

# Numerical Modeling of Oil Pollution in the Western Mediterranean Sea

Andrea Cucco and Pierre Daniel

**Abstract** In this chapter we analyze the last 15 years of oil spill numerical modeling applications in the Western Mediterranean Sea. From the literature, around 17 different scientific papers were published between the years 2001–2016 with a focus on this same subject, but using different ocean and atmospheric forecasting systems as well as of weathering and particle tracking models. All the considered applications were classified in relation to the type of adopted numerical tools, the covered area, and the system accessibility. Besides this analysis, a summary of the major oil pollution events that occurred in the Western Mediterranean subbasins and a comparison between the number and the types of numerical applications carried out for each Mediterranean subregions (western, central, and eastern) were reported. Finally, two different operational systems characterized by different numerical tools, the one developed at Meteo-France, the MOTHY system, and the one developed at the Italian National Research Council, the BOOM system, were described in details along with their applications to two pollution events, the *Haven* accident that occurred in 1991 in the Ligurian Sea and the Porto Torres spill event in 2011 in the Strait of Bonifacio. With this chapter, the authors want also to provide an overview on the capability of the Western Mediterranean countries to respond in case of oil pollution events by adopting oil spill trajectory forecasting systems.

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**Keywords** MOTHY, Numerical models, Oil spill, SHYFEM, Western Mediterranean

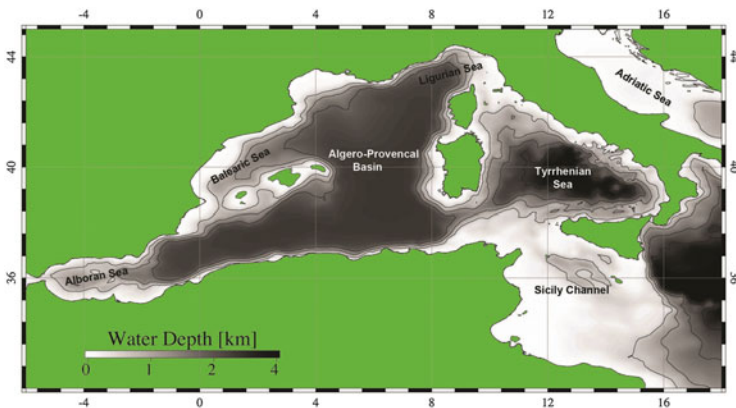
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## 1 Introduction

The Mediterranean Sea can be divided into two main regions: the Western Mediterranean (WM) and the Eastern Mediterranean (EM) separated by the Sicilian Channel generally identified as the Central Mediterranean (CM) (see Fig. 1). The Western Mediterranean region can be subdivided in turn into different basins: the Tyrrhenian Sea, the Ligurian Sea, the Algero-Provencal Basin, the Balearic Sea, and the Alboran Sea. The number of subdivisions is not univocal depending on the selected spatial scale and on the national context.

The WM is characterized by maximum water depths up to 3,700 m and is directly connected to the Atlantic Ocean through the Strait of Gibraltar (GS). The surface thermohaline circulation is anticlockwise with the Atlantic Waters (AW) entering through the GS, generating the Western Alboran Gyre and the



**Fig. 1** Geometry, bathymetry, and subdivision of the Western Mediterranean Sea

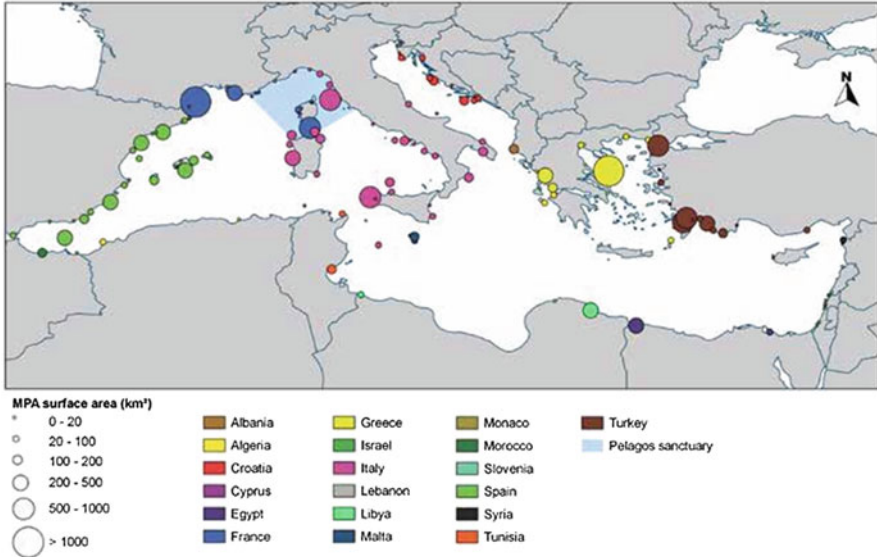
Eastern Alboran Gyre in the Alboran Sea and the Algerian Current along the African coastline. The AW entering the WM give rise to the Modified Atlantic Waters (MAW) which flow partially into the eastern regions through the Sicilian Channel and partially into the Tyrrhenian Sea generating a coastally trapped current moving northward. The northward flow converges to the Ligurian Sea to generate the Ligurian-Provencal or Northern Current which carries the MAW along the northern WM up to the Balearic Sea [1]. The inner parts of the WM subbasins are characterized by periodic and temporary mesoscale features generated by the baroclinic instabilities of the main thermohaline coastal flows. The WM is characterized by weak tides, around few cm [2], and by the seasonal occurrence of intense atmospheric phenomena generated by the periodical passage of cyclonic structure which lead to the formation of the three main wind regimes in the area: the mistral from northwest, the libeccio from southwest, and the sirocco from southeast [3].

