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Oil spills prediction in the Bonifacio strait area, western Mediterranean

A. Cucco[1], A. Ribotti[1], A. Olita[1], L. Fazioli[1], B. Sorgente[1], M. Sinerchia[1], A. Satta[1], A. Perilli[1], M. Borghini[2], K. Schroeder[2,*], and R. Sorgente[1]

[1]CNR IAMC U.O.S. Oristano, Oristano, Italy
[2]CNR ISMAR U.O.S. La Spezia, La Spezia, Italy
[*]now at: CNR ISMAR U.O.S. Venezia, Italy

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Correspondence to: A. Ribotti (alberto.ribotti@cnr.it)

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Abstract

An innovative forecasting system of the coastal marine circulation has been implemented in the Bonifacio Strait area, between Corsica and Sardinia, using a numerical approach to facilitate the rapid planning and coordination of remedial actions to oil spill emergencies at sea by local authorities. Downscaling and nesting techniques from regional to coastal scale and a 3-D hydrodynamic numerical model, coupled with a wind wave model, are the core of the integrated Bonifacio Strait system. Such a system is capable to predict the sea state and the dispersion of hydrocarbon spills in the area, providing the forecasts on oil spills through an easy-to-use graphical user interface. Scenarios and risk maps have been created to identify the most risky areas to oil pollution in relation to vessels traffic. The backward investigation technique has been exploited to trace the most probable area from which pollution was generated. The system has been operationally verified in January 2011 when an oil spill occurred in the area. Finally output data are daily released providing forecasting services to end-users through the web.

1 Introduction

The marine transport is one of the main sources of petroleum hydrocarbon in the Mediterranean Sea, crossed every year by about 220 000 vessels of more than 100 GRT each as estimated by the European Environmental Agency (EEA, 2006). These vessels approximately discharge 250 000 tons of oil due to shipping operations such as deballasting, tank washing, dry-docking, and fuel and oil discharges. In addition, approximately 80 000 tons of oil have been spilled between 1990–2005 from shipping accidents. Finally, incidents at oil terminals, together with routine discharges from land-based installations, are estimated at 120000 tons/year, thus leading to elevated oil concentrations in their vicinity (EEA, 2006).

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Due to its strategic position at the centre of the western Mediterranean Sea, between Corsica and Sardinia, the Strait of Bonifacio is annually crossed by an average of 3500 vessels, mainly solid bulk cargo ships and Ro/Pax, with a gross tonnage ranging between 500 and 25 000 tons (Sorgente, 2012), as calculated from 2000–2009 data from the local VTS named Bonifacio Traffic. This despite of the limitations from early '90s as Italian and French Ministerial Decrees, IMO Assembly Resolutions, the institution of national and international marine protected areas and parks or the recognition by IMO of the Bonifacio Strait as the first Mediterranean Particularly Sensitive Sea Area in July 2011. Hazards crossing the Strait are due to the presence of about hundreds of reefs, over seventy large or small islands, a strict eastern opening of about 6 km, and sea conditions that can suddenly change due to large-scale evolving weather patterns, often associated with the topography of Corsica and Sardinia that generates bad weather conditions often unexpected and unpredictable.

Numerical modelling is a good tool for the prediction of oil spill movement and to reduce its impact on the local environment allowing decision makers to promptly respond to environmental crises. A lot of operational systems, based on trajectories models linked to hydrodynamic and meteorological ones, has been developed in order to analyse the dispersion of oil spill in European seas (e.g. Garcia and Flores, 1999; Brickman and Frank, 2000; Huggett et al., 2003; Ferrer et al., 2004; Gonzales et al., 2008; Pinardi and Coppini, 2010).

These systems are generally not adequate in coastal waters as they use a fixed spatial resolution generally not lower then few kilometres. So downscaling and nesting techniques to downscale the larger hydrodynamic model solutions are successfully used to forecast sea currents and waves. Anyway these techniques must be overcome when simulated oil-droplets leave the high resolution restricted domain to enter into an extended domain. Unstructured grid models are a solution as they allow to reproduce the fluid motion and the oil slick transport processes over different spatial scales without adopting complicated nesting procedures (Umgiesser et al., 2004; Cucco and Umgiesser, 2006).

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This approach of an oil spill prediction system for coastal areas has been applied to the Bonifacio Strait, based on the use of operational finite element numerical models (Fig. 1).

In 2009 an innovative forecasting system of the coastal marine circulation was developed, using a numerical approach, under the framework of the European Integrated project MyOcean and of the Italian project SOS – Bonifacio, in order to facilitate the rapid planning and coordination of operations by the marine authorities to tackle pollution during oil spill emergencies.

