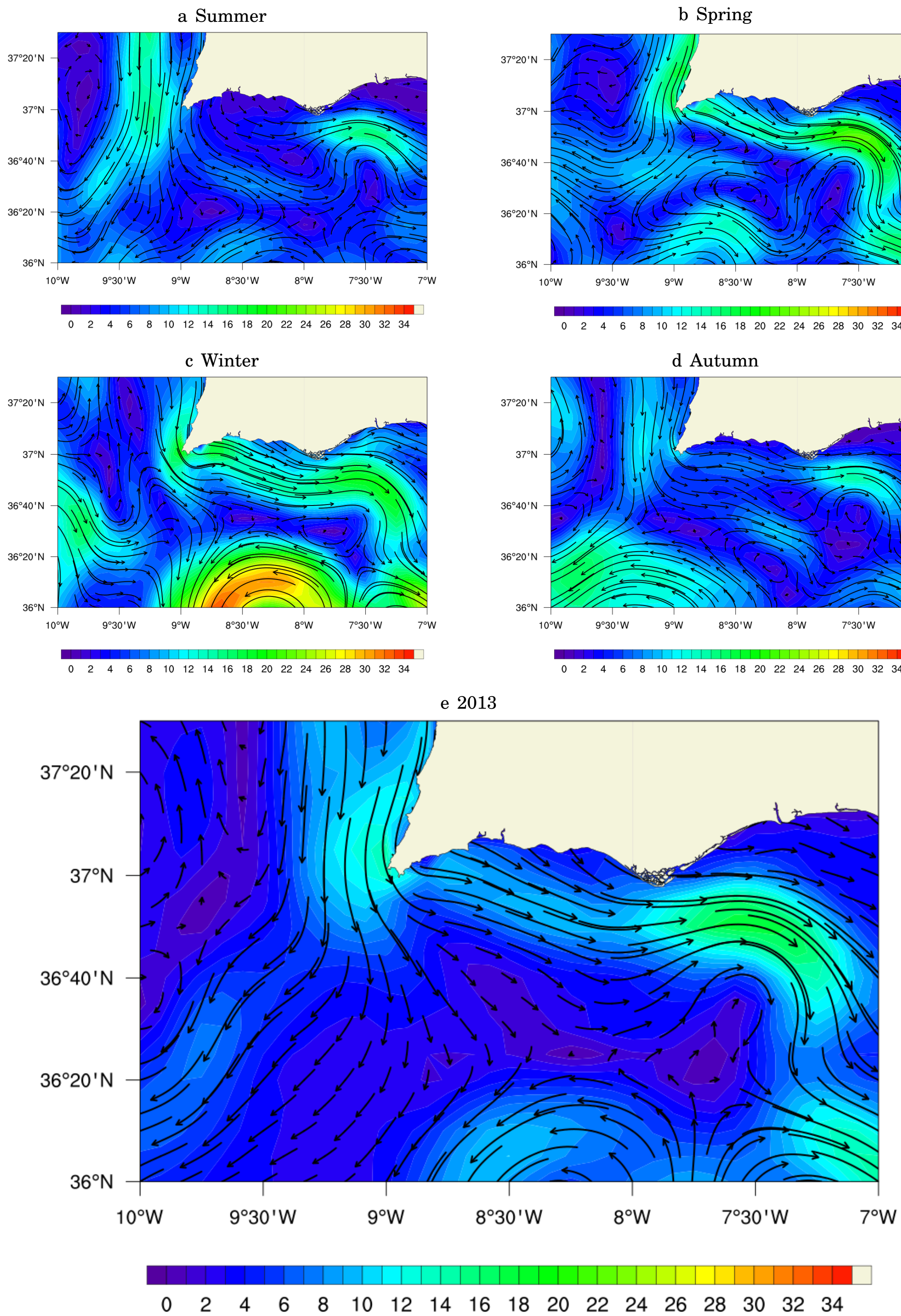


Figure 4.6: Surface currents for the year of 2013 and seasons (in cm/s).

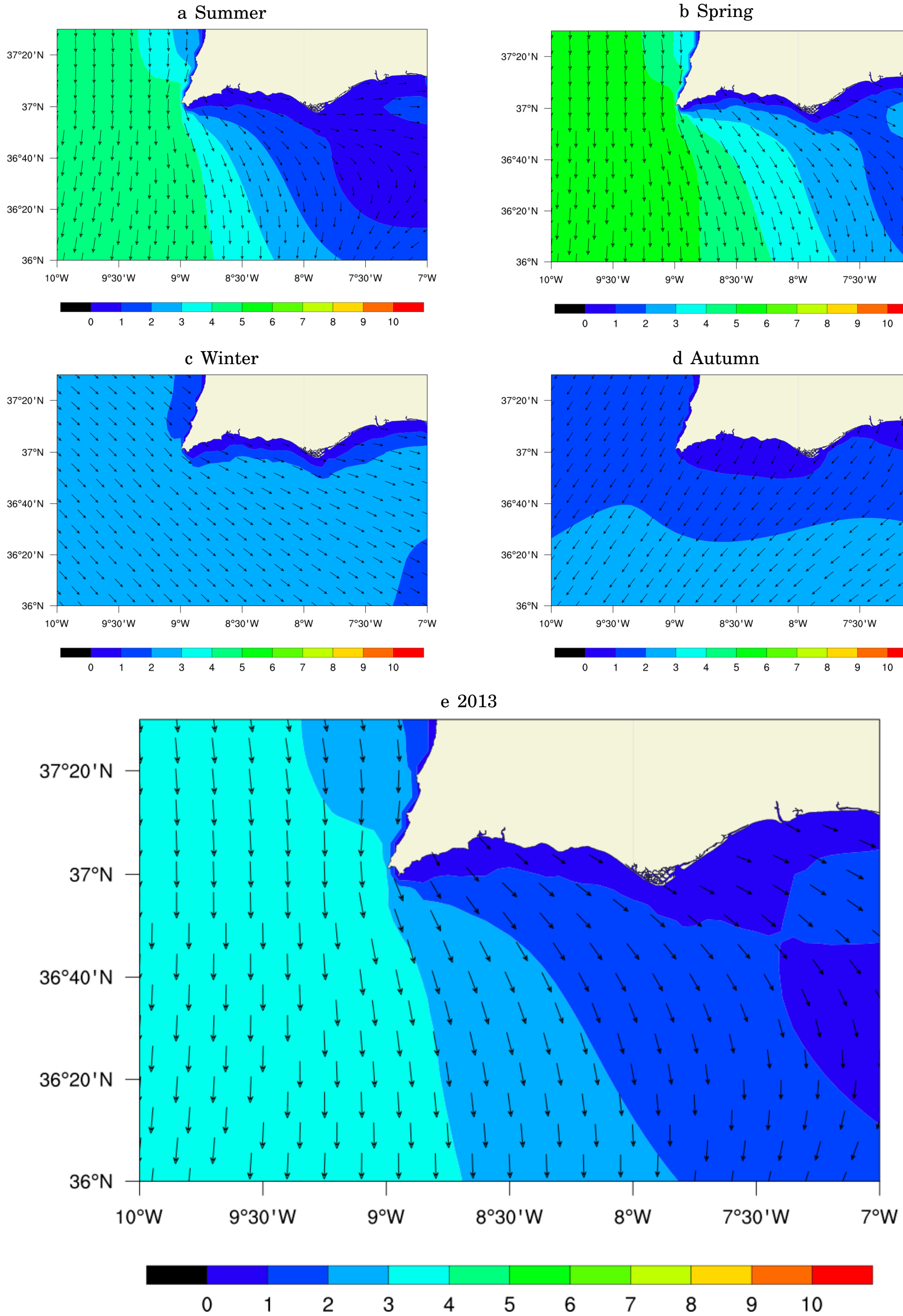


Figure 4.7: Stokes drift for the year of 2013 and seasons (in cm/s).

Average Stokes drift for the same period clearly showed an area of stronger equatorwards currents off the western coast (approx. 4 cm/s). Closer to the shore, the drift deflected to SE reducing in intensity. The south coast, due to limited fetch and lower wind intensities, showed very small drift, with values below the 2 cm/s.

The averaged meteoceanographic conditions for the year 2013 were especially favourable to oil beaching for the coastal RPs located off the western part of the Algarve. 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. Similar conclusion can be drawn for the coastal RPs off the south coast. Such observations indicate that yearly averaged Stokes drift and surface currents were not enough to describe the observed oil spill risk.

The map of the relative importance of each RP to the overall risk map is presented in Figure 4.8. The RP locate just off Portimao ranked as the most important source of risk to the Algarve, combining relevant traffic density and high probabilities of a spill to reach coastal resources with significant volumes. It coincides with the entrance of the port of Portimao, explaining its high traffic density. The influence of the traffic associated to the port is 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 situated in front of the eastern counties 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.

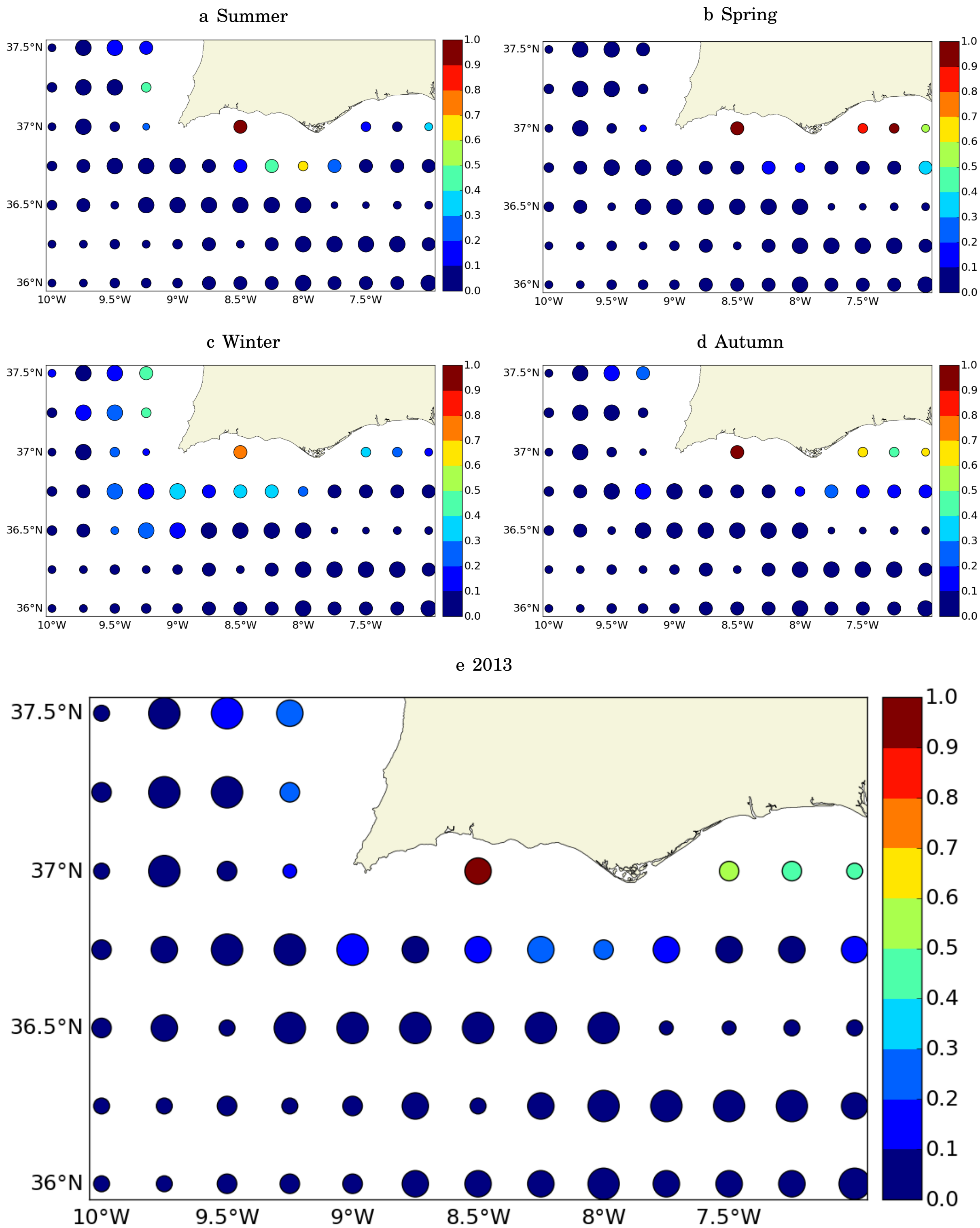


Figure 4.8: Sources of risk for the seasons of the year of 2013. The color inside the circles represents the computed level of hazard for the release point. The diameter of the circle represents the traffic density. The main shipping corridor is represented by the biggest circles.

The relatively high importance of the points located off the south coast corroborates with the assumption that average wave and current conditions are not enough to fully describe the oil spill risk in the Algarve. Following, the meteo-oceanographic conditions correspondent to the seasons of the year of 2013 are presented accompanied by the calculated risk in order to identify whether seasonal variations in the former can explain the risk distribution in the year of 2013 and in their respective seasonal risk maps.

The distribution of the risk during summer was considerably more balanced than for the year of 2013 (Figure 4.9a). The western counties ranked as the areas with the highest risk values ($0.8 < R < 1$) with high levels ($0.4 < R < 0.5$) also observed for the counties situated between the CSV and the CSM. Average Stokes drift in summer was characterized by an equatorward flow in the western part of the domain with intensities of up to 5 cm/s. The pattern becomes SE oriented close to the south coast, with intensities of less than 2 cm/s (Figure 4.7a). The surface circulation pattern was similar to the one observed in the annual average, with an equatorward flow in the western part of the domain which divided after the CSV, with one of the branches rotating SE towards the Gulf of Cadiz (Figure 4.6a). The core of the equatorward flow was found displaced westwards compared to position observed in the annual mean displacing the offshore poleward flow to the western border of the domain. In the south coast, currents described a SE pattern in the area between the CSV and the CSM, rotating towards E-NE after the CSV with intensities of about 15 cm/s.