The WM subregions are characterized by the highest species diversities among the other basins [4]. Contemporary, these regions are the areas with most frequent overlapping between high biodiversity and high threats. In 2008, the Marine Protected Areas (MPA) with national or international designation in the Western and Central Mediterranean Sea were 40, accounting for 42.6% of the total number of MPA in the whole basin, which were 92, and covering a total surface of about 100,000 km<sup>2</sup> with 160 km<sup>2</sup> of them characterized by special restriction rules (e.g., no-take zones) [5]. In 2012, the total number of MPA increased to 170, with 87 located in the western regions and most of them in the Algero-Provencal Basin and in the Balearic Sea (see Fig. 2 [6]). Despite the many efforts for a regional scale conservation planning, the Mediterranean MPA cover only 4.24% of the total basin surface which increase to the 5.26% if including both the Natura 2000 sites and the regulated fishing zones [6].

The risk of oil pollution in the Mediterranean Sea is very high due to the number of oil extraction and refinement sites along the basin coasts [7]. In the Mediterranean region the major importers are Spain (net oil import 1.5 million bbl/d in 2003), Italy (net oil import 1.71 million bbl/d in 2003), and Greece (net oil import 400,838 bbl/d in 2002) [8]. According to the Regional Marine Pollution Emergency Response Centre for the Mediterranean Sea (REMPEC), the Mediterranean Sea is Europe's main oil routes with about 350 million tons of oil and refined products annually transported, which cover about the 20% of the total world traffic [9].

Maritime activities in the western subbasins are intense if compared with the other subbasins. The highest vessel densities are found on the routes connecting the Strait of Gibraltar to the eastern regions and on the routes connecting the northern African ports to the European ports [4]. Along the coasts of the western subbasins, more than 17 major oil ports and 15 refineries are found especially along the Italian and Spanish coasts [10]. As an example, only for Italian ports facing the western subbasins, the total quantity of crude oil handled during the 2007 was estimated to be around 80 million tons [10].

While accidental pollution rarely occurs within the Mediterranean waters with three major accidents (large spills > 700 tons) that occurred from 1967: the *Haven* case in the Ligurian Sea in 1991, the *Irenes Serenade* case in the Aegean Sea in



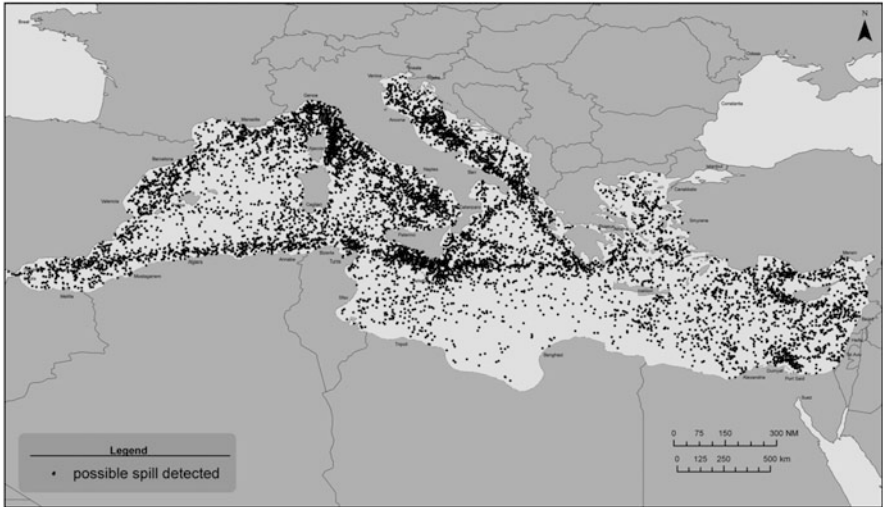
**Fig. 2** Distribution of MPA in the Mediterranean Sea in 2012 (Figure extracted from Gabrié et al. [6])

1980, and the Lebanon spill in 2006 [11], operational pollution is a common practice, representing the main source of marine pollution from ships. Illicit sources due to ship routine operations, as degassing, deballasting, and other actions involving the voluntary discharge of oil residues, in violation of MARPOL 73/78 Annex I, have been estimated to cause as much as eight times the yearly amount of oil pollution as accidental spills [12].

The oil spilled into the WM waters during the decade 2000–2009 has been estimated to be around 4,200 tons. Considering the other regions, the Eastern Mediterranean accounts for two-thirds of the total quantity spilled during this decade, with about 20,000 tons. Nevertheless If the Lebanese spill of 2006 is taken out of this calculation, the Western Mediterranean, the Central Mediterranean (the Sicilian Channel), and the Eastern Mediterranean spilled roughly the same quantities (between 4,000 and 6,000 tons), while less than 100 tons was spilled in the Adriatic Sea, according to REMPEC.