The system allows to obtain real time simulations to predict the fate of different types of oil at sea and forecasts of their dispersal in the marine environment within a time lag of 3 days. The main objective of this system is to provide assistance in the prevention and/or limitation of damages, the conservation of marine resources in coastal waters, especially the most vulnerable areas of high environmental value typical of the Strait. Additionally, this system provides assistance to local authorities for identifying responsibilities by tracing back the most probable trajectory followed by the oil, therefore restricting the area from which pollution was generated (backward investigation). This paper presents the backward investigation technique and some oil spill scenarios, risk analyses maps and a real case study for the response to oil emergencies at sea generated by the numerical simulations of the system named Bonifacio Oil spill Operational numerical Model (BOOM). They have shown all to be valuable risk management tools allowing to quickly select the most appropriate intervention strategy.

2 The BOOM system

The BOOM system is composed by a hierarchy of different nested numerical forecasting models covering from the basin to the coastal scale through the downscaling technique (Fig. 2). It is based on both structured and unstructured grids aimed to provide a prognostic tool for managing oil spill emergencies in the Strait of Bonifacio. The system is fully detailed in Cucco et al. (2012).

The coastal element of the system is composed by a set of finite element numerical models including a three-dimensional hydrodynamic model (SHYFEM3-D), a phase averaging Wind-Wave Model (WWM), a Lagrangian trajectory module and a "weathering" module (FEMOIL) coupled one to each other. Such numerical models are aimed to operationally reproduce the hydrodynamics and transport processes in a restricted domain corresponding to the Bonifacio Strait area. The domain has been reproduced by means of adaptive mesh generator onto a finite element grid composed by 33 563 nodes and 64 292 elements. The coastal system is nested to a sub-regional ocean forecasting system for the western Mediterranean Sea named WMED through the downscaling technique.

The SHYFEM3-D hydrodynamic model (Umgiesser and Bergamasco, 1993; Umgiesser and Bergamasco, 1995; Umgiesser, 2000; Umgiesser et al., 2004; Cucco et. al., 2009, 2012) uses finite elements and z-layers respectively for horizontal and vertical discretizations and a semi-implicit algorithm for integration in time. This model has been previously applied in coastal areas both operationally and not operationally (Scroccaro et al. 2004; Ferrarin and Umgiesser, 2005; Cucco and Umgiesser, 2006; Bajo et al., 2007; Bellafiore et al., 2008).

WWM (Cucco et al, 2011) is a phase averaging numerical model, which solves the Wave Action Equations by means of the finite element integration method (Hsu et al., 2005a, 2005b, 2006; Zanke et al., 2006; Roland et al., 2005, 2006a, 2006b, 2009). Its coupling with the SHYFEM model is based on FIFO (First In First Out) files, which allow two processes to communicate during the runtime of each source code. Details of numerical treatments are reported in Cucco et al. (2012).

A Lagrangian module and a weathering module (Cucco et al., 2009, 2012) simulate the behaviour of an oil-slick dispersed at the sea, including spreading, evaporation, dispersion, emulsification, sedimentation and biodegradation,,. So the fate of oil at sea is determined by environmental conditions as well as by its physical-chemical properties.

The coastal component is nested to the WMED through an interface for managing forcing and boundary data in real time which allows to receive daily both high resolution

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atmospheric and hydrological data along the domain boundaries for the following 3 days.

WMED, based on the Princeton Ocean Model (Blumberg and Mellor, 1987; Mellor, 1991), is a three-dimensional model covering part of the western Mediterranean area, between 3° E and 16.5° E. It uses a uniform horizontal orthogonal grid with a resolution of 1/32° (about 3.5 km) in longitude and latitude while vertically it is discretized by 30 sigma levels. At its lateral open boundaries it is nested with daily mean fields computed by the MyOcean-OPA regional model for the whole Mediterranean Sea with a horizontal resolution of 1/16° implemented at INGV in Bologna (Tonani et al., 2008).

Atmospheric conditions to the coastal component are provided by the very high resolution meteorological forecasting system named SKIRON, developed by the University of Athens (Kallos et al., 1997), while to the sub-regional forecasting system by the MyOcean key-user ECMWF.

Furthermore, a second finite element grid was built to simulate the wave generation processes occurring in the open sea then extending the previous high resolution mesh to the whole western Mediterranean and part of the Sicily Strait.

The BOOM system currently produces, daily and operationally since the end of 2010, a 3-days forecast of wind and wave fields, 3-D water circulation, temperature, salinity and of the fate of the oil slick at sea in the Bonifacio area. A Graphical User Interface (GUI; Ribotti et al., personal communication) provides a user-friendly accessibility, usability and interaction with the BOOM system by setting up scenarios, running simulations and analyzing the produced consequences of an oil spill.

3 Applications

The system has been used to provide analysis of scenarios and to evaluate the risk induced by an hypothetical impact of hydrocarbons in the coastal areas of the La Maddalena Archipelago. The results of these activities have been included in the “Local emergency operations plan against marine pollution by oil and other harmful

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substances" of the Coast Guard at La Maddalena. This plan is activated on the basis of art.11 of the Italian Law 979/82 of the "Regulations for the protection of the sea" in case of pollution or imminent threat of pollution of the sea caused by dumping, accidental event of oil or other harmful substances.