In general, the meteoceanographic conditions during summer were propitious to the oil beaching for the RPs closer to the coast on the west coast and in the CSM, partially explaining the distribution of the hazard among the RPs. But how to explain the relatively high hazard represented by the the RPs off Portimao, since both average currents and waves were not favourable to oil beaching in those areas (Figure 4.8a)?

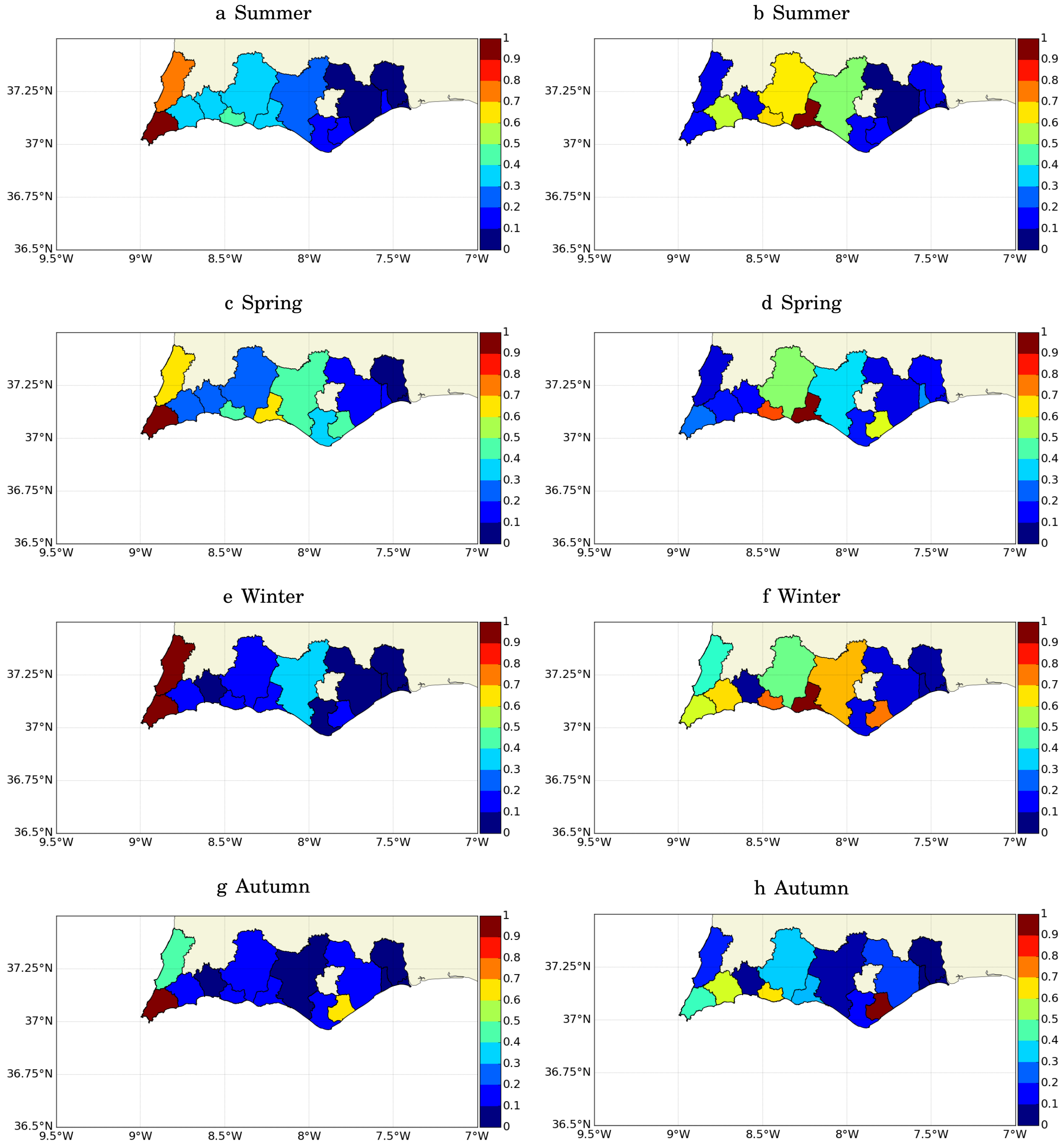
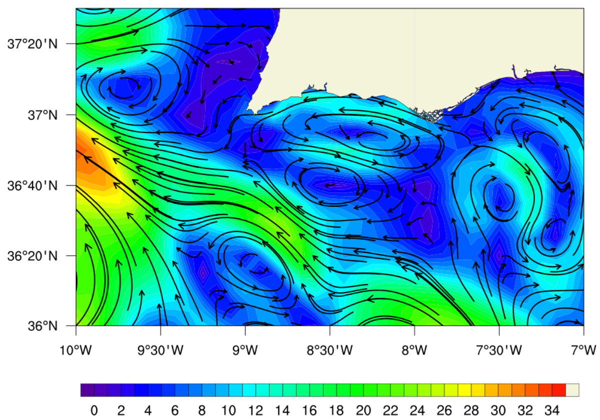


Figure 4.9: Seaonal risk maps. On the left, results for the accidental experiment. On the right, results for the operational experiment.

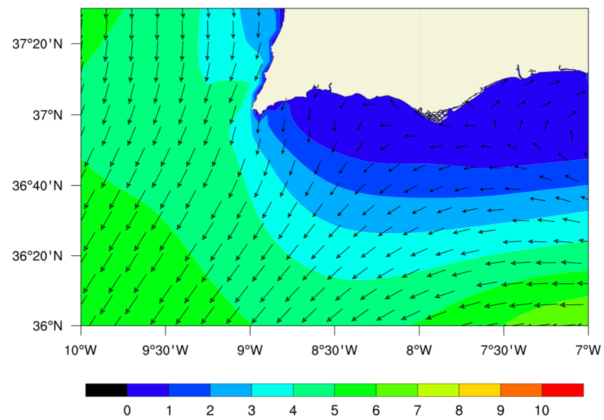
The literature has frequently described summer as a period in which mesoscale features dominate the local surface circulation in the Algarve [2, 88], with the development of strong upwelling events on the west coast and, less frequently, in the south coast forced by the northerly winds. Filaments associated to strong upwelling events export upwelled waters over 250km offshore with velocities of up to 50 cm/s [86, 88]. 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 0.18 m/s, turning polewards after the CSV and increasing in intensity to values of up to 0.3 m/s [32, 86]. Due to their short life span, by the order of days, mesoscale events are unlikely to leave a clear sign in the seasonal average, but can definitely contribute to the oil beaching under specific situations [54].

In order to demonstrate the actual importance of mesoscale events in the oil spill risk, an event in which the alongshore coastal current is fully developed was chosen to understand the eventual role such feature may have in modulating the oil trajectory. The period, included in the ensemble experiment, covers the interval between the 30/06/2013 and the 10/07/2013. In Figure 4.10a, it is possible to identify how the intense westward alongshore current (20 cm/s) on the southern shelf and the Stokes drift for the period (values very close to 0 cm/s) (Figure 4.10b) generated a resultant transport that disagrees with the average summer transport, favouring significant beaching in the area between the CSV and the CSM.

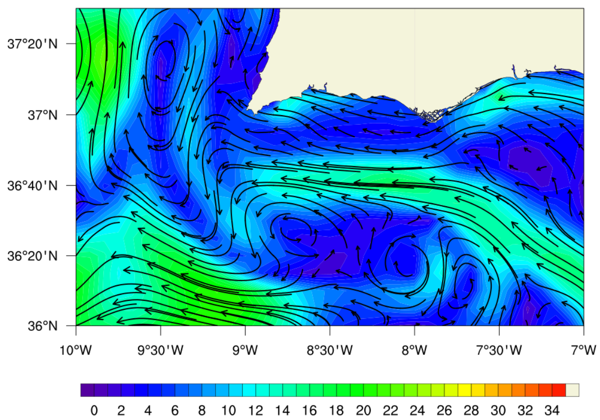
a Surface currents for the period between the 30/06/2013 and 12/07/2013 - (cm/s)



b Stokes drift for the period between the 30/06/2013 and 12/07/2013 - (cm/s)



c Surface currents for the period between the 04/12/2013 and 07/12/2013 - (cm/s)



d Stokes drift for the period between the 27/11/2013 and 09/12/2013 - (cm/s)

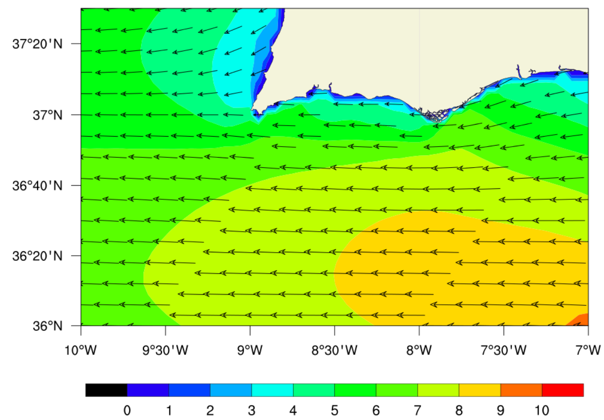


Figure 4.10: Surface currents and Stokes drift exemplifying the role of the mesoscale (a,b) and easterly winds (c,d) in the oil transport.

The risk map corresponding to the spring time presented the highest values in the west coast ($R < 1$ in VB and < 0.7 in Aljezur), intermediate levels for Lagos, Portimao and Silves ($0.3 < R < 0.4$) and high risk closer to the the CSM ($0.5 < R < 0.7$) (Figure 4.9c). The main sources of risk were the RPs close to the southern coast, with an preeminent contribution of the point in front of Portimao, extending to the point located at the 36.75N/7W, with little or no participation of the offshore points in the risk scenario (Figure 4.8b). The average Stokes drift followed a pattern similar to the one found in summer with stronger currents in the the western and southern offshore areas (Figure 4.7b). The spring mean surface circulation map shows that the core of the equatorward flow came closer to the west coast dividing into a coastal eastward oriented branch and an offshore southward oriented branche off the CSV (Figure 4.6b). The poleward current could not be identified. Comparing the spring risk map with the map of RPs for the season, it is verified that the counties with the highest risk values in the southern coast are situated eastwards of the main sources of risk, leading to the conclusion that a west-oriented flow would be paramount to transport the oil to those areas. Such statement diverges from the expectations based on the mean current map but does fit the observations of energetic mesoscale events made by Relvas and Barton [87], the conclusions of Janeiro et al. [54] and results shown in Figure 4.10a.

Winter was marked by the concentration of the risk on the western counties ($R < 1$) (Figure 4.9e). The map of RPs for the season shows an increase in importance of the points farther from the coast, including sources in the main shipping lane off the western and central parts of the Algarve (Figure 4.8c). The average Stokes drift in winter, with dominant SE direction and low intensity, contributed positively to the oil beaching on the west coast, explaining the high hazard values found for the release points in the area, and in Loule, for the spills originated in front of Portimao (Figure 4.7c). Winter currents showed slightly weaker eastward velocities close to the west coast with an intensification at the CSV (Figure 4.6c). The poleward current could be identified closer to the coast than in summer and winter. In the south coast, the the currents followed the E-SE pattern observed in spring with intensities between 15 and 20 cm/s.

The county of VB dominated the risk scenario in autumn ($R < 1$), followed by Aljezur ($R < 0.5$) and Olhao ($R < 0.7$) (Figure 4.9g). Surface currents for the period followed the pattern observed in the annual average with lower intensities (Figure 4.6d). Over the shelf, average currents flowed equatorward off the west coast and eastwards in the south coast. Weak SW-oriented Stokes drift ($< 2cm/s$) dominated the study area (Figure 4.7d). According to the map of RPs (Figure 4.8d), the point in front of Portimao represented an important source of risk. The surrounding points, unlike the maps of the other seasons, did not show great importance leading to the conclusion that the RP off Portimao is the one responsible for most of the beaching in the central part of the Algarve.

Winter and autumn in the Algarve have been described as periods of high atmospheric variability. Fiúza et al. [32] and Relvas et al. [88] have described the wind regime during these seasons as south-easterlies with episodic perturbations due to the passage of frontal systems resulting the temporary prevalence of easterlies. During events of easterly winds, waves from SE with Hs between 1 and 2m [74] are generated in the Gulf of Cadiz mainly affecting the southern Algarve. Easterly winds have also been acknowledged to generate reversions in the average eastwards circulation in the south Algarve shelf [19, 36]. In Figures 4.10d and 4.10c, a scenario of Easterlies is presented, demonstrating how waves (generating westwards currents of up to 7 cm/s close to the shore) and currents (with westward velocities of up to 15 cm/s) during such events can contribute to significant beaching in the south of the Algarve.