From satellite Synthetic Aperture Radar (SAR) images collected during the period 1999–2004, the high densities of oil spill in the western regions were found in the Ligurian Sea and the northern Tyrrhenian Sea and along the main traffic routes off the African coastlines. A total of 9,299 possible oil spills were detected which interested a rough area of about 15,533 square degrees and with peaks in summer due to the intensification of maritime activities (see Fig. 3 [13]).

The satellite monitoring by SAR is, potentially, an effective tool to discourage the illegal practice of oil discharge [14]. Nevertheless, in Mediterranean regions, due to the high density of maritime traffic, its efficiency is not ensured



**Fig. 3** Possible oil spills detected in the Mediterranean Sea during the period 1999–2004 (Figure extracted from Ferraro et al. [13])

[15]. Therefore, along with these surveillance systems, specific tools supporting the management of the pollution events once individuated are needed. In fact, as worldwide recommended, response plan must include, besides the continuously monitoring of the sea surface, specific systems based on operational ocean, and meteorological models to routinely provide information on surface ocean dynamics [16]. These operational tools, capable of predicting ocean and weather conditions as well as oil spill trajectories, allow decision-makers to promptly respond to environmental crises.

These systems are generally constituted by three different numerical components: an ocean and wave model (OM), an atmospheric model (AM), and a particle trajectory and oil weathering module (OSM). The three components are generally uncoupled, with OM and AM implemented for specific regions and daily providing the input data to the OSM which is constituted by a Particle Tracking Module (PTM) and a Oil Weathering Module (OWM) needed to simulate the advection and diffusion of the spilled oil as well as its biochemical transformation. The input data provided by the OM and AM to the OSM include surface currents, sea surface temperatures, main wave parameters, wind speeds and direction, and air temperatures. These operational systems guarantee a forecasting time lag varying between 3 and 5 days with a spatial coverage spanning from basin scale, whole Mediterranean Sea, to local scale, less than 1 km and often are equipped with a graphical user interface (GUI) to facilitate the usage for non-expert users.

This chapter is organized as follows: A list of the main oil pollution events that occurred in the WM is detailed in Sect. 2; an overview of the major research program focused on oil spill modeling in the WM and a review of the main numerical applications carried out within the last decades are reported in Sect. 2;

in Sects. 3 and 4 the description of two different prediction systems developed for the WM regions, the MOTHY [17] and the BOOM [18, 19], respectively, and their applications to real events are reported. Finally the concluding remarks are included in Sect. 5.

## 2 Main Oil Pollution Incidents in the Western Mediterranean Sea

During the last years, several oil spill events generated by maritime accidents occurred in the Western Mediterranean waters. A detailed description of the main pollution events that occurred during the last 50 years is reported in the following:

- On January 11 1978, the *Pavlos V* was traveling from Wilhelmshaven (Germany) to Milazzo (Italy) when a fire broke out in the machine room and spread throughout the entire vessel. The severely damaged tanker finally sank off the port of Trapani (Sicily). About 1.5 tons of fuel oil were spilled into the sea.
- The Cypriot tanker *Haven*, a 313 m long oil tanker, caught fire and suffered a series of explosions on April 11 1991 while at anchor seven miles off the coast of Genoa (Italy). The vessel was carrying approximately 144,000 tons of crude oil, and it is estimated that over 50,000 tons of fresh and partially burnt oil were spilled into the Ligurian Sea. Despite considerable pollution response operations at sea, oil slicks drifted westward, thus hitting various parts of the Ligurian coast and then reaching the French Riviera as far as Hyeres. This caused the worst oil pollution incident ever in the Mediterranean Sea.
- On October 21 1991, on its way from Ashdod (Israel) to Rouen (France), the bulk carrier *Erato* encountered very bad weather conditions and ran into difficulty. It sank off Algeria with a cargo of 25,894 tons of phosphate. During this accident, 500 tons of bunker fuel was discharged at sea.
- On January 20 1996, the cargo vessel *Kaptan Manolis I* suffered a leak while sailing off Cap Bon (Tunisia). The ship sank with its cargo of 5,000 tons of phosphates and 104 tons of bunker oil.
- On May 6 1999, during a loading operation onto the oil tanker *Enalios Thetis*, 55,650 liters of crude oil were spilt into the sea at Sarroch oil terminal (south of Sardinia, Italy). About 13 km of the shoreline were polluted due to the oil spill.
- On September 8 2000, the bulk carrier *Eurobulker IV* ploughed into rocks while attempting to enter the port of Portovesme (Sardinia, Italy). The vessel was carrying 17,000 tons of coal, 35 tons of diesel oil, and 170 tons of bunker fuel. The hull was considerably damaged by the rocks and 60 tons of bunker fuel leaked out. In spite of difficult conditions at sea, booms were deployed to protect the coastal zone. Several response vessels were also sent on-site.
- On August 12 2007, a collision occurred near the coast of Gibraltar between a double-hulled oil tanker and the bulk carrier *New Flame* which resulted in the sinking of the latter. As the accident happened in relatively shallow water, the

vessel subsequently settled on the bottom with bow submerged at a depth of 30 m and part of its decks above water. In the weeks following the collision, 780 m<sup>3</sup> of fuel were successfully removed from the vessel. No oil slick was detected on the sea surface during the operation.