Furthermore a technique for tracking back in time the oil trajectories has been developed. The adopted method known as "backward investigation" allows to identify the most probable initial area where a spilling occurred.

In the following sub-paragraphs, results obtained by a selected simulated scenario, including a selected risk analysis, an example of backward investigation and the use of the system in a case study are reported and discussed.

3.1 Oil spill scenarios

A series of numerical simulations were carried out in order to reproduce the most probable pollutant scenarios, and the areas with the highest risk of accident, affecting the Strait of Bonifacio. These scenarios have been chosen considering local climate condition, maritime traffic and historical maritime emergencies records for the last 16 years. Six main macro-scenarios have been defined, differing by the spilling area and the type and amount of hydrocarbons released. For each macro-scenario, eight simulations are carried out in order to consider the seasonal variability of wind regime and water temperature. For all the simulations, stationary open boundary conditions and wind forcing are defined and a spin-up time of 3 days is selected to eliminate the noise generated by the imposed initial conditions. Wind-wave propagation and the 3-D water circulation is reproduced for the Strait area. For each considered macro-scenario, a defined quantity of numerical particles are initialised in the selected area of the oil spill. Each particle represents a quantity of oil released in the water with an associated density, depending on the type of oil considered. The amount of oil released varies between 10 000 kg and 100 kg, and oil density is representative of fuel oil, marine diesel and crude oil.

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About 50 scenarios are considered and the following results are obtained:

- wave and surface current velocity fields;
- hourly field of oil slick depth;
- hourly field of Lagrangian particle position and impacted areas on shore;
- time series of oil quantity dispersed at sea or beached.

Here we show the results obtained for a scenario simulating a real accident with hydrocarbon spillage occurred in 1994 to the French ferry Montestello, on the route Livorno-Barcelona, run aground inside the La Maddalena Archipelago during a strong Mistral wind storm. The simulated accident is set in the same period and with the same original weather conditions and an initial spill of 30 m^3 of fuel oil. The surface water circulation and the wind wave field computed by the model are shown in Fig. 3. The strong Mistral wind (13 $m\,s^{-1}$) generates an eastward water circulation with currents velocities reaching about 1 $m\,s^{-1}$. The wind induced wave field is moved south-easterly with a significant wave height (HS) decreasing eastward. Maximum values of significant wave height (HS) reaching 3 m are found outside the Strait while inside the La Maddalena Archipelago the HS is always less than 0.8 m.

The Lagrangian particles released are quickly transported eastward due to the combined effect of wave, water currents and wind drift. Six snapshots, illustrating the computed particles distribution in the water are shown in Fig. 4. Seven hours after the release, all the particles reach the coast, particularly around the islands of La Maddalena and Caprera (see green dots in Fig. 4).

The temporal variation in the total amount of oil, split between quantity still in the water and quantity beached, is shown in Fig. 5. The oil mass dispersed in the water (red curve) quickly decreases during the first 3–4 h due to high evaporative processes. After this period, the recorded reduction is due to the oil reaching the coast, as shown by the increase in the green curve. After the beaching, the total quantity is still diminishing

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due to evaporative and emulsification processes occurring on the oil that re-enters the sea due to the wind-wave impacts on the shore.

3.2 Risk analysis

The BOOM system has been used to produce probabilistic estimates of the oil impact on the coast as a function of oil type and a risk index for coastal pollution. Three different kind of accidents are considered involving an oil-tank vessel, a cruise-ship and a ferry boat, and a quantity of oil as that contained in the bunkers of each of the three vessels.

For each category, a one-year simulation is carried out, forcing the hydrodynamic and wave model with wind and open boundary data provided by the meteorological and the oceanographic models. Each simulation is initialised with an amount of particles statistically sufficient to cover the paths corresponding to the maritime traffic routes followed by the considered ship categories crossing the Strait.

The "seeding" of particles is repeated daily in order to take into account the influence of the meteorological variability on the Lagrangian transport. Each particle represents a possible spill event of a defined quantity and type of oil, which could occur anywhere along the whole maritime route and at any time of the year. The computed water currents, wave propagation and wind drift transported all the particles within the numerical domain. Each particle is also influenced by weathering and stranding processes, leading to a reduction in the quantity of oil at sea.

At the end of each model run, the quantity and the number of oil particles beached on the coast are computed. The coastline is divided in 200 m cells and, for each cell, the total amount of oil beached during each month of the simulated year is calculated. The cell values are then normalized to the maximum quantity of oil beached on a cell during the considered month and, for each category, 12 maps consisting on the distribution of a relative risk index which ranges between 0 and 1 are produced.

The derived risk index aims to describe, in a probabilistic way, the risk of oil spilled reaching the coast, as a function of a geophysical forcing only. Neither vulnerability

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aspects (biological resources, environmental values, anthropic values, etc.) nor accessibility of the coast have been considered.