4.4.4.1 Sensitivity analysis - operational spills

The reference member showed concentrations of oil on the coast ranging between 0 and 4 g/m2 (Figure 4.3b). The highest concentrations were found in VB and Aljezur on the west coast, Lagos, Lagoa and Silves in the area between the CSV and the CSM, and Olhao and VRSA in the eastern part of the domain. The higher volume of oil spilled in member 2 produced a dramatic increase in the oil concentrations, with values reaching the 150 g/m2 on the west coast, Lagos, Lagoa, Silves and Olhao (Figure 4.3d). The relative spatial distribution observed in member 2 followed the one observed in member 1. Lower oil density (member 3) did not result into dramatic differences in the beaching scenario, with small detectable changes in Castro Marim and Vila Real de Santo Antonio (VRSA), where lower oil density meant lower volumes of beached oil (Figure 4.3f). Longer spill duration (member 4) resulted in lower volumes of oil on the coast with significant reduction in the western side of VB, part of Lagos, Olhao, Castro Marim and VRSA (Figure 4.3h). The removal of the Stokes component from the calculations (member 5) meant an important reduction in the beaching process for the whole coast, with special attention to the west coast, the western end of the south coast and Castro Marim/VRSA (Figure 4.3j).

4.4.5 Risk mapping - operational spills

Since the operational experiment was carried out under the same meteoceanographic conditions of the accidental experiment, no comments will be presented regarding how waves and currents may have modulated the observed oil spill risk. Instead, for the sake of keeping the analysis concise, the interpretation of the results obtained with the operational experiment was focused on the spatial variations of the risk.

In the annual scale (i.e. 2013), the Pb (Figure 4.5b) and C (Figure 4.5d) maps generated by the operational experiment showed similar patterns to their respective maps in the accidental experiment. Consequently, the relative spatial distribution of the hazard was found to be analogous. However, the actual concentrations of oil on the coast suffered dramatic reductions directly impacting the oil spill risk. No concentration values above the $100g/m^2$, threshold proposed by Schmidt-Etkin [94] for ecological impacts of oil spills, were found in the Algarve. On the other hand, the $1g/m^2$ threshold, minimum concentration of oil on the shore to impact socioeconomic activities, has been exceeded along most of the coastline. Since no ecological impacts are expected, the calculation of the risk for the operational experiment was focused on the socioeconomic dimension solely.

Lagoa was the county under the highest levels of risk for the year of 2013 ($R < 1$), followed by Albufeira ($R < 0.8$) and Lagos, Silves and Olhao ($R < 0.7$) (Figure 4.5h). Risk values below the 0.4 level were found in VB and Silves. Winter time caused an increase in the risk levels in the west coast counties of Aljezur ($R < 0.5$) and VB ($R < 0.7$) (Figure 4.9f). Compared to annual average, risk also increased in the counties of Albufeira ($R < 1$), Loule ($R < 0.8$) and Olhao ($R < 0.8$). The relative importance of Lagos ($R < 0.4$) and Silves ($R < 0.5$) decreased.

The risk in the western part of the Algarve dropped to values below 0.3 in spring (Figure 4.9d). Albufeira ranked as first ($R < 1$), followed by Lagoa ($R < 0.9$), Olhao ($R < 0.7$), Silves ($R < 0.6$) and Loule ($R < 0.4$). During summer, risk was concentrated in the region between the CSV and the CSM, again peaking in Albufeira ($R < 0.1$), followed by Lagos, Silves and Lagoa, with risk values below the 0.7 level, and Loule ($R < 0.5$) (Figure 4.9b). Finally, the risk scenario in autumn was dominated by Olhao ($R < 1$), with levels below the 0.7 threshold in Lagos and Lagoa, and between 0.3 and 0.4 in VB, Silves and Albufeira (Figure 4.9h).

Since the meteoceanographic conditions during the operational ensemble experiment were identical to those used in the accidental experiment, the distribution of the hazard among the RPs for the two experiments was found to be very similar. In order to avoid repetitions, the analysis of RPs in the OSRA was concentrated on the results generated by the accidental experiment.

4.4.6 The distribution of the impacts of oil spills on coastal resources

In Sepp Neves et al. [95], the authors compute the uncertainty of their oil beaching estimates through the coefficient of variation (CV). In their experiment, a limited number of ensemble members was employed and the distribution of the results was then assumed to be Gaussian based on previous studies (e.g. Olita et al. [75]).

The results obtained in the present experiment, with more than 25,000 simulations in each experiment, suggest that the assumption made by Sepp Neves et al. [95] and other authors may be misleading. In Figure 4.11, the histogram of the simulated beached volumes for the coast of Lagoa in the year of 2013 is presented. The curve obtained indicates that observations do not fit a Gaussian distribution but a Poisson distribution. Such conclusion indicates that the way oil spill impacts are treated nowadays may have to be reshaped, adapting it to the characteristics of Poisson distributed data.

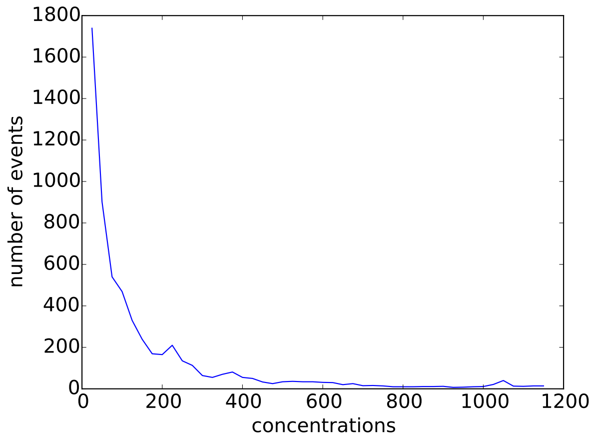


Figure 4.11: Histogram of the modeled concentrations of oil on the coast in Lagoa for the year of 2013. Concentrations in g/m2.

Devanney and Stewart [24] faced a similar situation when analyzing historical data sets of oil spill events. They observed that the variability in the spilled volumes was high enough to question any attempt of describing the uncertainties in the estimates. The value of employing the mean value as a descriptor of the data set was also questioned due to the very high data variability. Back to the present experiment, two points should be therefore clarified:

1. due to the recent discovery regarding the distribution of the concentrations of oil on the coast generated by ensemble oil spill simulations, the conservative approach of not quantifying uncertainties was taken.

2. following the observations of Devanney and Stewart [24] and the results of the present experiment, the average concentrations employed in the risk estimates should be interpreted with care and used more like as an indication of higher/lower hazard than an actual exepected concentration of oil on the coast.

4.5 Conclusions and final remarks

In the present paper, the OSRA framework proposed by Sepp Neves et al. [95] was improved establishing the IT-OSRA. The new methodology was applied to the coast of the Algarve, addressing accidental and operational spills associated to the maritime traffic. The oil spill risk and its seasonal variability were quantified.

Variability of waves and currents in the seasonal scale was found to contribute to significant changes in the spatial distribution of the risk in the Algarve. The role of higher frequency events in the ocean (i.e. mesoscale features) and in the atmosphere (i.e. easterly events) was shown to be paramount in the final definition of the risk scenario.

The outputs of the IT-OSRA have demonstrated that accidental spills do represent a source of ecological and socioeconomic risk to the Algarve. "Typical" operational oil spills posed as a source of socioeconomic risk in the area and, in addition, "worst-case" operational spills may lead to beached oil concentrations high enough to impact not only socioeconomic aspects on the coast but also the local biota.

The IT-OSRA method generated visual outputs able not only to communicate the actual risk and its components but also to support decisions among risk reduction alternatives.

The number of simulations performed allow to infer that the typical assumption of a Gaussian distribution of the modeled concentrations of oil on the coast may not be the most appropriate, demanding an innovative way to deal with the outputs of ensemble oil spill modelling applied to OSRA.

Chapter 5

Results transferable to the public domain

Strong and weak points of the available literature in OSRA were identified through extensive literature review. Based on a critical adaptation of the ISO 31000, a new OSRA framework was proposed addressing the identified weak points: (1) the role of operational spills in the pollution of the marine environment has been neglected, (2) uncertainties in the risk estimates have been disregarded or not properly addressed, (3) the format of presentation of the risk analysis results was usually not adapted to inform the stakeholders and support the decision, and (4) no standard framework for OSRA had been adopted until then.

The new OSRA framework, IT-OSRA, was validated in a real oil spill case being able to compute the oil spill risk, its components and address its uncertainties. A set of graphs for the visual communication of the risk and the uncertainties was devised. Areas under higher oil spill risk and measures necessary to treat the risk were identified.

Necessary improvements in IT OSRA were identified in order to make it fully relocatable: a method to address more sources of uncertainty (i.e. location of the spill, time of spillage, skill of the meteo-oceanographic models and oil spill model setup), different sources of risk (i.e. sources variable in time and space) and different types of event (i.e. operational and accidental spills) should be developed.

The IT-OSRA was applied to a complex oil spill risk scenario, the coast of the Algarve. The necessary improvements in IT OSRA were made mainly through the setup of an ensemble oil spill modelling experiment covering over 52,000 different spill scenarios. The results showed that accidental oil spills represent a threat to socioeconomic and ecological aspects of the coast while, operational spills, due to the smaller volumes involved, represent risk to the socioeconomic aspects.

Significant seasonal variability in the oil spill risk was found in the Algarve due to variations in meteo-oceanographic variables. During winter and autumn, risk was mainly concentrated on the western counties. During spring and summer, risk was distributed among the counties located in the southern coast. Meteo-oceanographic variability by the order of days was also found to contribute significantly to the final risk scenario.

Secondary shipping lanes connecting the main maritime corridor off the Algarve and the local ports were found to represent the main sources of risk in area, combining shorter distance to the coast and relatively dense traffic. The main shipping corridor, far from the shore, did not pose as a major source of risk although increasing in importance during winter time.

In the risk evaluation phase, it was identified that Portugal follows the guidelines proposed by the International Maritime Organization on risk reduction. However, IT-OSRA points out that although all the items may have been fulfilled, the actual efficiency of the implemented mechanisms seem to be insufficient to actually reduce the oil spill risk in the Portuguese coast.

Finally, the massive number of simulations performed in the Algarve experiment allowed to conclude that the distribution of the concentrations of oil on the coast do not follow a Gaussian but a Poisson shape. Such discovery questions the available literature that was based on the assumption of a Gaussian distribution. New approaches to compute the oil spill risk and its uncertainties must be devised in the future.

Appendix A

Back in 2012, in the first year of research of this thesis, an experiment of operational oil spill modelling in the Tuscany archipelago, Italy, was performed by the HIDROTEC laboratory. The author worked on the validation of the hydrodynamic model which resulted in a peer-reviewed publication.

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Enhancing the management response to oil spills in the Tuscany Archipelago through operational modelling

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A B S T R A C T

A new approach towards the management of oil pollution accidents in marine sensitive areas is presented in this work. A set of nested models in a downscaling philosophy was implemented, externally forced by existing regional operational products. The 3D hydrodynamics, turbulence and the oil transport/weathering models are all linked in the same system, sharing the same code, exchanging information in real time and improving its ability to correctly reproduce the spill. A wind-generated wave model is also implemented using the same downscaling philosophy. Observations from several sources validated the numerical components of the system. The results obtained highlight the good performance of the system and its ability to be applied for oil spill forecasts in the region. The success of the methodology described in this paper was underline during the Costa Concordia accident, where a high resolution domain was rapidly created and deployed inside the system covering the accident site.

1. Introduction

While short sea shipping is, and will continue to be, a central part of Europe's logistics chain for transport, this growing sea activity places an also growing burden on marine and coastal zone environments due to the risk of pollution. This risk arises not only from pollution caused by accidents with tankers, but also from illicit sources due to ship routine operations. In fact, degassing, deballasting and other ship operations that involve the voluntary discharge of oil residues (including sludge and bilges) in violation of MARPOL 73/78 Annex I, have been estimated to cause as much as eight times the amount of oil pollution each year as accidental and negligent spills such as the Exxon Valdez (OECD, 2003). According to PriceWaterhouseCoopers (2006) this means, that in 2005, approximately 50,100 tonnes of illegal oil entering EU seas produced an estimate of €7.5 billion leaving EU safes in economic costs (including environmental degradation and all other economic and societal costs), estimated following the methodology of Etkin (2004). Acknowledging the paramount socio-economic and environmental impact of illegal oil spills, under the establishment of the European Union Ship Source Pollution Directive (EU/2005/35) and the operational mandate for the European Maritime Safety Agency (EMSA) in the field of oil pollution monitoring with the CleanSeaNet system, there is now the requirement for each Member State and EMSA to prevent illegal discharges through routine surveillance.

With the status of Special Area according to MARPOL 73/78 Annex I since October 1983, the Mediterranean Sea is particularly sensitive to this type of operational pollution. Here, according to the Regional Marine Pollution Emergency Response Centre for the Mediterranean Sea (REMPEC), 360–370 million tons of oil and refined products are transported annually, representing between 20% and 25% of the world total, and being one of Europe's main oil routes (REMPEC, 2002). Although, due to the lack of confirmed oil spills, exact figures for illegal oil spills are difficult to estimate, the work of Ferraro et al. (2009) based on the analysis of 18947 SAR images between 1999 and 2004, produced an oil density distribution for the Mediterranean Sea (Fig. 1A). When comparing the high oil density areas with the distribution of Marine Protected Areas (MPAs) in the Mediterranean Sea (Fig. 1B), it becomes imperative to ensure measures that address the protection and preservation of these areas against oil pollution. The study site considered was the Tuscan Archipelago in Italy (Fig. 1), which is one of the areas with the highest oil spill density according with the work of Ferraro et al. (2009). Located in the Mediterranean Sea, between the Ligurian Sea and the Tyrrhenian Sea, the Archipelago is a Natura 2000 network that comprises the largest protected area of the European seas, and in which lays the Pelagos Sanctuary (Fig. 1B), an area of the International Sanctuary for the protection of sea mammals in the Mediterranean.