- On January 10 2011 during the operation of oil transfer from a ship tanker at the offshore pipe station in front of the harbor of Porto Torres in the Strait of Bonifacio (Sardinia, Italy), about 50 m<sup>3</sup> of heavy crude oil were released into the sea. The oil drifted eastward beaching along a wide trait of the coast.

### **3 Oil Spill Modeling in the Western Mediterranean Sea: A Review**

In recent years, several initiatives funded by both National and EU Research Programs were carried out to improve the effectiveness of decision-making processes in case of oil spill pollution in the Mediterranean Sea.

Two main projects were funded by the EU Commission throughout the MED Program: the TOSCA project, acronym for “Tracking Oil Spills and Coastal Awareness network” (<http://www.tosca-med.eu/>), and the MEDESS-4MS project, acronym for “Mediterranean Decision Support System for Marine Safety” (<http://www.medess4ms.eu/>). TOSCA and MEDESS-4MS were complementary to each other, with the first one mainly emphasizing the observational component, constituted by coastal high-frequency radars and on Lagrangian drifters, and the latter focused on the development and application of operational systems based on numerical modeling for predicting the fate of spilled oil. Both projects included partners from both western and eastern side of the Mediterranean with the ambition of supporting, with observational networks and operational forecasting systems, the management of oil spill pollution for the whole basin.

Similar programs were also funded by the National Research Programs of the main Mediterranean countries with the scope of improving the management of oil pollution in specific areas of the Mediterranean Sea (e.g., national waters, Mediterranean subbasins, or specific coastal areas).

As a result of all these initiatives, many European institutions, local agencies, and research centers currently host operational systems that provide short-term predictions of oil spill fate and dispersion as a support for managing oil pollution emergencies in the Western Mediterranean waters. All these operational systems have been developed within the last 15 years and constitute the final results, and the applicative aspects of decades of research activities carried out to develop specific numerical tools suitable for the Mediterranean environment.

Between 2001 and 2016 more than 40 different numerical tools and applications were reported and described in the scientific literature. The relative distribution of the oil spill modeling applications among the three main Mediterranean regions is analyzed. In terms of number of published papers, most of the efforts were focused



on the numerical applications at basin scale or on study cases located in the eastern [20–31] and western subbasins [16, 18, 19, 32–45]. Only few and more recent applications involved case studies located in the central areas of the Mediterranean Basin, e.g., Sicilian Channel [15, 46, 47], and in the Adriatic Sea [48, 49].

At first sight, the discrepancies in the abundances of the numerical applications in the different areas could be related to the differences between the quantities of spilled oil in the considered regions. This could justify the higher number of applications for the WM and EM and the lower number for the Adriatic Sea. An exception is the Sicilian Channel, which, as reported by REMPEC [9], suffered similar amount of spilled oil of the WM and EM areas but with a lower number of reported numerical investigations.

An alternative explanation could be found considering the perception of the risk of oil pollution due to the past events. For both the WM and EM, in the last decades there have been disastrous accidents with important oil discharge events, as reported in previous section. This probably generated a higher sensibility to this type of risk for these areas. A confirmation of this assumption is the timing of the first applications, which for the WM and EM regions occurred after the major accidents.

The role of the risk perception in promoting the implementation of prevention tools is evident also for the Sicilian Channel and Adriatic Sea regions. For such areas, even if no major accidents occurred during the last decades, the perception of the risk from oil pollutions increased in the last years after the *Deepwater Horizon* disaster that occurred in 2010 in the Gulf of Mexico. This is particularly true for the Sicilian Channel where oil and gas drilling activities are frequent and the numerical applications have been carried out only in the last years and mainly focused on oil spill events from oil platforms.

In the Western Mediterranean region, during the last years, as reported from the literature, the applications of oil spill models and the implementation of operational forecasting systems have been homogeneous in time. In Table 1, a synthesis of the main applications carried out between 2001 and 2016 is reported. Along with the references, each system is described in terms of spatial scale and resolution of the adopted OM, type of OSM detailing if computing or not both the oil trajectories with a PTM, and the oil degradation processes by means of an OWM. Finally the presence of GUI allowing a non-expert user to interact with the system is evidenced.

Most of the applications were at subbasin scale with a focus on specific areas of the WM. The adopted OM, based on 3D hydrodynamic numerical models, were applied with a resolution ranging between 15 km and 1 km. Nesting procedures were used to provide open boundary conditions from already existing oceanographic forecasting systems based on state-of-the-art ocean and wave model applied to the whole Mediterranean (e.g., MFS, [50], Mercator Ocean [51]). Typical examples of applications (see [27, 32, 34, 42–45]) use a set of different OM and nesting procedures to simulate the current fields in selected areas of the WM with a spatial resolution up to 1 km.