As an example, the yearly map of risk induced by the impact of oil on the coast, as released by cruise ships travelling through the Bonifacio Strait, is reported in Fig. 6. The maximum risk of impact is found along almost the whole length of the channel between Sardinia and the La Maddalena Archipelago.

3.3 Response to emergency

3.3.1 Backward investigation

When accidents occur, leading to large oil spill, national authorities are usually quick to respond and identify the responsible. Nevertheless, most of the "small" oil spill events are caused by the common illegal practice of refuelling or pumping oily bilge water overboard. Even if they constitute small spills, their intense frequency can have significant negative effects on the marine environment. In these cases, identification and quantification of the responsibilities is very difficult and often quite impossible.

In order to provide a support to the local Italian Coast Guard for detecting the responsibilities for such events, a numerical tool for carrying out the so-called "backward investigation" was developed. The system, based on the BOOM, aims to track back in the past the probable path followed by the oil dispersed in the water.

The method consists on performing a sequential run of 2 simulations, one "forward" and the other "backward". In the forward run, the hydrodynamic and wave models reproduce the water circulation and wave field in a selected period (DT) before the time (TF) when the oil slick has been detected in its final position (XF). The obtained results are stored in external files and processed in order to invert both the temporal order of the fields sequence and the direction of current and wave propagation. The "backward" run is then performed and the Lagrangian advection model used to transport and diffuse a quantity of particles representing the amount of oil spill detected in the final position XF at time TF. The simulation runs to a time corresponding to DT using,

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as input, the stored and processed current and wave data. Therefore, the obtained results provide a tracking of the detected oil spill from the moment TF and the final position XF, back in time to TI = TF - DT and to the initial most probable position (XI).

An example of a backward analysis carried out to backtrack a fuel oil slick of about 30 m^3 detected in XF at noon of the 27 August 2008 is shown in Fig. 7. The first frame refers to time TF whereas the last to time TI, 6 days before, then 21 August. At time TI the position of the slick is located on the main maritime traffic route (XI), where the release probably occurred. In particular, for the simulated event, comparison between the numerical results and traffic data reveals that the hydrocarbon spill detected on August 27 was probably generated in the recommended route area, corresponding to the position XI. During this period, 21 transits of Ro/Pax, Ro/Ro ships, cargos and cruise ships through the Strait are recorded. Furthermore, considering the kind of ship and their routes, the number of possible responsible can reduce to 15 vessels therefore increasing the probability of its identification.

3.3.2 The Porto Torres event: a case study

The system simulation has been qualitatively verified in early January 2011 during a case study when an oil spill occurred in the harbour of Porto Torres (PT), north-western Sardinia.

During the operation of oil transfer from a ship tanker at the off-shore pipe station in front of PT harbour, about 50 m^3 of heavy crude oil (API 19.7°) were released into the sea. The oil spilled out continuously for about 18 h starting from 10 January 2011 at the 10:18 p.m. of local time.

The slick moved north-eastward for about a 5 days interesting the coast in several points between the villages of PT and Santa Teresa di Gallura (Fig. 8). On 17 January at 12:00 a.m. of local time, 7 days after the accident, an oil spill was found during an air survey in the coastal waters at the entrance of the Bonifacio Strait (see Fig. 8). The local authority in order to verify the connection between the pollutant and the PT accident and to exclude further sources of spills in the area (e.g. tanks cleaning

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bilge waters), run the BOOM in backward mode. The obtained results revealed that the provenience of the spilled oil was from the PT area. Samples of floating oil were successively collected and chemically analyzed in laboratory certifying its origin from PT.

Subsequently a new simulation was carried out to verified the model capability in reproducing the fate of the occurred spill in forward mode. The model domain was extended to the interested area increasing the mesh resolution to reproduce the local bathymetric and morphodynamic features (see Fig. 8). A 9 days simulation run was performed releasing the oil in continuous mode for about 20 hours starting from 10 January at 10 p.m. The atmospheric field produced from SKIRON for the first day of prediction were used to force the model domain. The model was initialized with water levels and current speeds generated by the BOOM system and open boundary data from WMED were used.

The model reproduced fairly well the probable trajectory followed by the spilled oil during the whole period. This is evidenced by the position of the oil particles beached on the shore which mainly corresponds to the coastal area impacted by the pollutants during the event, as reported in Fig. 8. Furthermore, the model was able to reproduce the fate of the oil in water simulating the presence of oil particles on water at the entrance of the Strait during the 7 days after the released time at PT location, in agreement with the experimental evidence.

4 Conclusions

The BOOM represents an innovative operational system developed to provide support to the Italian Coast Guard in managing oil-spill emergencies in the coastal area of the Strait of Bonifacio.