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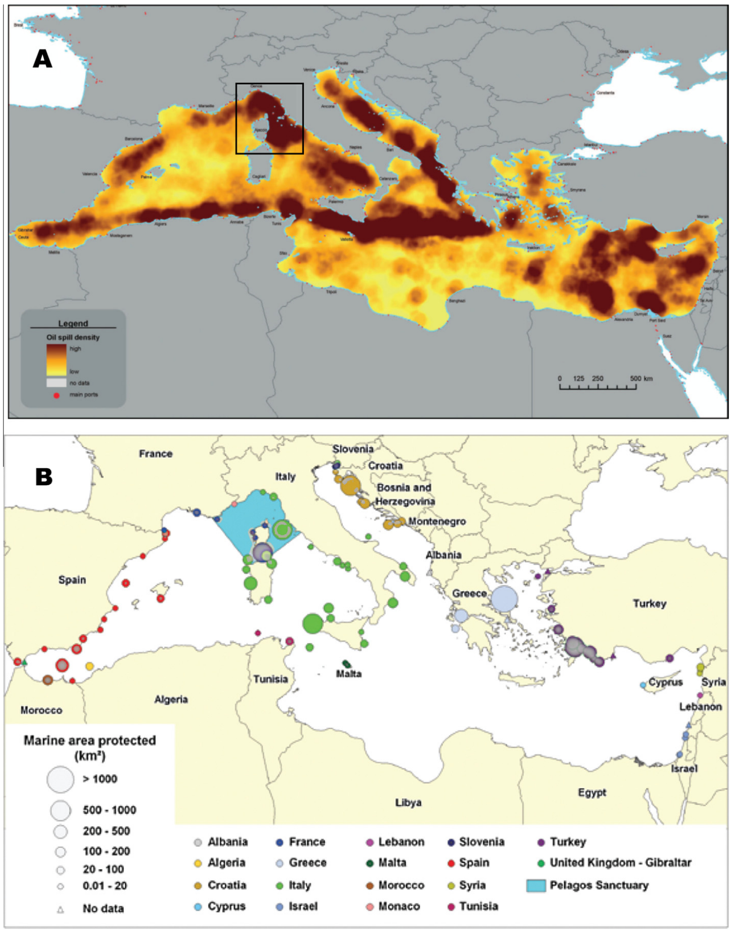

Fig. 1. SAR monitoring of the Mediterranean Sea from 1999 to 2004, with a zoom at the Tuscany Archipelago study area. (A) Oil spill density estimation (extracted from Ferraro et al., 2009. (B) Distribution of MPAs in the Mediterranean Sea (extracted from Abdulla et al., 2008).

Although detection (e.g. SAR imagery, electronic nose, mooring buoys) is the first step to prevent and act in the event of an oil spill, forecasting its trajectory is a key factor to response and clean-up operations. In fact, the integration of satellite detection systems with operational regional sea models applying state of the art algorithms to model the drift, weathering and impact of oil spill in the coastal zones is an outlook onto the future of EU operational services for Member States in this field (Trieschmann, 2008).

Several operational hydrodynamic and wave models are implemented in the Mediterranean, providing regional (e.g. the Mediterranean Forecasting System), sub-regional (e.g. Adriatic Forecasting System) and shelf (e.g. Malta Shelf Hydrodynamic Model) coverage for almost the entire Sea. Regional models (horizontal resolutions between 10 km and 5 km), have data assimilation methods implemented using available observations (SST, SSH, ARGO, XBT and mooring buoys) and supply 5–7 days of ocean forecasts that typically are use to drive sub-regional and shelf models (horizontal resolutions between 5 km and 1 km). Increasing model horizontal resolution brings the potential to improve model results. This is true for trajectory modelling, particularly near the coast, where adequate bathymetry data and coastline resolution can impact the quality of results. Oil pollution response is then one of the operational applications that can benefit from this increase in resolution.

A review of two operational systems (POSEIDON and CYCOFOS-MEDSLIK) in place to support the decision process in the event of oil spills in the Mediterranean Sea can be found in Janeiro et al. (2012). Typically ocean forecasts from operational models are used to force oil drifting and weathering models, which in general run offline of the operational system. In this study, an already implemented regional operational system for the study area was used to provide initial and boundary conditions, being the focus of this work to downscale its solution to the local (coastal) scale (1 km). At this scale, local effects of wind, waves and currents are important to the trajectory of a spill, and cannot be disregarded. The MOHID water modelling system (Martins et al., 2001; Balseiro et al., 2003; Leitão et al., 2005) was applied in this study. It is a modular system including modules for several processes of the marine environment (physical, chemical and biological). This modular system where all the modules are included in the MOHID architecture is the main difference when comparing with other operational modelling systems, as it allows the exchange of information in real time between all the modules.

The principal aim of this research paper is to evaluate the benefit of a high resolution integrated hydrodynamic and oil spill model for oil spill forecasts. Model implementation and validation results will be presented and discussed to evaluate the quality of the system and its suitability to be used as an oil spill forecasting tool. The paper is organised as follows: in chapter 2 the operational system and its several components are described; chapter 3 will focus on the validation of the system; in chapter 4 the results are discussed and chapter 5 summarises the main conclusions of this study.

2. The operational system

2.1. Hydrodynamic model description and implementation

To solve the spatial hydrodynamic variability of the region without compromising the computational requirements of an operational system, a three level nesting downscale methodology was implemented. Level1 (Fig. 2A) is a two dimensional barotropic model with a constant horizontal resolution of 6.5 km. The main purpose of this level is to propagate tide for Level 2 at the same time allowing the solution from Level 2 to freely propagate outward, avoiding reflections and spurious flows at the boundaries. Tide is imposed at the open boundaries of Level 1 using the FES2004 solution (Lyard et al., 2006).

Level 2 (Fig. 2B) is a three-dimensional model, with a constant horizontal resolution 6.5 km, 71 unevenly spaced Z coordinate levels and a time discretization of 30 s. Boundary conditions for temperature, salinity and velocities are extracted every day from the Mediterranean Forecast System (MFS) daily solution, operationally available from the MyOcean 2 server. A complete description of the MFS model can be found in Tonani et al. (2008). At the boundary, a Blumberg and Kantha (1985) condition is applied to the water level and a Flow Relaxation Scheme (FRS) Martinsen and Engedahl (1987) is used for the velocities, salinity and temperature. This allows for a slow forcing of the model and a weighting of internal and external solution to prevent an overshoot of the dynamic equilibrium. In the outer grid cells a sponge layer was applied to attenuate reflected spurious baroclinic flow oscillations. To increase the model resolution in the Tuscan Archipelago, a more refined model grid was created for this region. Level3 (Fig. 2C) is a three-dimensional model with a regular 1.5 km spatial resolution grid, which includes the Archipelago islands. The bathymetry was created using the GEBCO Digital Atlas published by the British Oceanographic Data Centre on behalf of IOC and IHO (2003). It has 71 unevenly spaced Z coordinate levels and a time discretization of 15 s. The communication between Levels 2 and 3 is made by relaxation of the zonal and meridional horizontal velocity components, through an eight cells band adjacent to the lateral boundary. The FRS is also used to pass the information from Level 2 to Level 3. The use of these boundary conditions is consistent with the conclusions of Blayo and Debreu (2005) that considered relaxation methods to be suitable boundary conditions, giving reliable results in practical applications. To calculate the turbulent diffusion coefficient, MOHID embeds the General Ocean Turbulence Model (GOTM, Burchard et al. 1999; Umlauf and Burchard, 2005). The mixing-length scale parameterization proposed by Canuto et al. (2001) is used.

Atmospheric forcing conditions are supplied by the regional weather forecasting system SKIRON, developed for operational use at the Helenic National Meteorological Service (Kallos, 1997; Papadopoulos et al., 2001). The SKIRON model is a non-hydrostatic NWP model (Janjic et al., 2001), which includes a 3D data assimilation package to produce high-resolution analysis fields (Albers, 1995). It provides hourly data of wind U and V components, air temperature, specific humidity, total cloud cover, sea level pressure, total precipitation, upward and downward long wave flux, evaporation, latent heat flux and sensible heat flux at a resolution of 5 km. SKIRON results are used in the operational system as forcing fields for the hydrodynamic, wave and lagrangian models.

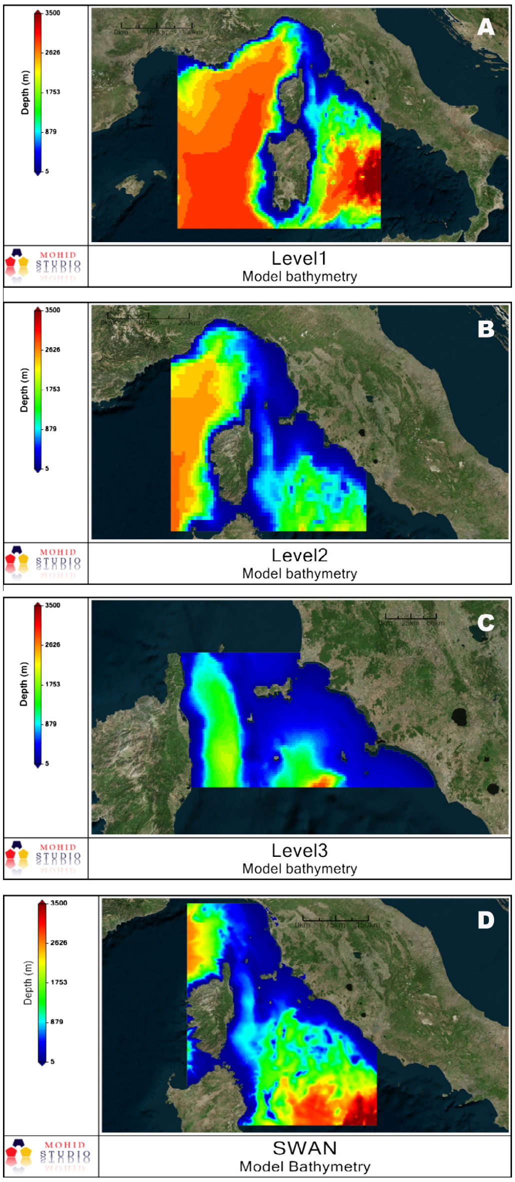

Fig. 2. Model implementation region and bathymetry for: (A) hydrodynamic level 1; (B) hydrodynamic level 2; (C) hydrodynamic level 3; (D) SWAN wave model.

2.2. Wave model description and implementation

Wave forcing is coupled in the operational system by means of a local SWAN implementation for the study area. Fig. 2D shows the computational domain of SWAN and the model bathymetry. A complete description of the SWAN model can be found in Booij et al. (1999) and SWAN Team (2009). For this study, the SWAN wave model was favored over other wave models due to the complex bathymetry of the Tuscan Archipelago. The latter dictated the need for a resolution higher than that typically used in deep water applications, capable of resolving important regional features, and for a model of high numerical stability. The computational domain extends (from 8.6°E to 12.5°E and from 40.2°N to 44°N) and grid resolution (2 km) has been determined considering a balance between accuracy and computational efficiency (Fig. 2D). Temporal discretization has been defined at 60 s. The bathymetry used as input to SWAN is the GEBCO bathymetry (IOC and IHO, 2003). The wave forcing at the lateral boundaries of SWAN consists of wave spectra given at 0.1° spatial intervals and updated every hour. The wave spectra was provided by the 3G spectral wave model WAM, operational at the National University of Athens (UoA) (AMandWFG, 2010). The model is forced with hourly wind fields of the same horizontal resolution and operates in deep water mode without refraction. This is particularly important for obtaining accurate results in sub basins characterised by complex topography, like is the Tyrrhenian Sea (Ardhuin et al., 2007; Sotillo et al., 2008). The surface wind fields input to SWAN to force local wind-wave generation are supplied by the SKIRON weather forecasting system.

2.3. Lagrangian and oil spill weathering models

Lagrangian models are very useful to simulate localised processes with sharp gradients like oil spills (Carracedo et al., 2006; Janeiro et al., 2008). MOHID's Lagrangian module uses the concept of particles, being its position (x,y,z) the most important property of a particle . The spatial evolution of the particles is computed integrating the definition of velocity:

$$\frac{dx_i}{dt} = U_i(x_i, t) \quad (1)$$

where

$$U_i = u_{1i} + u_{2i} + u_{3i} + u_{4i} + u_{5i} \quad (2)$$

In traditional Lagrangian models a particle is tied to a specific mesh, so, when a particle leaves the mesh it is eliminated. In the ocean this is not necessarily true, because if the flow inverts the particle could potentially return to the model domain. MOHID Lagrangian module uses a multi-mesh approach. Here, particles are able to change seamlessly between different model meshes (Fig. 3). The association between a particle and the mesh is made via the particle position, with the user defining the descending priority of each nested meshes. This is useful when several domains/data sources with different resolutions exist. Depending on its position, a particle gets the hydrodynamic and wave information from the high-resolution mesh available, while being able to move to other lower resolution grids if its position changes in time.