**Table 1** Oil spill modeling in the Western Mediterranean Sea, numerical features

NUM. APP. from literature	SYS. acronym	OM spatial scale	OM spatial res.	OSM type	GUI
Daniel et al. [32, 34]	MOTHY	Subbasin, WM CM EM	9–0.5 km	PTM + OWM	Yes
Jordi et al. [16]	–	Local area, Southern WM	15–0.01 km	PTM + OWM	Yes
Periáñez [33, 35, 36, 38, 39]	GISPART	Subbasin, Alboran Sea	3–1 km	PTM + OWM	Yes
Jorda et al. [37]	CAMCAT	Subbasin, South- ern WM	1.5 km	PTM + OWM	Yes
Mestres et al. [40]	–	Local area, Southern WM	0.04 km	PTM	–
Cucco et al. [18, 19] and Olita et al. [41]	BOOM	Local area, Cen- tral WM	5–0.05 km	PTM + OWM	Yes
De Dominicis et al. [42]	MEDSLIK	Subbasin, North- ern WM	6.5–2.2 km	PTM + OWM	Yes
Janeiro et al. [43]	–	Subbasin, Tyrrhenian Sea	1.5 km	PTM + OWM	–
Sayol et al. [44]	–	Subbasin, South- ern WM	1.8 km	PTM + OWM	–
De Dominicis et al. [52]	MEDSLIK	Subbasin, Tyrrhenian Sea	10–1.2 km	PTM + OWM	Yes

In these cases the adopted OSM included both the PTM and the WM and were generally constituted by stand-alone numerical tools such as MEDSLIK-II [52], MOTHY [17], and GNOME [53]. Most of these applications were carried out to reproduce hypothetical scenarios of oil pollution or to reproduce the paths followed by released drifters in specific areas. Numerical experiments were carried out in the Tuscany Archipelagos in the Tyrrhenian Sea [43, 44], in the Gulf of Lion, in the Ligurian Sea [32, 34, 45], and in the Balearic Sea [37, 44].

Similar in terms of spatial scale and resolution but different for the simplification of the adopted OM are the set of applications carried out by [36, 38, 39] to simulate hypothetical oil pollution scenarios in the Strait of Gibraltar and the Alboran Sea.

In some specific applications, the OM were implemented and applied to local areas with spatial resolution of the order of 0.01 km with the aim of reproducing the wave and current field as an input to specific OSM tool. An example is the system developed and applied by [16] which used a hierarchy of OM and nesting procedures to reproduce hypothetical oil spill in the Bay of Palma. Other examples are the applications carried by [18, 19, 41] in the Strait of Bonifacio between Corsica (France) and Sardinia (Italy), which implemented a high-resolution OM and specific nesting procedures to simulate both synthetic pollution scenarios and real oil spill events that occurred in the area.

Finally, the application of [40] reproduced hypothetical oil spill scenarios in the Tarragona harbor in the Balearic Sea, by means of high-resolution hydrodynamic

model coupled with particle tracking module and forced by synthetic open boundary conditions.

In the following section a detailed description of two different oil spill modeling applications and operational systems are reported: the MOTHY oil spill model and its application to the *Haven* accident that occurred in 1991 in the Ligurian Sea and the Bonifacio Oil Spill Model (BOOM) and its application to the Porto Torres discharge event that occurred in 2010 in the Strait of Bonifacio.

## 4 The MOTHY Operational System

MOTHY is a drift model implemented by Météo-France [17]. The system is operated since 1994 on demands of the French authorities for support of the oil spill fighting operations and on demands of the Maritime Rescue Co-ordination Centres for support of the search and rescue operations.

A meteorologist on duty in the marine forecast section at Météo-France is able to run the model around the clock. About 800 interventions each year are conducted with an averaged time response of 30 min. The system can be used worldwide. About a quarter of the requests concern the Mediterranean Sea.

MOTHY has been extensively used for the Erika and the Prestige incidents in the Atlantic Ocean. In the Mediterranean Sea, two major incidents (*Haven*, 1991, and *Lyria*, 1993; see Sect. 2) were revisited [31, 33]. No major accidents in French waters have taken place since the system is in place. About 50 oil drifts are performed each year in this area for small-scale pollution.

MOTHY oil spill model is one of the three versions of the drift system (the two others are for containers and search and rescue targets). Currently the mixed layer is computed using a combination of a shallow water model driven by the wind and the atmospheric pressure, coupled with an analytical turbulent viscosity model, so as to represent vertical current shear, and a background current provided by an oceanic model (MERCATOR or MFS). A continuous profile from surface to bottom describes the water column.

An extensive drifter experiment took place in 2007 in the Western Mediterranean Sea to assess the accuracy of drift models [54, 55]. The evaluation lasted for 2 months and included several drift, atmospheric, and ocean models. The main conclusions were that models perform relatively well along the coast, while the performance decreases in the open ocean, such as the Balearic Sea and in the open Mediterranean, where a number of mesoscale or sub-mesoscale eddies are not properly located in ocean models.

MOTHY system consists of four modules: a setup module to specify the model domain and parameters the atmospheric and oceanic forcings, and the pollutant description; a run module that performs the simulation; a visual interface for viewing the outputs; and a broadcast interface to send the results (several formats are available) to the end user (website, e-mail, fax).

#### **4.1 The Haven Accident Test Case**

The accident of the tanker *Haven* in April 1991 occurred 3 years before the MOTHY system was established. This accident was later used to verify the suitability of the MOTHY system to properly reproduce the drift of the oil slicks.