This is an integrated numerical tool whose coastal core is organized in a set of fully coupled high resolution numerical models based on the finite element method. The models include a 3-D hydrodynamics model, a wind-wave model, a Lagrangian trajectory model and a module for reproducing the main weathering processes interesting the oil slick. BOOM is fully operational since the end of 2010 at the Italian Coast Guard in La Maddalena island (Sardinia, Italy), realized in the framework of the Italian project "SOS- Bonifacio" and of the European project MyOcean. The system allows, through the interaction with an easy-to-use GUI, to operationally forecast the fate of oil spills in the whole area of the Bonifacio Strait and La Maddalena Archipelago.

The innovative approach consists on the use of operational finite elements numerical models with a spatial resolution up to 10 meters, fully nested with an open ocean operational model based on the finite differences method (WMED) to reproduce the transport processes occurring in coastal areas characterized by a complicated geometry.

Currently the system produces, daily and operationally, a 3-days forecast of wind and wave fields, 3-D water circulation, temperature and salinity for the area of interest. Furthermore, it was used to investigate the consequences of oil-spills events, to produce risk maps identifying the most exposed areas to the risk of oil impact in relation to both period of the year and type and quantity of spilled oil and as a tool for tracking back the surface trajectories of oil slicks. The operational validation of the system has been realised in January 2011 when an oil spill occurred from the harbour of Porto Torres. The results of the simulations are well comparable either with beached oil and with oil slicks positions at sea then giving valuable information to the Coast Guard on the their origin and on the area covered by the accident.

Simulation results of oil spill scenarios can provide the local Coast Guard with information on the fate of oil spills, those most probable in the area. In particular the hourly maps of oil slick position and those showing which areas would be most probably impacted, as a function of different meteorological conditions, provide a useful tool to improve the management of oil spill emergencies at sea. For this reasons, the local Coast Guard in La Maddalena has inserted the simulated scenarios in its "Local anti-pollution plan for 2009" requested by the Italian Ministry for Environment. These simulations will be used to predict in advance the trajectory of the oil, then permitting

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decision makers to plan the optimal remedial action for minimizing oil pollution and reducing time response and costs.

Further information are also provided by the risk analysis and the coastal risk index tools, which allow the local Coast Guard to identify the most exposed areas to the risk of oil impact during the year. These are also useful for the identification of the most suitable areas, where instruments and resources should be concentrated.

Finally, even if the backward investigation cannot exactly pinpoint the initial position of the oil spill, it still provides information on the most probable path followed by the oil slick, since its detection.

All the described above tools define the BOOM as a useful instrument for any local Coast Guard in the management of oil spill events in a coastal area like that of the Bonifacio Strait and La Maddalena Archipelago, characterized by a wonderful marine and terrestrial environment daily threatened by the passage of tens of vessels. Finally, the daily forecasts of currents and waves in the area are used by local final users (fishermen, sportsmen, SMEs, etc) during their activities as proved by contacts received since the activation of the system on the web.

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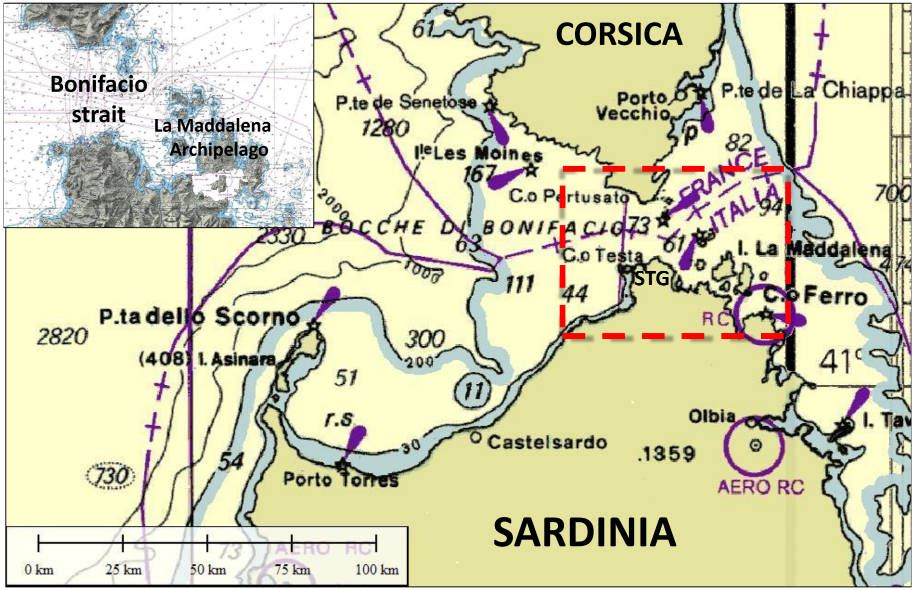

Fig. 1. Geographical setting.

