MODELING THE HIGH-IMPACT LOW-PROBABILITY OIL SPILLS IN THE MEDITERRANEAN

Svitlana Liubartseva, Giovanni Coppini, Pierre Daniel, Megi Hoxhaj

Abstract: Despite considerable efforts to improve scientific understanding and risk management, governments and businesses remain insufficiently prepared to confront large oil spills considered to be the so called 'high-impact low-probability' disasters.

To alleviate this problem, we focus on the historical *HAVEN* oil spill (off the Port of Genoa, 1991) recognized not only as the largest shipwreck in the European waters, but also as one of the worst oil pollution cases in the Med.

We reconstruct this spill with the Lagrangian oil spill model MEDSLIK-II forced by the to-date high resolution meteo-oceanographic datasets.

Moreover, we run the *HAVEN* oil spill scenario stochastically sampling virtual spills randomly in space and time. The results are presented as the pollution hazard indices in probabilistic terms, which is supposed to be a representative indicator of future accidents. The highest indices are found in the Alboran Sea, Algerian and Liguro-Provençal subbasins, and in the center of the Ionian Sea. Conversely, the southern part of the Ionian, the areas east of Sardinia and west of Corsica, the Gulf of Lion, the northern Adriatic, and north-eastern Aegean Sea do not reveal high hazards.

Keywords: oil spill modeling, hazard mapping, Copernicus Marine Service

Svitlana Liubartseva, Global Coastal Ocean Division, Italy, svitlana.liubartseva@cmcc.it, 0000-0002-0219-7543
Giovanni Coppini, Global Coastal Ocean Division, Italy, giovanni.coppini@cmcc.it, 0000-0003-3664-3983
Pierre Daniel, Département Prévision Marine et Océanographique, France, pierre.daniel@meteo.fr, 0000-0002-1111-034X
Megi Hoxhaj, Global Coastal Ocean Division, Italy, megi.hoxhaj@cmcc.it, 0009-0001-5640-5539

Referee List (DOI 10.36253/fup_referee_list)
FUP Best Practice in Scholarly Publishing (DOI 10.36253/fup_best_practice)

Svitlana Liubartseva, Giovanni Coppini, Pierre Daniel, Megi Hoxhaj, *Modeling the high-impact-low-probability oil spills in the Mediterranean*, pp. 911-922, DOI: 10.36253/979-12-215-0556-6.79

Introduction

Large oil spills can be considered the High Impact Low Probability (HILP) events that confront scientists and decision-makers with new challenges. In both environmental and economic terms, the costs of these spills are considerable. Marine biota can be seriously affected due to direct toxic effects and physical smothering. Loss of natural habitat or shelter might lead to elimination of vulnerable species. Fishery and mariculture resources can be severely damaged due to toxic effects on stock and disruption of business activities. In addition to the costs incurred in cleaning up oil spills, serious financial losses are experienced by economic sectors that rely on clean seawater and clean coastal areas: tourism, salt production, sea water desalination, and power plants.

Occurrence of large oil spills is fundamentally a matter of probability. The DeepWater Horizon (DWH) oil spill (the Gulf of Mexico, 2010) is a canonical example of such a 'high-impact low-probability' catastrophe. The extent of exposure has been extensively studied, and many researches confirmed its disastrous impact (e.g., [1, 2]). Moreover, some oil residues buried in beaches are found to persist for years to decades [3].

Actually, a common feature of such the extreme oil spills is that they rarely occur, and few data are available to statistically describe them [4]. Nevertheless, the probability of catastrophic oil spills can be assessed by the Extreme Value Theory (EVT). Applying EVT to the US outer continental shelf areas, it was concluded that a spill as large as the DWH spill will take 165 years to return. Notably, a 95 % confidence interval has found to be quite wide ranging from 41 to over 500 years [5].

Dealing with the Mediterranean, we focus on the historical VLCC *HAVEN* oil spill (off the Port of Genoa, 1991), which was recognized not only as the largest shipwreck in the European waters, but also as one of the worst oil pollution cases in the Mediterranean.