There is some uncertainty on the quantities of oil that drift on the sea surface. At the time of the accident, 144,000 tons of heavy Iranian crude oil and 1,223 tons of fuel oil and diesel were present on board. The total amount of hydrocarbons that burned during the 70 h following the first explosion was estimated at about 100,000 tons, while 3,000 tons were still trapped inside the wreck. The rest of the cargo was dispersed by the Liguro-Provencal Current and the winds mainly west-southwesterly. Once spilled at sea, the oil products were exposed to a series of physical and chemical processes that determined their fate at sea. Some of the spilled oil was collected directly from the sea surface, some was washed ashore, another part spread out from the intervention area, and the remaining part sunk.

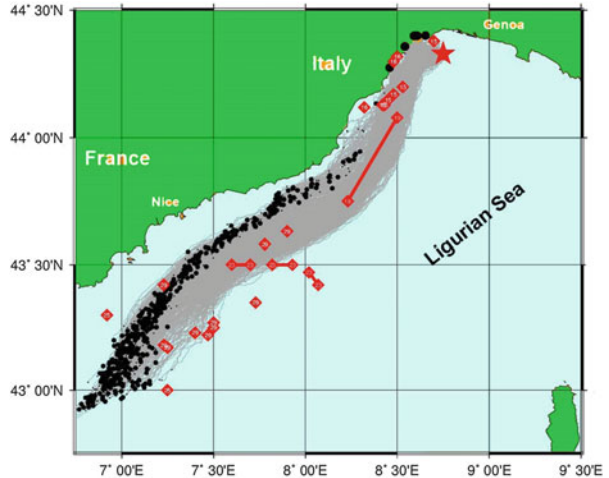
In an oil drift model, environment data (wind and currents) are critical to accurately forecast the drift of the oil. At the time of the *Haven* accident, wind forecasts from atmospheric model were available. At Meteo-France, the limited area grid-point weather prediction model PERIDOT provided forecasts on a 35 km grid mesh (today the AROME model provides forecast on a 1.3 km grid mesh). In 1991, the operational oceanography systems did not exist yet. The surface current data came from scattered observations or inaccurate climatology. At the beginning of the 2000s, the combination of progress in Earth observation by satellites and drift buoys on the one hand and assimilation of the resulting data for 3D numerical modeling on the other led to the birth of a new scientific discipline: operational oceanography.

These new sources of data provide a more accurate picture of the surface currents and enable to revisit the *Haven* accident with regard of the oil drift. The MOTHY system was then used to reproduce the drift of the oil slicks of the *Haven* accident, using these new data. The drift of the slicks within the Liguro-Provencal Current and the coastal pollution of the French Riviera are more precisely reproduced as depicted in Fig. 4.

### **5 The Bonifacio Oil Spill Operational Mode**

The Strait of Bonifacio is located between the islands of Sardinia and Corsica and separates two distinct Mediterranean subbasins, the Tyrrhenean Sea and the Sardinian Sea (see Fig. 5, upper panel). This area hosts two marine national parks, one Italian and one French, and is part of the International Sanctuary for the Protection of Marine Mammals. In contrast with this environmental relevance, maritime accidents have been occurring during the years with consequences on the marine life due to adverse impact of pollutants, such as hydrocarbons.

**Fig. 4** Oil slick trajectories computed by MOTHY for a 2-week forecast run using MERCATOR currents. *Red star* represents the Haven accident location, *red diamonds* the observations, *black dots* the final position of the slick forecasted by MOTHY, and *gray lines* the computed trajectories (Figure extracted from Daniel et al. [32])