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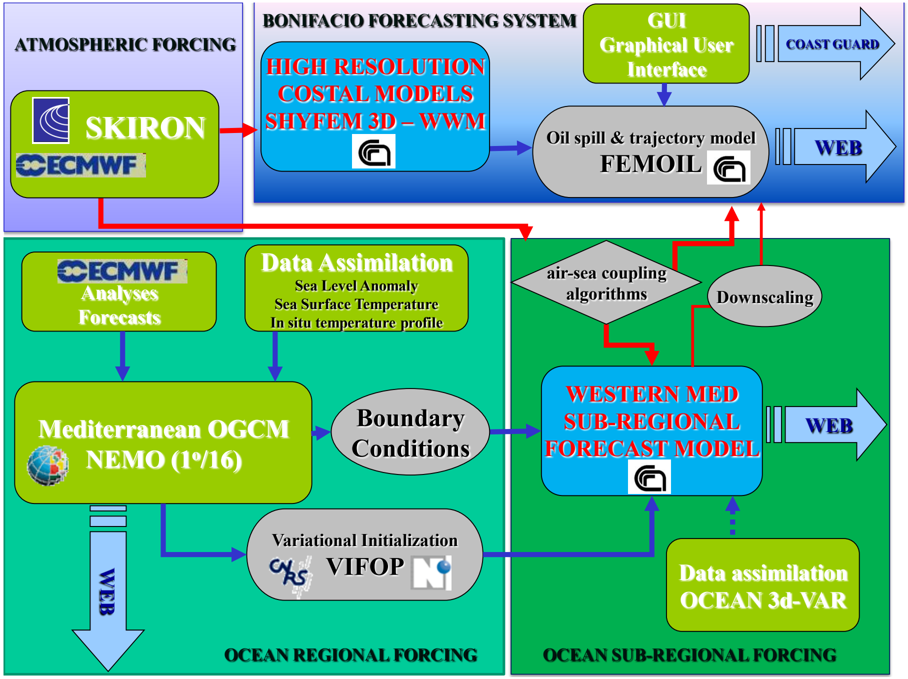

Fig. 2. Scheme of the whole system with different nested numerical forecasting models covering from the basin to the coastal scale, oceanographic and atmospheric.

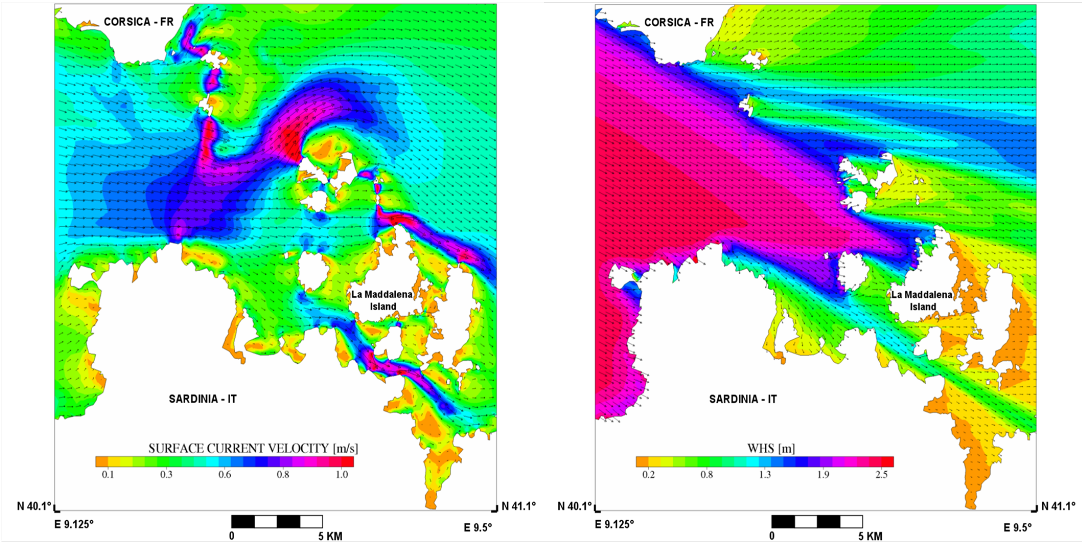

Fig. 3. Surface current speed and significant wave height induced by a 13 m s^{-1} Mistral wind in the Bonifacio Strait and La Maddalena archipelago area.

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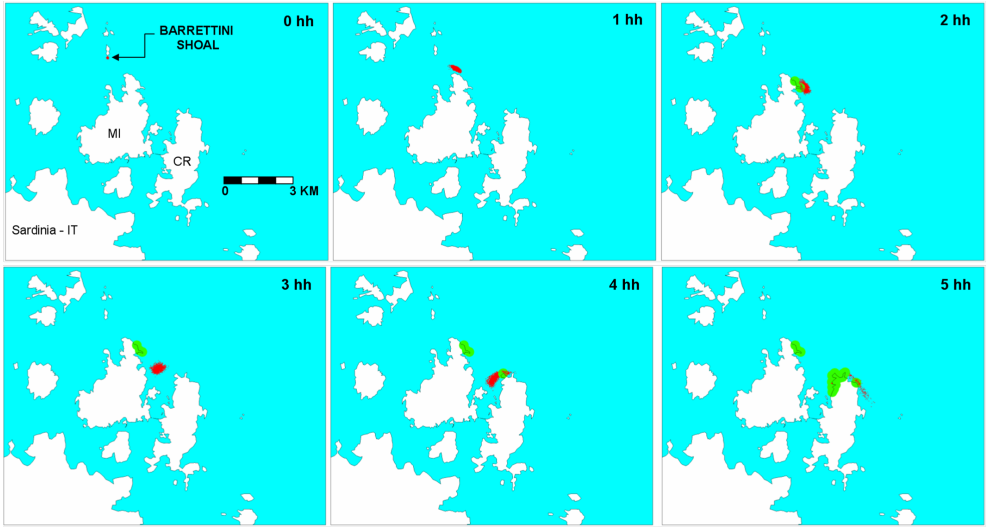