In this work, we present a model-based reconstruction of this spill movement using the freely available hindcast of the marine hydrodynamics provided by the Copernicus Marine Service and the wind speed by the European Centre for Medium-Range Weather Forecasts (ECMWF). Model results are validated with the available observational data.

Since any reliable statistics on past oil spills is not available for the Mediterranean [6], we could hardly estimate the return period for the *HAVEN* oil spill. We can only hypothesize that the corresponding confidence interval will be approximately as wide as the DWH interval. However, we can compute a conditional probability, assuming that a large oil spill, such as the *HAVEN* spill, will occur at a certain location in the Mediterranean in the future.

To this end, we launch stochastic oil spill simulations [7 - 9] to map oil pollution hazards in probabilistic terms. For the various areas of the world ocean, such kind of simulations were run many times from point-type and distributed sources (find some overviews in [10, 11]), but for the first time, we initiate them from non-uniformly distributed sources across the entire Mediterranean.

To model oil drift and transformation, we use the Lagrangian oil spill model MEDSLIK-II [12]. Initial distribution of oil spill sources is currently associated with large uncertainties. Recent satellite-derived maps of chronic oiling [13] are employed to seed virtual spills in the stochastic mode.

In this work, preliminary oil pollution hazard maps are presented to identify the most/least impacted areas in the basin.

Hazard maps can be used to develop response and mitigation strategies as well as to support biodiversity conservation efforts, which is in line with the flagship NECCTON[1] project (New Copernicus Capability for Trophic Ocean Networks). In the project's framework, new operational tools and products are designing to strengthen the Copernicus Marine Service capability of modeling marine pollution.

Materials and Methods

The MEDSLIK-II[2] oil spill model [12] is a free-access community model that has been successfully used for more than 12 years to simulate the transport and fate of oil spills in both deterministic and stochastic modes. A full list of the published MEDSLIK-II applications can be found at the referred website. In the model framework, the oil slick is discretized into constituent particles. Each particle moves due to currents, wind, and waves, data on which are provided by external oceanographic and atmospheric models or observations. Subgrid processes that are not resolved in the meteo-oceanographic models are taken into account with the 'random walk' scheme. The oil transformation processes are calculated by means of the bulk formulae, which formalize the changes in the surface oil volume due to three main processes known collectively as weathering: viscous-gravity spreading, evaporation, and natural dispersion. The formation of water-in-oil emulsion is also taken into account. MEDSLIK-II simulates the interaction of oil with shoreline considering the probability that oil may be washed back into the water. At each time step, MEDSLIK-II computes the geographical coordinates of particles as well as oil concentrations at the sea surface, in the water column, and on the coast. The model allows the choice of oil types from the Regional Marine Pollution Emergency Response Centre for the Mediterranean Sea (REMPEC) database composed of 225 constituents.

To force oil drift and transformations MEDSLIK-II requires the input of data about atmospheric wind, sea surface temperature, and sea currents. For the reconstruction of the *HAVEN* oil spill, we use the 6-hour wind speed data provided by the ERA5 reanalysis of 0.25° latitude-longitude grid (∼25 km in the Mediterranean). While for the stochastic MEDSLIK-II simulations, we use the 6-hour datasets provided by ECMWF at a 0.125° horizontal resolution (∼12.5 km in the Mediterranean). In both cases, we employ the Copernicus Marine Service daily oceanographic reanalysis data[3] on currents and temperatures with a horizontal resolution of 1/24° (~4 km) [14].

[1]https://www.neccton.eu (Accessed online: April 2024).
[2]http://medslik-ii.org (Accessed online: January 2024).
[3]https://data.marine.copernicus.eu/product/MEDSEA_MULTIYEAR_PHY_006_004 (Accessed online: April 2024).