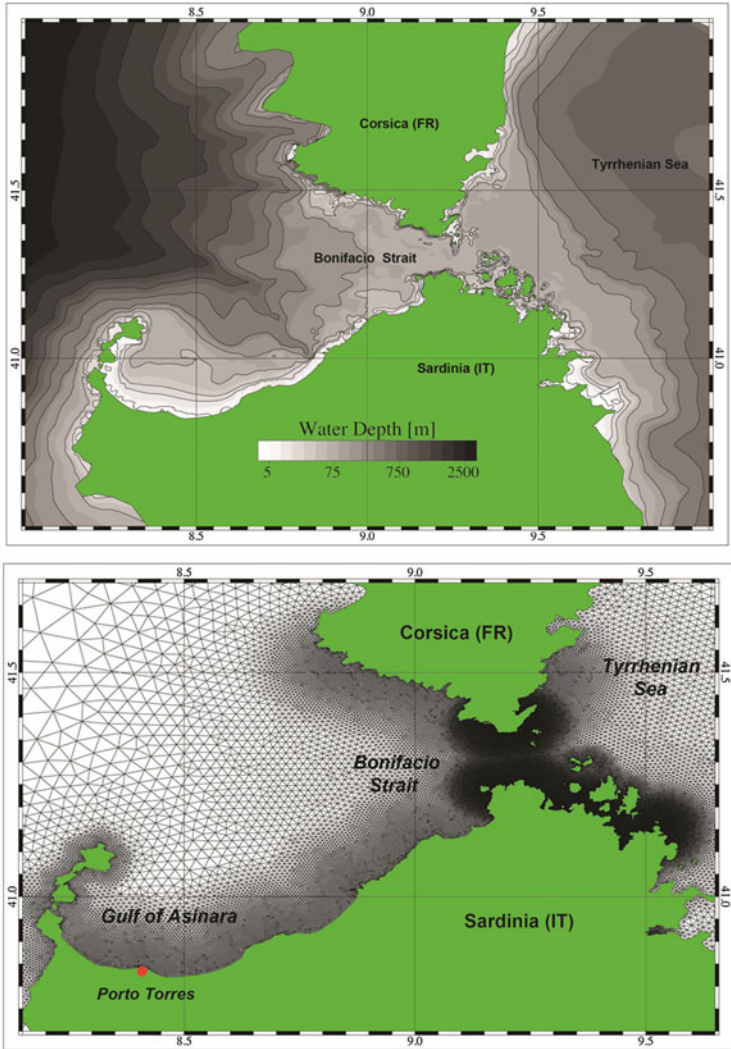


In order to facilitate the rapid planning and coordination of operations by the marine authorities to tackle pollution during oil spill emergencies in the Strait of Bonifacio, an operational forecasting system was developed under the framework of a project named “SOS – Bocche di Bonifacio” funded by the Italian Ministry for Environment.

The system, named BOOM, the acronym for Bonifacio Oil Spill Operational Model, is composed by a hierarchy of different numerical models and facilities to provide a prognostic tool for managing the oil spill emergencies in coastal waters.

The core of the BOOM is composed by a set of finite element numerical models, including a three-dimensional coupled hydrodynamic and wind wave model (SHYFEM, [56]), a PTM, and an OWM [18]. SHYFEM was adopted to reproduce the wind, tide, and thermohaline surface water circulation in the Strait of Bonifacio. The model domain was discretized by an unstructured mesh composed by 33,563 nodes and 64,292 triangular elements (see Fig. 5, lower panel) with a spatial resolution varying between a few km to 50 m. SHYFEM resolves the shallow water equations integrated over each layer in their formulations with water levels and transports.

The influence of the offshore water circulation was taken into account throughout a nesting procedure with a regional open ocean forecasting system, the WMED [57], which covers the Western Mediterranean area with a full three-dimensional implementation of the Princeton Ocean Model [58]. Surface boundary conditions were provided by the high-resolution meteorological forecasting system SKIRON [59]. The simulation of the oil trajectories and oil mass degradation was carried out using the PTM and an OWM coupled off-line with the hydrodynamic model. The system was validated through the comparison with experimental data consisting of surface current and transport data collected during several oceanographic campaigns carried out in the Strait area.



**Fig. 5** Geometry and bathymetry of the Strait of Bonifacio area (*upper panel*) and zoom of the unstructured mesh used as BOOM numerical domain (*lower panel*)

BOOM is fully operational since the end of 2010 and provides daily and operational a 3-day forecast of surface water circulation and wave fields for the Strait of Bonifacio and Gulf of Asinara. A GUI allows a non-expert user to interact with the system by setting up scenarios, running simulations, and analyzing the produced consequences of an oil spill within a time lag of 72 h both in the past (backward simulations) and in the future (forward simulations) [60]. Besides the operational usage, the system has been also adopted to evaluate the risk induced by a hypothetical impact of hydrocarbons in the coastal areas of the Strait [41] and to

provide a set of scenario analysis as a support to the pollution emergency operations plan of the coast guard [19].

### ***5.1 The Porto Torres Oil Spill Test Case***

The BOOM has been used operationally in early January 2011 during the accidental pollution event that occurred in the harbor of Porto Torres in the western side of the Strait of Bonifacio (see Sect. 2).