Fig. 4. Snapshots of oil particles distribution dispersed in the water (red dots) and beached on the shore (green dots).

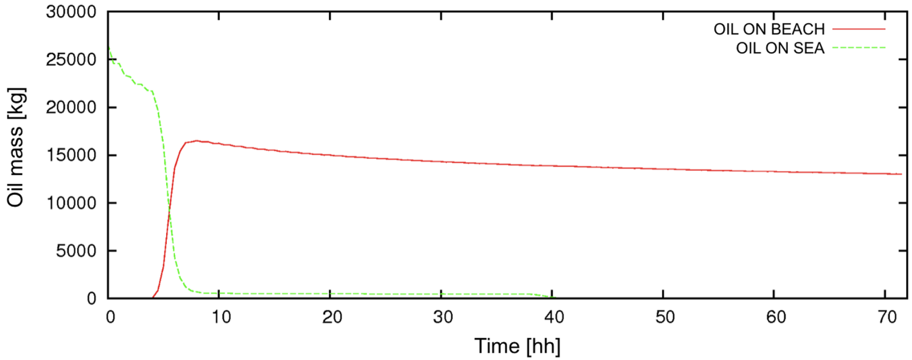

Fig. 5. Temporal variation of the total amount of oil quantity dispersed in the water column (red curve) and beached on the shore (green curve).

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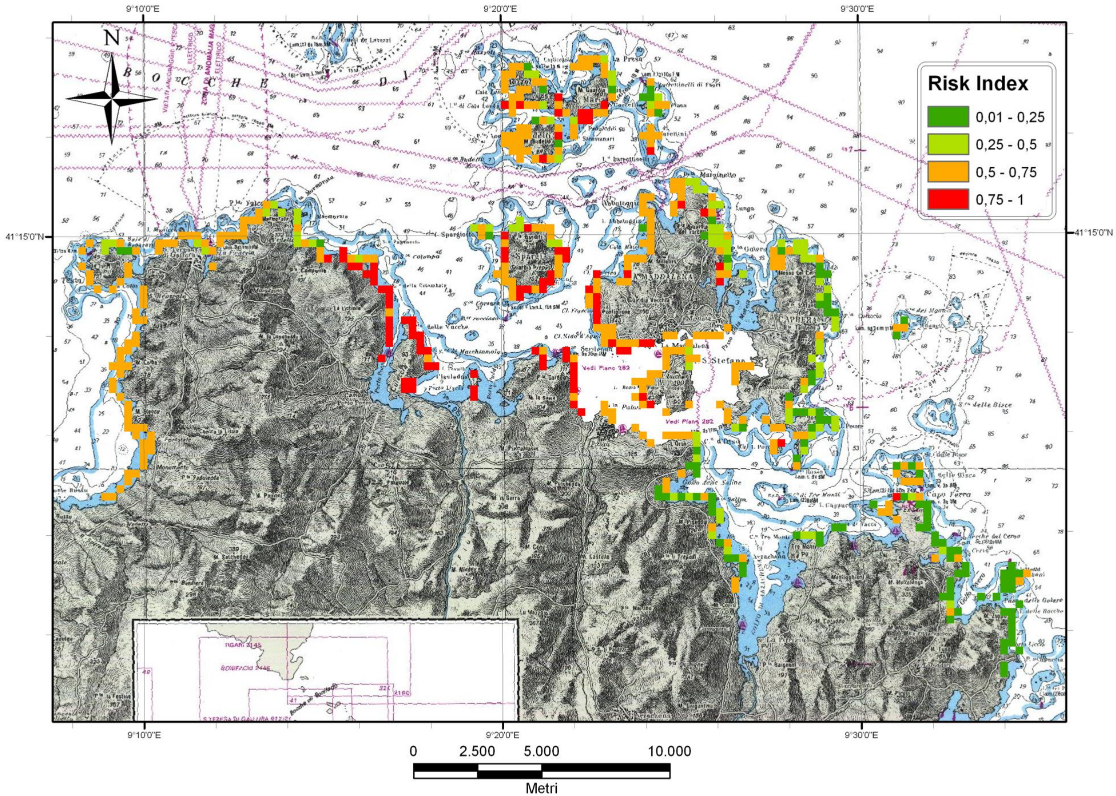

Fig. 6. Risk map of oil impact on the coast as consequence of a potential release from cruise-ships.