Looking at Eq. (2), u_{1i} is the current velocity calculated in the hydrodynamic module and taken at a user specified depth. In our approach both the hydrodynamic and the Lagrangian modules share the same model architecture, thus the Lagrangian module runs in real time with the hydrodynamic module. The time step used in both modules can be of the same magnitude, which avoids unnecessary interpolations, improving model trajectories by avoiding "sliding effects". These occur when the time step of the Lagrangian module is much larger than the time step of the hydrodynamic module. When that happens, in curvilinear regions of the flow the curvilinear path of the particles cannot be simulated smoothly, being approximated as straight leaps tangential to the streamlines for every time step. The result is a particle trajectory diverging from the theoretical trajectory. Nevertheless no sensitivity analysis was done on this assumption, and the time discretization used in the lagrangian module was 60 s. u_{2i} is the drift velocity due to the wind defined as:

$$U_{wind} = C_D \times W_{x_{10}}$$
$$V_{wind} = C_D \times W_{y_{10}} \quad (3)$$

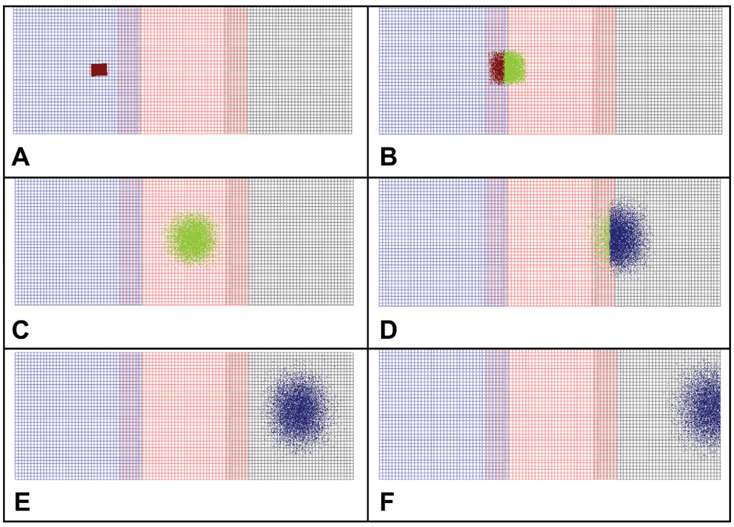

Fig. 3. A cloud of particles being advected across three horizontally aligned grids. The grids order of priority is the following: blue, red and grey. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

where C_D is a user defined wind drag coefficient and $W_{x_{10}}$ and $W_{y_{10}}$ are respectively the zonal and meridional components of the wind speed at 10 m height. Although several authors (e.g. ASCE, 1996; Reed et al., 1994) mentioned that the wind induced speed of the oil typically varies from 2.5% to 4.4% of the wind speed, with a mean value of 3–3.5%, this approach is usually used to account with the effects of courser numerical grids, which might not solve accurately the Ekman surface currents. In this study the top layer has a 3 m thickness which is considered small enough to solve the Ekman boundary layer, thus drift velocity due to the wind was not considered ($C_D = 0$). u_{3i} is the velocity due to the spreading of oil (which is calculated in the oil module and updated by the lagrangian module). The algorithm used to compute spreading is based in the thickness differences inside the oil slick assuming that the existence of a thickness gradient generates a "spreading force" opposite to the gradient direction (NOAA, 2000). The tracers will thus move from computational cells with larger thickness to cells with smaller thickness. The velocities in the x and y directions are computed in each cell face as (NOAA, 2000):

$$u_{cell} = k\frac{\Delta h}{\Delta x}$$
$$v_{cell} = k\frac{\Delta h}{\Delta y} \quad (4)$$

where $\frac{\Delta h}{\Delta x}$ and $\frac{\Delta h}{\Delta y}$ are the thickness gradients of the cell, based on the thickness of the particles present inside it. k is the spreading coefficient given by:

$$k = k_1\sqrt{\left(\frac{\Delta g V^2}{v_w^{1/2}}\right)^{1/3}} \quad (5)$$

where V is the volume of the oil, v_w is the water kinematic viscosity and k_1 is a sensitivity parameter dependent of the grid geometry. u_{4i} is the random velocity due to diffusive transport (Allen, 1982):

$$u_{4i} = K_x \times v_w(x, y, d) + K \quad (6)$$

where $u_w(x, y, d)$ is the water velocity at the specified depth, and K_x and K are the turbulent diffusion coefficients used to define the variance of the random movement velocity. Random displacement

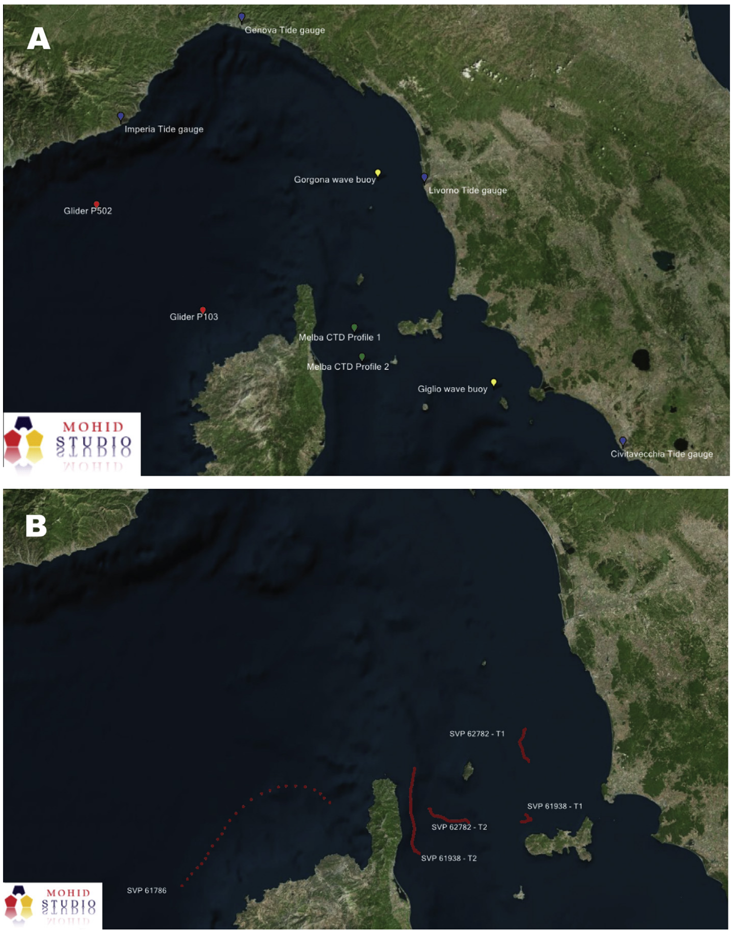

Fig. 4. (A) Geographical location of the stations used to validate the hydrodynamic and wave models; (B) Drifter's trajectories used to validate the lagrangian model.

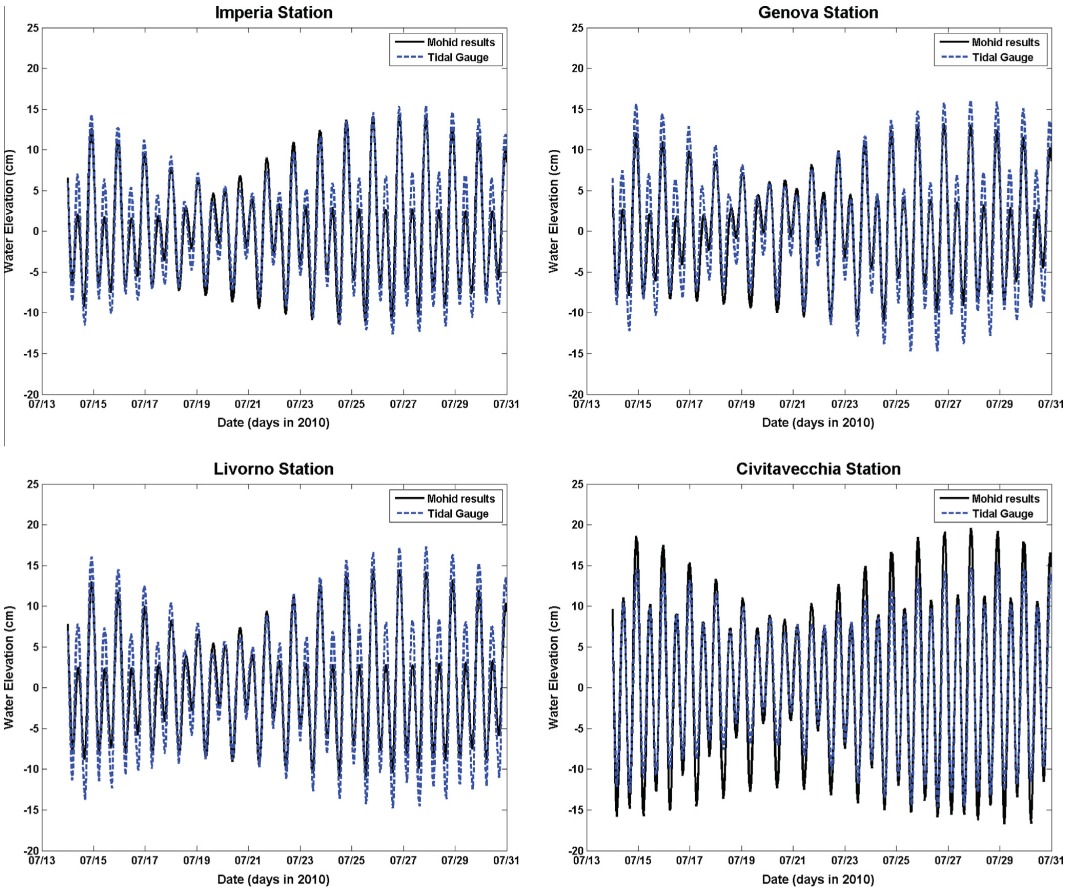

Fig. 5. Comparison between observed and modelled tide elevation in four tide gauge stations along the Italian coast.

Table 1
Estimated errors between observed and modelled water level results for each tide gauge station considered in the study.

Station	R
Imperia	0.9549
Genova	0.9469
Livorno	0.9565
Civitavecchia	0.9832

is computed using the mixing length and the standard deviation of the turbulence velocity component, as given by the turbulence closure of the hydrodynamic model. This velocity is maintained by the particles during the time needed to perform the random movement, which is dependent of the local turbulent mixing length (Miranda et al., 1999). This represents another advantage of the shared architecture, as turbulent quantities are made available to the Lagrangian module in real time throughout the run.

Wind-waves may contribute to the advection of the oil particles through three different mechanisms: (1) through a wave-induced net transport in the direction of wave propagation, broadly known as Stokes drift (Stokes, 1847); (2) through the induction and/or modification of nearshore currents as a result of wave-induced stresses, known as wave radiation stresses (Longuet-Higgins and Stewart, 1960); (3) through turbulence by injecting turbulent kinetic energy (TKE) at the surface to simulate the effect of breaking waves (Craig and Banner, 1994).

Although all the above mechanisms are accounted in MOHID code, only Stokes drift was considered in this work. Wave-induced stresses are particular important to simulate processes in the nearshore and breaking zone, which, although important to model more accurately the dynamics of oil spills near land, is out of the scope of this study. Nearshore processes encompass even higher grid resolutions requirements to the ones considered in this approach, making them infeasible to be used in this operational modelling system. The effect of breaking waves in the turbulence, as proposed by Craig and Banner (1994), can be simulated with the injection of TKE at the surface that leads to a thin surface boundary layer, in which the vertical transport of TKE and its dissipation approximately balance. This layer is sometimes called the transport layer. As shown by Craig and Banner (1994), an analytical solution for the one-equation model can be derived, but only inside the transport layer, according to which the TKE (and all other turbulence quantities) follows a power-law. In this study this effect was not considered, as the model vertical resolution at the surface

(3 m in the first layer) is not high enough to effectively simulate this transport layer.

The stokes drift (u_{5i}), is defined as (Daniel, 2003; Longuet-Higgins, 1953):

$$U_{5i} = a^2 \cdot \omega \cdot k \frac{\cos h[2 \cdot k(z-h)]}{2 \cdot \sin h^2(k \cdot h)} + C \quad (7)$$

where h (m) is the water depth, z (m) is the depth of the particle, a (m) is the wave amplitude ($a = H/2$), ω (rad/s) is the wave circular frequency ($\omega = 2\pi/T$) and k (m^{-1}) is the wave number. C is a depth dependent term:

$$C = \frac{a^2 \cdot \omega \cdot \sin h(2 \cdot k \cdot h)}{4 \cdot h \cdot \sin h^2(k \cdot h)} \quad (8)$$

The wave parameters from SWAN are interpolated to force the Lagrangian module. To simulate the weathering processes that affect a spill in the ocean, the lagrangian module interacts with the oil weathering module (Janeiro et al., 2008). This module calculates the physical processes of the oil (density and viscosity) and the weathering processes (e.g. evaporation, dispersion, emulsification, dissolution) that affect them. A detailed description of the MOHID oil module and the oil weathering processes implemented can be found in Janeiro et al. (2008).