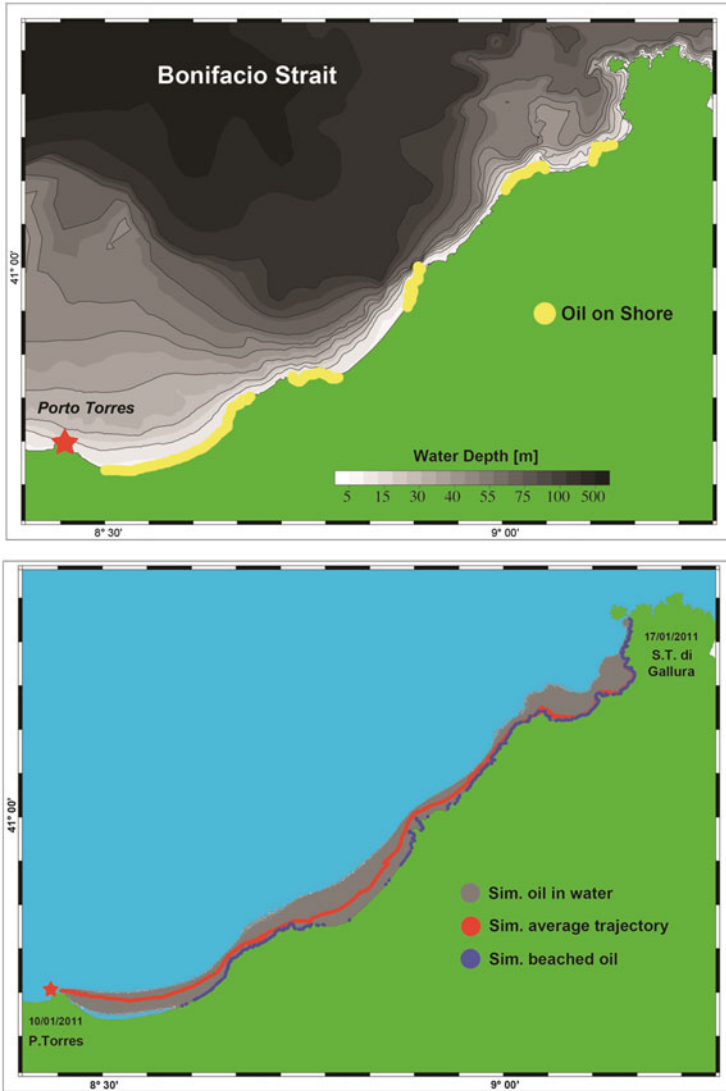
During the operation of oil transfer from a ship tanker at the offshore pipe station in front of Porto Torres, about 50 m<sup>3</sup> of heavy crude oil were released into the sea. The oil spilled out for about 18 h starting from January 10 2011 at 10:18 p.m. The slick drifted eastward for 5 days interesting the coast for more than 20 km from the accident location. On January 17, 7 days after the accident, an oil slick was individuated in the coastal waters at the entrance of the Strait of Bonifacio (see Fig. 6, upper panel).

The local authority run the BOOM system in backward mode to verify the connection between the oil slick and the Porto Torres accident in order to exclude any other sources of spills in the area (e.g., tanks cleaning bilge waters). The simulation results revealed that the source of the oil slick was the accident site. Samples of floating oil were then collected and analyzed certifying its origin from the Porto Torres event confirming therefore the BOOM results.

Subsequently, a set of hindcast simulations were carried out to verify the system capability in reproducing the fate of the oil spill in forward mode. A 10-day simulation run was performed using atmospheric field and open boundary data produced by SKIRON and by WMED. The model reproduced with accuracy the most probable trajectories followed by the spilled oil during the whole period. This was confirmed by the predicted position of the oil particles beached on the coast, which mainly corresponded to the areas impacted by the pollutants during the event (Fig. 6, lower panel). Furthermore, the system simulated the presence of oil particles on water at the entrance of the Strait after 7 days from the released time at accident location, in agreement with both the experimental evidence and with the results obtained from the operational backward run (Fig. 6, lower panel).

## **6 Concluding Remarks**

Eight countries facing at the Western Mediterranean Sea characterized by different political, social, and economic condition: Spain, Gibraltar (UK), France, Monaco, Italy, Tunisia, Algeria, and Morocco. All are parties to the Barcelona Convention and most of them are EU nations; nevertheless, the cooperation and the coordination actions necessary to prevent and to manage oil pollution emergencies at regional scale need to be improved. Following the example of the RAMOGEPOL



**Fig. 6** Map of the area interested by the accident of Porto Torres that occurred in January 2011 (*upper panel*) and the hindcast simulation results (*lower panel*). *Upper panel*: red star indicates the accident location; in yellow, the coastal areas hit by the oil spill after the release. *Lower panel*: red lines indicate the average trajectory followed by the simulated particles; gray points indicate the position of particles during the whole simulated period; in blue, the coastal areas hit by the oil spill after the release as predicted by the model results (Data extracted from Cucco et al. [19])



Plan between Italy, France, and Monaco, promoted by REMPEC [9], which organize yearly anti-pollution exercises including oil drift forecast, further active bi- or trilateral cooperation agreements among borderers of WM countries should be promoted in the WM region to guarantee an effective response action in case of transnational pollution events.

While operational oceanography and numerical modeling techniques are widely considered as essential tools to face at oil pollution emergencies at sea, their usage is not homogeneously widespread among the WM countries. Most of the numerical applications that have been analyzed in this chapter were carried out and implemented by Research Institutions and Agencies within EU countries and often with a focus on their national waters. As a consequence, from the literature, most of the coastal sea areas of the southern WM, facing at sea traits with a high density of maritime traffic, have not been specifically considered as study site for numerical modeling applications. Of course, many of the oceanographic and oil spill operational systems currently active at Mediterranean basin and subbasin scales (e.g., MOTHY and MEDSLIK) are capable to provide a support in case oil spill events occurring in such areas. Nevertheless, the lack of specific applications and the consequent absence of direct experiences on the forecasting assessments for the local ocean dynamics can be an obstacle to the improvement of the pollution response capability for such areas.

A further effort should be made to both assess cooperation statements between WM borderer countries in order to successfully respond in case of oil spill pollution events at subregional scale and to improve the already existing state-of-the-art operational systems based on off-line oil spill models (e.g., MOTHY and MEDSLIK) by coupling them with forecasting systems able to provide reliable predictions of the main atmospheric and ocean dynamics at different spatial scales (e.g., ocean model based on unstructured mesh as SHYFEM) in order to properly respond in case of pollution events involving both the open sea and the coastal waters.

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