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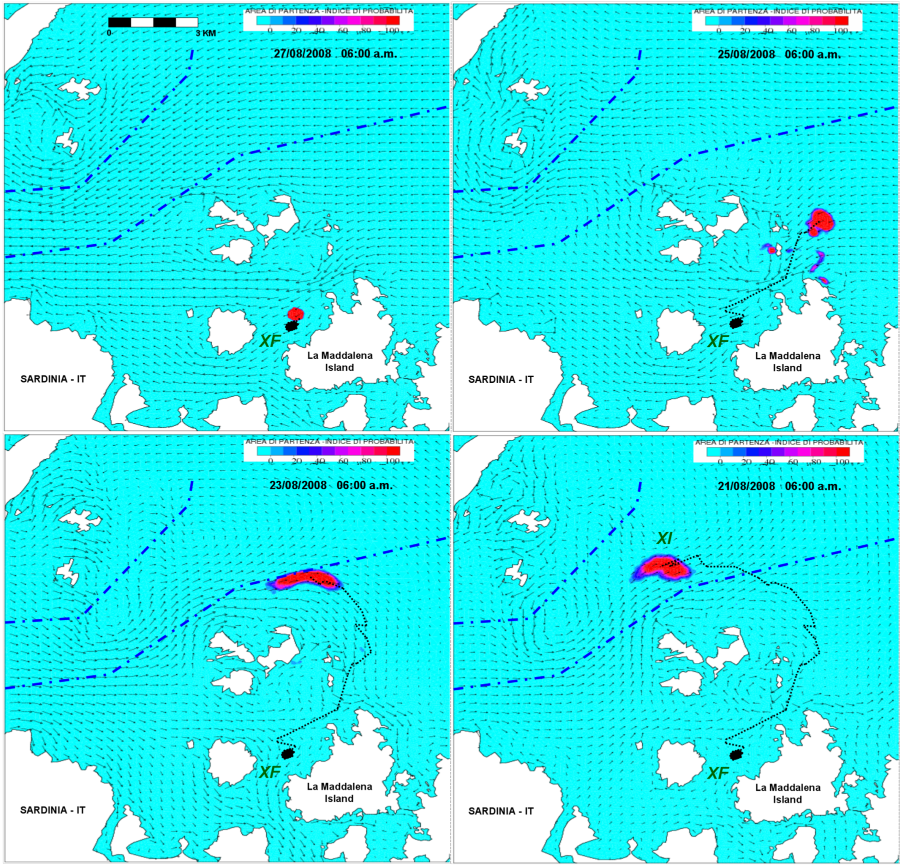

Fig. 7. Results of the backward investigation: XF and XI are the final and the most probable initial positions of the oil slick respectively at time TF (27/08/2008 06:00 a.m.) and at time TI, which corresponds to 6 days before TF (21/08/2008 06:00 a.m.). The areas between the blue dashed lines correspond to the maritime traffic route through the Strait of Bonifacio.

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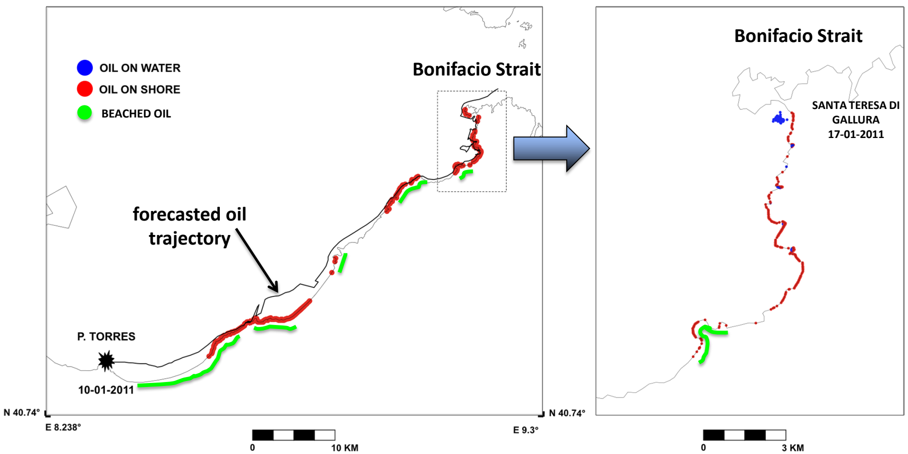

Fig. 8. Map of the area interested by the accident of Porto Torres occurred in January 2011 and the hindcast simulation results. Red lines indicate tracts of coastal area impacted by the oil; green lines the sampled beached oil. The blue circle indicates where the oil at sea was detected by airborne surveys close to the entrance of the Bonifacio Strait. On the left panel the black line indicates the average trajectory followed by the particles on water. On the right panel a snapshot of model results at the 12:00 a.m. of 17 January 2011.

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