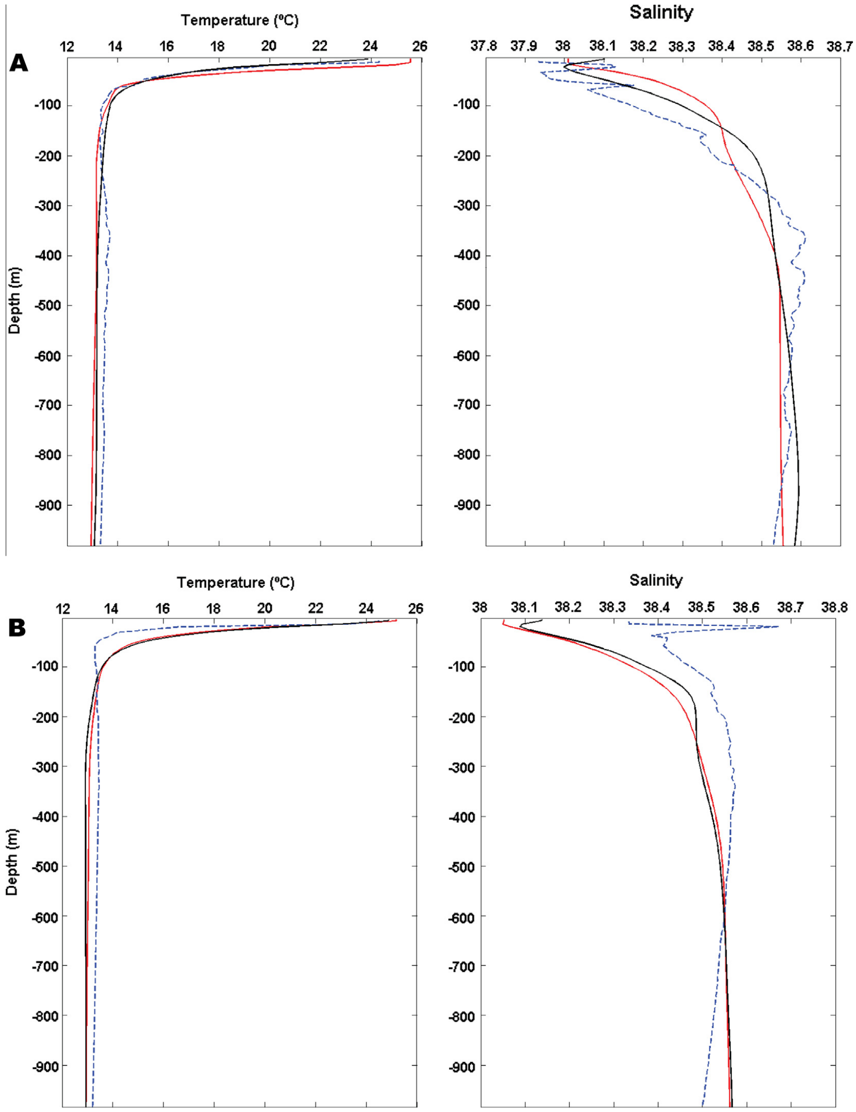

Fig. 6. Temperature and salinity vertical profiles in glider station P103 (A) and glider station P502 (B). MOHID results (red) are plotted against the observed glider profile (blue), both compared with MFS forcing conditions (black). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

3. Model validation

3.1. Hydrodynamic validation

Data collection effort to validate a system of models such as the one presented is a demanding task, thus it was decided to use available data provided freely by the scientific community (e.g. Coriolis and MyOcean portals). The stations used for validation of both hydrodynamic and wave models are presented in Fig. 4A. To estimate the quality of the comparisons, quantification of the differences between measured and modelled elevations were performed using the Pearson correlation coefficient (R) defined as:

$$R = \sum_{i=1}^{i=N} \frac{(\hat{\partial}_i - \bar{\partial})(\partial_i - \bar{\partial})}{(N-1)S\hat{\partial}S\partial} \tag{9}$$

where $\hat{\partial}$ represents model predictions, ∂ represents the observed values, N is the sample size, and $S\hat{\partial}$, $S\partial$ are the sample standard deviations of the model predictions and observed values respectively. When measuring the linear relationship between two interval level variables, the stronger the association of the two variables, the closer R will be to either +1 or -1 depending on whether the relationship is positive or negative, respectively.

The water height results given by the model were assessed using tidal gauge data from Istituto Superiore per la Protezione e la Ricerca Ambientale (ISPRA) network of coastal monitoring stations from 14-07-2012 to 31-07-2012. In order to avoid high frequency signals present in the tidal record, a Fourier analysis was performed in both modelled and observed data, using the methodology proposed by Pawlowicz et al. (2002). This filter is needed as the forcing solution from FES do not include subinertial (meteorological) components. From this analysis, significant constituents were retrieved and used to synthesize the elevation for each station. Fig. 5 shows the comparison between observed and model results, while Table 1 resumes the R values obtained. The modelled elevation results can be considered good reproductions of the observed elevations.

Two glider profiles located near the model boundary (Fig. 4A) were used to validate the model ability to reproduce vertical variations in temperature, salinity and density. Fig. 6 shows the comparison between the two glider profiles and Level 2 results for temperature and salinity. A profile from the MFS forcing solution was also considered here to assess the behaviour of the boundary conditions implemented. For each of the two glider profiles, both MFS and the Level 2 have R value above 0.9 for temperature, while for salinity R is above 0.6 in profile 502 and above 0.9 in profile 103 (Table 2). R values between Level 2 and MFS are quite similar, showing a good performance of the boundary conditions chosen. Two CTD profiles collected by the French Oceanographic unit Europe, managed by Ifremer, during the campaign MELBA-2011 were used to validate the high resolution Level 3 (Fig. 7). A quantitative analysis of these results is presented in Table 2. R values are above 0.9 for temperature in both CTD profiles, while property salinity is above 0.8 on CTD profile 2, being better represented on CTD profile 1.

Sea surface temperature (SST) from Level 2 was compared with satellite images from MODIS Aqua SST in three different seasonal conditions (Winter, Spring and Summer). Satellite data was retrieved from NASA's Ocean colour webpage (NASA, 2012) and it consisted on a dataset of 10 days in the months of January, April, May, July and August 2012 for MODIS binned 4 km (night time 11 μm) daily images. From this dataset of images a quality control was applied. Based on the flagging methodology only "excellent data" (FLAG 1) was considered. Fig. 8 shows the comparison between MODIS daily 4 km and Level 2 for the periods described above. Qualitatively, the results indicate a good agreement between Level 2 and MODIS. The main features in the images are reproduced to a good extend by the model throughout the three scenarios, with a small bias in the maximum temperatures registered.

Table 2
Error estimation between MOHID results, GLIDER observations and MFS forcing (Level2) and between MOHID results and CTD profiles (Level3).

Model	Profile	Property	R
MFS	GLIDER_P502	Temperature	0.9166
		Salinity	0.6413
	GLIDER_P103	Temperature	0.9782
		Salinity	0.9464
MOHID	GLIDER_P502	Temperature	0.9357
		Salinity	0.6778
	GLIDER_P103	Temperature	0.9738
		Salinity	0.9350
MOHID	CTD Profile 1	Temperature	0.9879
		Salinity	0.9386
		Density	0.9981
	CTD Profile 2	Temperature	0.9740
		Salinity	0.8879
		Density	0.9967

3.2. Wave model validation

The SWAN model implementation was validated using data from two wave buoys available in the study area (Fig. 4A). A time-series comparison between H_s, and mean wave period (T_m) parameters obtained from the wave buoys and those computed by SWAN for December 2009 and February 2010 is presented, respectively, in Fig. 9A and B. Statistics for the above comparisons, obtained in accordance to Eq. (4), are included in the figures. Generally a good agreement between SWAN H_s and measured H_s exists, whilst a fairly good agreement is found for T_m. SWAN seems to underestimates the wave height at the area, leading always to a negative relative bias. Nonetheless, it is observed herein that SWAN H_s underestimation is common in low to medium values of H_s whilst H_s peaks are occasionally overestimated. An overall underestimation of T_m is observed. More specifically, and in terms of statistics, in December 2009 at Giglio (Fig. 9A), H_s underestimation by SWAN around H_s peaks is up to 34% (peak at 573 h). Overestimation of H_s by SWAN ranges from 5% to ≈ 30% at the 336 h peak. During the high storm of long duration between 400 and 500 h, SWAN overestimates H_s by up to 11% with the overall R being 0.891. At the same buoy, in February 2010 (Fig. 9B), the picture shows again a H_s underestimation, which varies from 18% to up to 60% around the 500 h peak. Occasional H_s overestimation does not exceed 10%. The overall statistics are similar to the ones obtained for December 2009. At Gorgona, alike the situation at Giglio, SWAN H_s overestimation occurs mainly in December while in February underestimation is dominant. The former is mostly less than 10% whilst the latter varies mostly within the range 16–30%. The overall statistics are generally worse than those obtained at Giglio (except for R in December). With respects to T_m, this is clearly underestimated by SWAN for T_m < 4 s. This may be partly explained by the typical cut-off frequency of a wave buoy that does not exceed 0.3–0.5 Hz corresponding to a wave period of 2–3 s, below which the cut-off frequency value is assigned. Nevertheless, some of the high peaks in the record are still overestimated by SWAN. The overall statistics are better at Giglio than at Gorgona. Specifically, R at Giglio is 0.868 and 0.738 whilst at Gorgona is 0.825 and 0.728.

Fig. 10 compares SWAN output and wave buoy measurements in terms of wave direction. Specifically, the directional distribution of H_s is depicted in the form of wave roses. Results for both

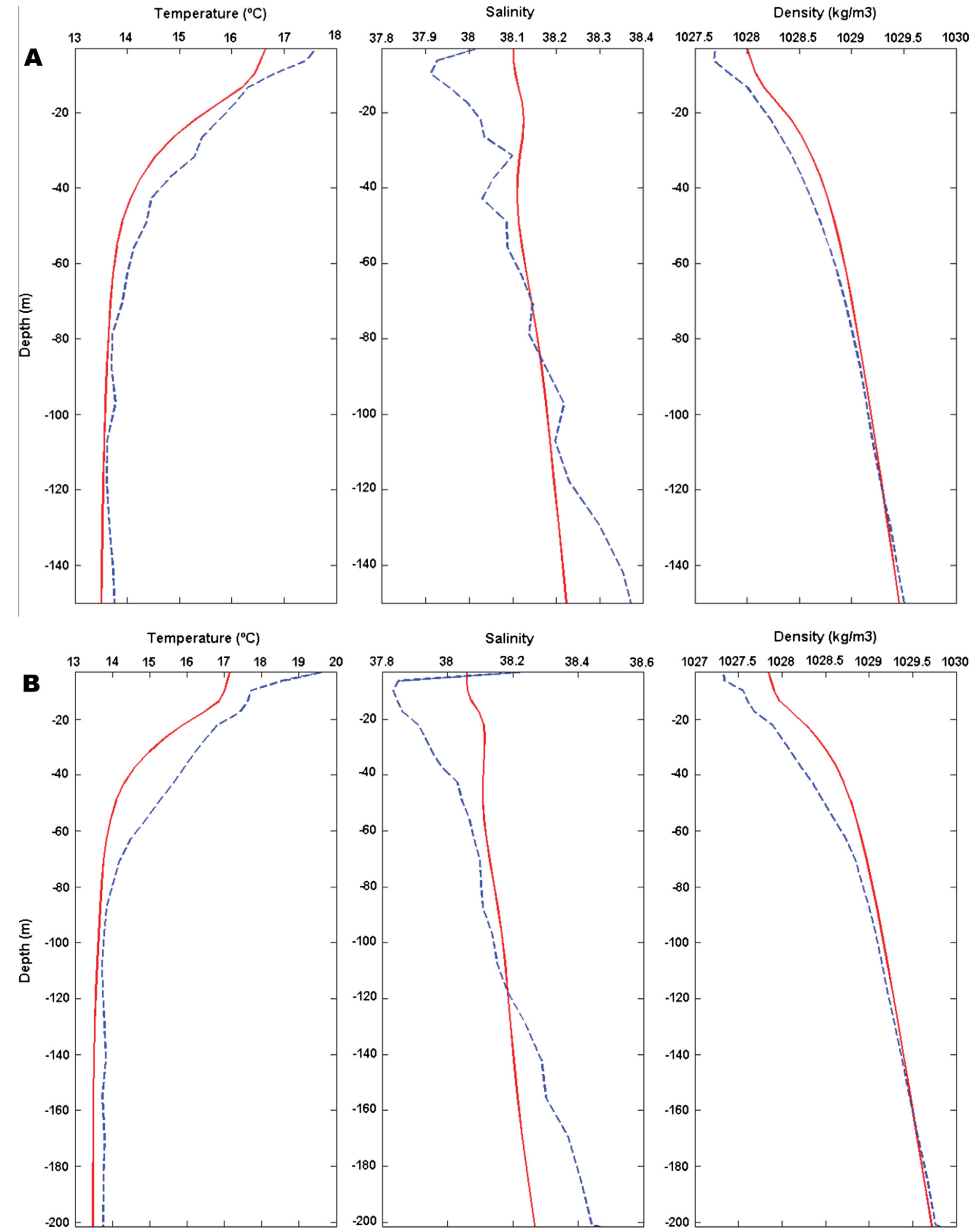

Fig. 7. Temperature, salinity and density vertical distribution for CTD profile 1 (A) and CTD profile 2 (B). Model Level3 results (red) and CTD observations (blue). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

December 2009 (top 4 plots) and February 2010 (bottom 4 plots) are presented. In all occasions, it appears that the dominant directions – SW and W at Giglio and SW at Gorgona – are coinciding with the directions of approach of the highest waves in the time series, being well represented by SWAN. Nevertheless, with the focus on Giglio, the model returns more frequent and higher waves

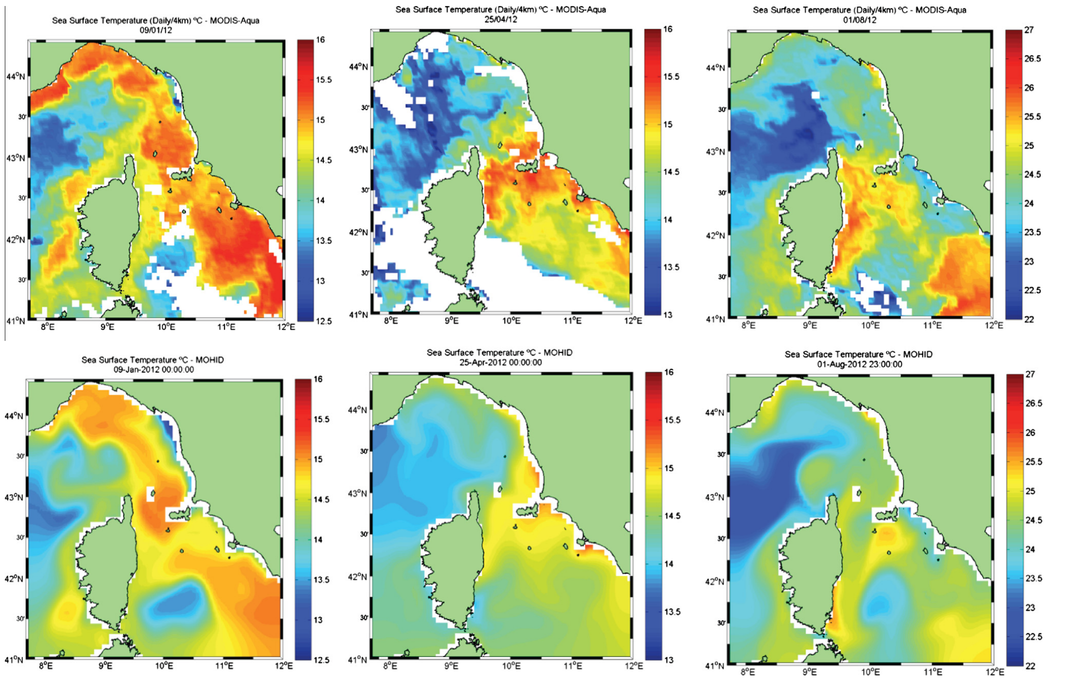

Fig. 8. Comparison between MODIS 4 km daily SST images (top) and MOHID Level 2 (bottom) SST results for three seasonal periods in 2012. From left to right, Winter, Spring and Summer situations.

from the dominant sectors in December. In February, SWAN waves from these sectors match better the observations in terms of percentages but remain somewhat higher.

3.3. Lagrangian model validation

Several studies (e.g., Thompson et al., 2003; Barron et al., 2007) suggest that model simulated drifter trajectories can be directly compared with independent drifter experiments. Model drifters are released in the location where satellite-tracked drifters are observed, and their separation distance is a direct measurement of the trajectory model skill. This method was carried out using available published data from five Surface Drifting Program (SVP) drifting buoys with an anchor depth of 50 m (Fig. 4B) and sparse in time. The data was collected and made freely available by the Coriolis project and programmes contributing to it (http://www.coriolis.eu.org). The buoys positions were compared with the simulated trajectory of 200 lagrangian particles during two days. The total release may be envisaged as a particle "cloud" which represents the probability of the buoy position, being thus described as a "probability cloud". In this approach a particle cannot be subdivided and is unable to interact with other particles.

The multi-mesh approach ensures that the high resolution hydrodynamics (Level 3) is used whenever the particles move into its geographical boundaries. Turbulent diffusion coefficients were adjusted to better represent the drifters spreading. The cloud of lagrangian tracers will spread based on this turbulent diffusion coefficient (K_x), therefore high current velocities will increase tracers spreading due to high standard deviations for the random velocities. The optimal combination was then considered to be $K_x = 0.05$ and $K = 0.0$ for the turbulent diffusion coefficients. To compare the buoy trajectory with the model results, the centre of mass of the lagrangian particles outputted by the model was calculated. The centre of mass in a system of cloud particles is defined as the average of their positions, weighted by their masses (m):

$$\overline{X} = \frac{\sum m_i x_i}{\sum m_i}, \quad \overline{Y}\frac{\sum m_i y_i}{\sum m_i} \tag{10}$$

To access the performance of the model, a Lagrangian trajectory-based non-dimensional index proposed by Liu and Weisberg (2011) was applied. Defined as:

$$S = \sum_{i=1}^{N} d_i \Big/ \sum_{i=1}^{N} l_{oi} \tag{11}$$

d_i is the separation distance between the modelled and observed endpoints of the Lagrangian trajectories at time step i after start, l_{oi} is the length of the observed trajectory, and N is the total number of time steps (Liu and Weisberg, 2011). In this way a total agreement is reflected by an s value equal to zero.

As an initial step, a model scenario assuming the release of 200 particles at 50 m depth (anchor depth of the drifters) was simulated. The s results for the five drifters considering the 50 m model depth are presented in Table 3. At this depth, discrepancies were found in four of the five comparisons, which presented a high s with the exception of drifter 61938 T1 ($s = 0.29$). While several factors might be directly affecting the drifters' trajectories (e.g. change in anchor depth), in practical terms the current velocity responsible for the drifters trajectories is not just the current velocity at the anchor depth but rather an integration of the current velocities from the surface to the anchor depth, along the connecting cable, considering that velocities in depth will have more weight than the ones at the surface due to the drifter's sock. To

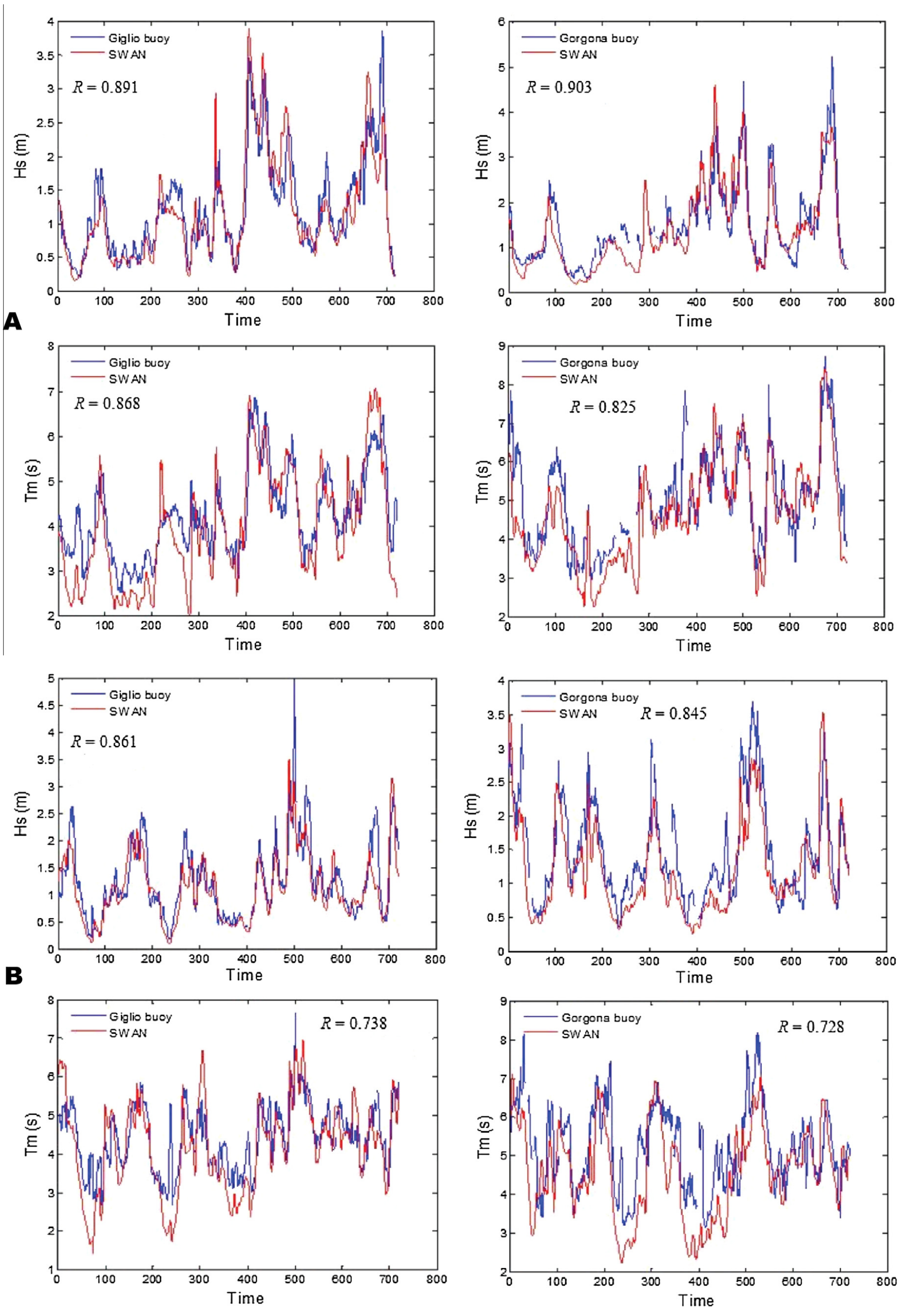

Fig. 9. Accessing SWAN H_s and T_m performance against Giglio and Gorgona wave buoys during: (A) December 2009 and (B) February 2010.

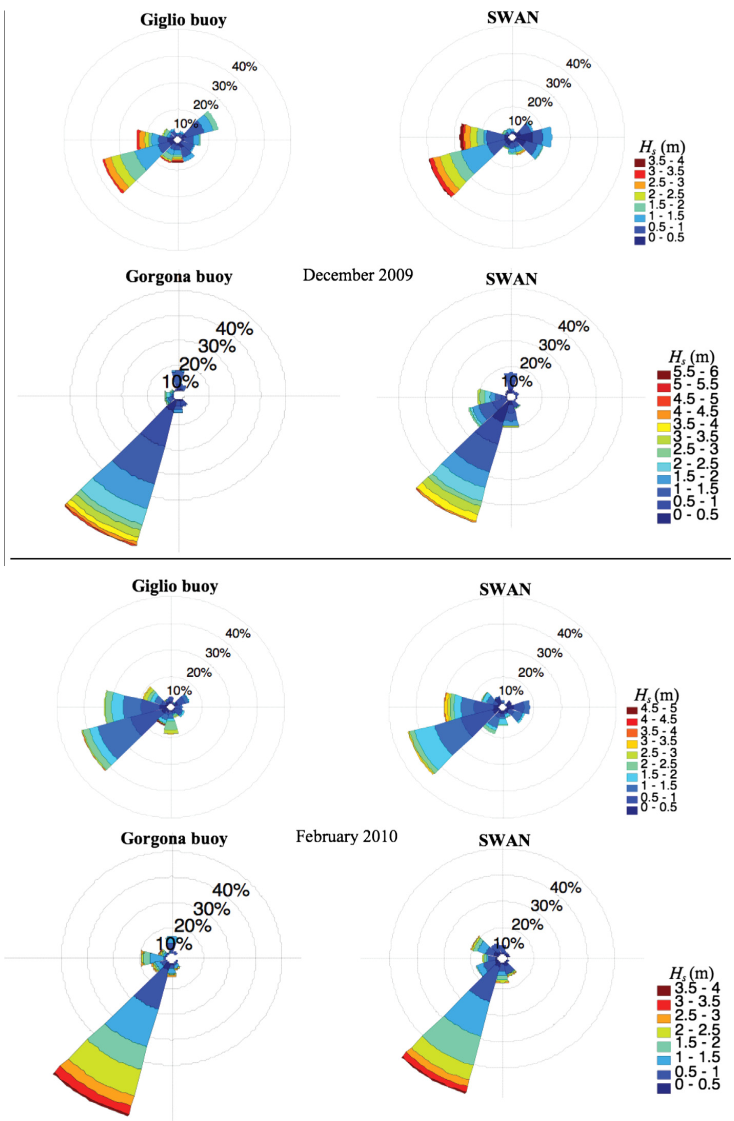

Fig. 10. Directional distribution of H_s obtained from the wave buoys (left) and output from SWAN (right) for December 2009 (top) and February 2010 (bottom).

further investigate the discrepancies, simulations using the surface as release point for the lagrangian particles were run. Since at the surface the main physical factors affecting the model particles are hydrodynamics and the Stokes drift effect, scenarios with and without Stokes drift were simulated. This allowed accessing the impact of the Stokes drift on the ability of the model to reproduce more accurately the drifters trajectories. A clear improvement was achieved in the three of the drifters when comparing their trajectories with the model trajectories at the surface. Exceptions are drifters 61938 T1 and 61938 T2. While for the first drifter the *s* index is almost unchanged throughout the scenarios, for the second drifter the *s* index value of 0.65 at 50 m depth deteriorates to 0.84 and 0.89 for the surface scenarios with and without Stokes drift respectively. Nevertheless the *s* index values achieved for this drifter are relatively high when compared to the ones found for the rest of the drifters. Graphically, Fig. 11A and B present the trajectories for the three drifters that show significant improvement in *s* values when considering the surface. In Fig. 11A model results (green) are compared with the trajectories (orange) obtained at 50 m depth, while in Fig. 11B the results obtained for the surface release can be observed for the two Stokes drift scenarios considered: with Stokes drift (red) and without Stokes drift (blue).

Table 3
Results obtained for the validation of the Lagrangian module using the Lagrangian trajectory-based non-dimensional index proposed by Liu and Weisberg (2011).

Drifter code	Model depth	Stokes drift	S index
SVP 61786	50 m	Considered	0.50
	Surface	Not Considered	0.42
		Considered	0.44
SVP 61938 T1	50 m	Considered	0.29
	Surface	Not Considered	0.32
		Considered	0.30
SVP 61938 T2	50 m	Considered	0.65
	Surface	Not Considered	0.89
		Considered	0.84
SVP 62782 T1	50 m	Considered	0.93
	Surface	Not Considered	0.31
		Considered	0.37
SVP 62782 T2	50 m	Considered	0.94
	Surface	Not Considered	0.45
		Considered	0.45

Regarding the use of the Stokes drift in the simulations, there is no clear trend in the s index results. While for some drifters (61938 T1) an improvement is achieved when including the Stokes drift, for others (62782 T1 and 61786) the same does not happen.

4. Discussion

Based on results obtained in the validation procedure, the presented operational system has proved to simulate hydrodynamics, waves and drifter trajectories with good accuracy in the study area. Nevertheless, differences between observations and model results were found and are worthwhile to discuss. As pointed by Price and Bush (2006), the differences between models and observations can be due to many factors: the input fields (winds, waves and currents) are provided by numerical models which have their own errors. Also the satellite-tracked drifters may contain location errors due to their long period at the sea, which directly affects the comparisons. In the hydrodynamics, the bathymetry resolution can explain the differences found between tidal gauge observations and model results. This is more relevant in the proximity of land, where the tidal gauges are located. In these areas bathymetric gradients are sharper, giving a possible explanation to the differences observed. The validation of temperature and salinity in depth, despite the good results achieved, also presented some errors in both glider and CTD profiles. As the major differences between observations and model results occur at the surface (above 100 m), part of the errors can be due to the vertical discretization used in model. The freshwater water balance (Evaporation-Percipitation-Runof) in the region is not being taken into account by the model also

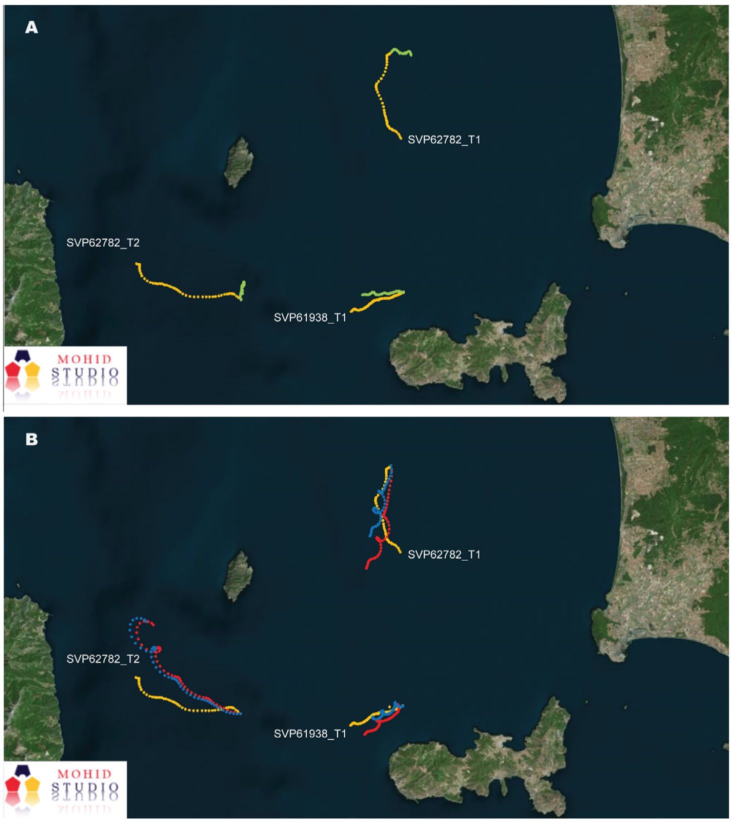

Fig. 11. Lagrangian model validation accessed by comparing the trajectories of drifting buoys (orange) with model tracers centre of mass. (A) Validation with tracers trajectories at 50 m depth (green); (B) Validation with tracers at the surface considering the Stokes drift effect (red) and not considering it (blue). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

explaining part of the errors. This is especially true for salinity, which presents lower *R* values when compared with temperature. The SST bias verified in the model validation with MODIS images can be explained if we consider that satellite images capture the temperature of the ocean surface skin layer, with a few millimeters thick, while on the other hand, the surface layer in the model has 3 m due to computation limitations. These different vertical scales can explain the cooling bias observed.

Regarding waves validation, overestimation of the high Hs peaks at Giglio buoy may be associated with waves approaching from W-SW sectors. Besides that, SWAN also produce more waves from the E and SE sectors in the expense of waves from the S and NE. SWAN underestimation of the highest waves directly from the S is noticeable in both months examined. At Gorgona, the highest waves from the dominant SW sector do not seem to be overestimated by SWAN. On the contrary, in December, they appear somewhat underestimated whilst at the same time a lower percentage of waves from this sector are simulated. This overestimation is in agreement with other Mediterranean wave model implementations (e.g. Magne and Ardhuin, 2009) and has been attributed to an underestimation of wind speeds in the Mediterranean Sea, varying from place to place, being more severe over regions of complex orography, especially over the Tyrrhenian Sea (Cavaleri and Sclavo, 2006; Ratsimandresy et al., 2008). In both months, especially in December, modelled waves are more spread around the dominant direction. Furthermore, in February, SWAN simulates a substantial number of waves from the NW, almost inexistent in the measurements. At the same time, modelled waves from the W and N are less frequent compared to the observations. In terms of statistics, the simulated mean wave direction at Giglio diverges from the measured one by 43° in December and 37° in February. At Gorgona, this deviation is 23° and 26° respectively.

As mentioned above, the lagrangian tracers are forced by the hydrodynamics, the turbulence and the waves, integrating these effects in its movement. This fact makes drifter comparisons a good validation tool for the entire system.

In overall terms the lagrangian module is considered validated with results reproducing to a good extend the trajectories of satellite-tracked drifters. While in the initial simulation at 50 m depth (Fig. 11A) there were discrepancies in the comparisons, they seem to be solved when the surface was considered in the model (Fig. 11B). This points out for the fact that the hydrodynamics affecting the drifter movement is the entire water column from the surface to the anchor depth of the drifter.

While the model results obtained are considered good reproductions of drifter trajectories, focusing in the ability of the model to solve the Ekman surface layer to a good extend, the fact of considering the surface in the validation, instead of the drifters anchor depth (or for this matter an integrated velocity from the surface to the 50 m depth), may raise the question that the model might be underestimating the surface velocities. As mentioned above, the 50 m anchor depth given for the drifters may not reflect their actual depth, as the sock may have been deteriorated with time since their release. This is a plausible explanation that also encompass the fact the model results at 50 m depth present a better comparison with drifter 61938 T1 than when using the surface. Considering the drifters anchor depth unchanged, in fact, a possible underestimation of the surface velocities may occur. The vertical discretization implemented – that affects the baroclinic component of the hydrodynamics – together with underestimations in the wind fields calculated by the atmospheric model – affecting the model velocity in the Ekman layer – appear as the most likely explanation for this possibility. With no available current measurements either at surface or at depth to validate the model hydrodynamics, only these hypothetical assumptions can be discussed.

As noted by Price et al. (2006) and later by Abascal et al. (2009), estimating the separation distance between model and satellite-tracked drifter trajectories during short time scales, is useful to assessing applications to oil spill trajectories. Hence, the Lagrangian results were also accessed in terms of absolute distance from model to drifter (Fig. 12). The improvement when using the surface forcing is clear. In average terms, and except for drifter 61938 T2, the separation distance is approximately 5 km. This value is half the average separation distance when we consider the 50 m depth in the model.

Regarding the use of the Stokes drift in the simulations, the differences found are not significant enough to lead to a conclusion. The more likeliness of such differences might be associated with

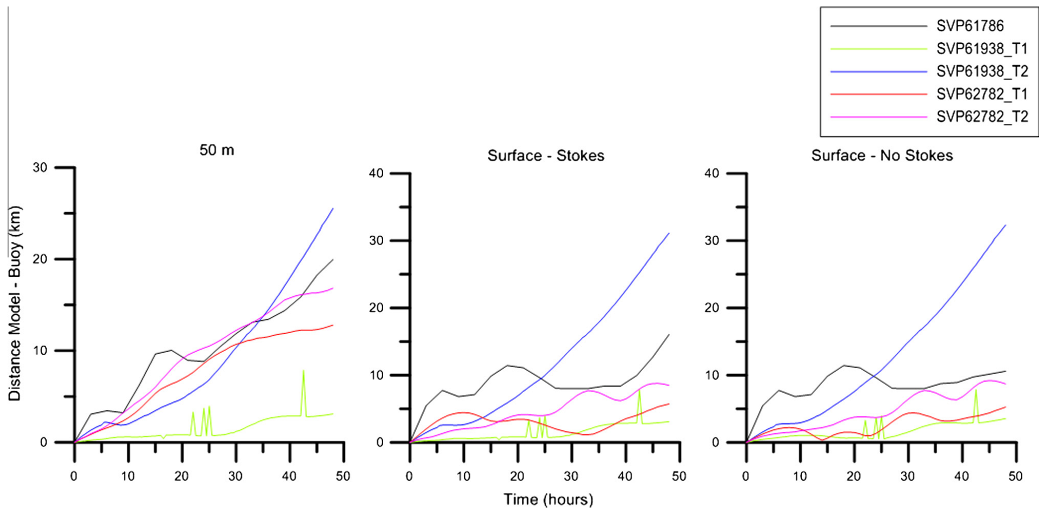

Fig. 12. Distance model to buoy computed for the drifting buoys considered in this study. The depths considered were: 50 m and surface (with and without Stokes drift effect).

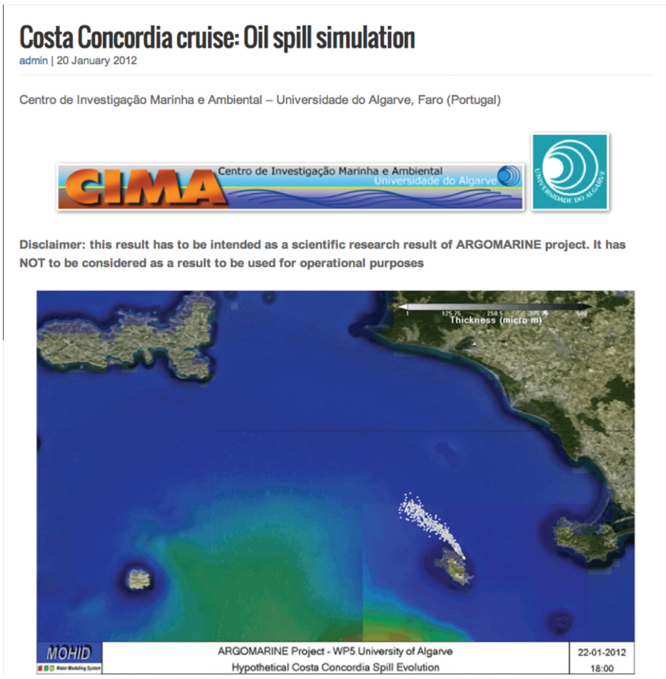

Fig. 13. Operational oil spill scenario simulated during the fuel diesel removal operations from the Costa Concordia ship.

the ability of the wave model to better reproduce the wave fields in some situations than others, as discussed previously. Nevertheless the relative importance of the Stokes drift in the trajectory of oil spills is considered a topic for further research.

The development of fast, easy deployable and semi-automatic mechanisms to create high-resolution emergency oil spill simulations is one of the future applications for this type of methodology. With this approach, coastal areas with complex bathymetries can be easily integrated in regional operational systems and respond quickly to punctual emergency situations. An example was the Costa Concordia accident, which occurred in Giglio Island in January 2012, inside the domain of the operational system. Quickly after the accident this downscaling methodology was applied, and a 250 m grid was created around the accident location as a submodel of Level 3. This configuration of the system was producing operational forecasts during the fuel diesel removal operations from the ship (Fig. 13).

5. Conclusions

An operational model to plan and respond to oil spill accidents was successfully implemented in the Tuscany Archipelago region. The integration of the hydrodynamics, oil trajectories and weathering processes in the same model architecture ensures reduced lagrangian forcing errors, while it allows downscaling the model solutions to very high resolutions. In overall terms the results obtained for the several components of the model were considered very satisfactory and the model considered fit to represent the hydrodynamics of the region. Some discrepancies were identified during the validation of the hydrodynamics and wave models, which were associated with the model resolution, vertical discretization implemented, errors in forcing conditions and errors associated with the numerical limitations of the methods used. Results for the comparison of model trajectories with satellite-tracked drifter trajectories in general were also found precise, with the model presenting a good ability to simulate the drifter's trajectory. This fact, besides adding assurance in the hydrodynamics results, also highlights the advantages of the downscaling methodology used for oil spill simulations, which represents a clear step forward in the operational modelling of oil spill accidents in coastal regions.

Acknowledgments

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Appendix B

In 2015, the preliminary results of the thesis were presented in the 47th International Liege colloquium in Marine Environmental Monitoring, Modelling and Prediction. By September, 2015 the final version of the work will be submitted to the special issue organized by the conference in the Ocean Dynamics journal. The abstract submitted is presented below.

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

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Every year, over 410,000 tonnes of oil are introduced to the oceans through accidental (26[*Sepp-Neves et al. (submitted to the Journal of Environmental Management)*] proposed a new OSRA framework based on the ISO 31000:2009 standard, obtaining significant improvements compared to the original standard and to other frameworks. In addition to the inclusion of operational spills in the calculation of risk, the authors employed, for the first time in the literature, ensemble oil spill simulations to address uncertainties in the calculation of the risk. Their positive results encouraged its application to a wider area and to a more complex risk scenario. Based on the methodology proposed by [*Sepp-Neves et al.*], so-called Information Technology (IT)-OSRA, we estimated the oil spill hazard represented by vessel-related operational and accidental spills in a traficked coastal area. Six ensemble members were generated covering different oil spill characteristics (i.e. oil density, spill volume and duration of the spill) and hydrodynamic forcings (operationally available outputs of MERCATOR, IBI-ROOS and MOHID-PCOMS systems) in order to address the main sources of uncertainties in oil spills events. Simulations were repeated along a release grid every 10 days throughout a year. The experiment was performed in the Southern Portuguese coast, Algarve. The area is known for its high ecological value and its high dependence on marine resources. Concomitantly, the area is exposed to one of the busiest maritime routes in the world in which over 200 million tonnes of oil flow yearly. The results obtained are paramount for the definition of necessary oil spill response equipment and for the positioning of traffic lanes.

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