In accordance with historical records, on April 11th, 1991, while the Very Large Crude Carrier (VLCC) *HAVEN* was anchored in front of the Port of Genoa, two violent explosions started a fire within the ship that was extinguished only 70 – 99 hours later when *HAVEN* sunk. At the moment of the disaster, which killed six crew members, 144 000 tons of heavy Iranian crude oil and 1 223 tons of fuel oil and diesel were on board. The vessel broke into three sections with one section sinking close to the anchor location. A large quantity of burnt oil rapidly sank in form of bitumen, while the rest of the cargo was transported by currents and waves in the densely populated coastal region of the Liguro-Provençal basin.

During the emergency phase, two important decisions were taken: to tug the remaining main ship section coastward and to allow the burning of the greatest part of the oil spilled at sea.

An environmental assessment of the affected region indicated the injury from the spilled oil to subtidal *Posidonia*/*Cymodocea* (seagrass) beds, the deep-sea benthic community and associated commercial fisheries [15]. Although recovery typically takes place within one to three years [16], a restoration program was on the way 12 years later mainly dealing with the tar residuals laying on the seabed and with the oil products still contained in the wreck.

We specify the *HAVEN* oil spill scenario based on [15, 17–19] as follows:

- starting time of the spill is 11th April 1991 12:30 pm;
- initial spill coordinate is 44°20'N, 08°45'E;
- the continuous 50-hour release with a spill rate of 200 ton/hour gives the total spilled oil volume of 10 000 tons;
- the type of the oil is heavy Iranian crude oil (API = 31);
- the simulation length is chosen to be 432 hours (18 days) until 29th April, when the last spill observations arrived;
- the Stokes drift is taken into consideration by means of the empirical JONSWAP wave spectrum as a function of wind speed and fetch.

The 26 field detections 11 April – 29 April 1991 composed of the point- and segment slicks provided courtesy by Météo-France are used for the model restarts (Fig. 1).

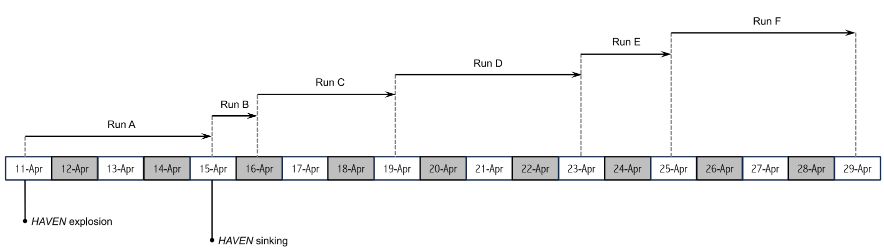

Figure 1 – Timeline of the observations (dotted vertical lines) and the MEDSLIK-II restarts (horizontal arrows Run A ÷ Run F).

If the exact times of observation are not available, we use the best-in-time hours to calculate the performance metrics.

For the stochastic simulations, we use almost the same scenario applying randomization to starting time and locations. The simulation length is chosen to be 600 hours (25 days) assuming that such a long-lasted tracking is enough for the oil to reach the coastlines or to be removed from the surface by weathering.

To account for the slow weathering processes as biodegradation, photooxidation, etc., we have modified the MEDSLIK-II code adding a simplified first-order oil decay term with a constant rate of 0.04 day^{-1} [20].

To reduce computation time in stochastic mode we apply a 1 % windage coefficient instead of the JONSWAP-based Stokes drift; and we decrease a default number of Lagrangian particles of 100 000 to 40 000.

In contrast to temporal randomization, which type does not have a critical impact on the final hazard maps, spatial randomization of virtual spill sources is crucial. Considering our previous experience, we expected hazard indices to correspond to the distributions of the oil spill sources with some spatial distortion controlled by the meteo-oceanographic conditions in the basin.

At the pre-processing stage, an original seeding algorithm (Fig. 2a–d) has been developed starting with a cumulative spatial distribution of oil slicks (Fig. 2a) detected by the Sentinel- 1A/1B synthetic-aperture radars [13].

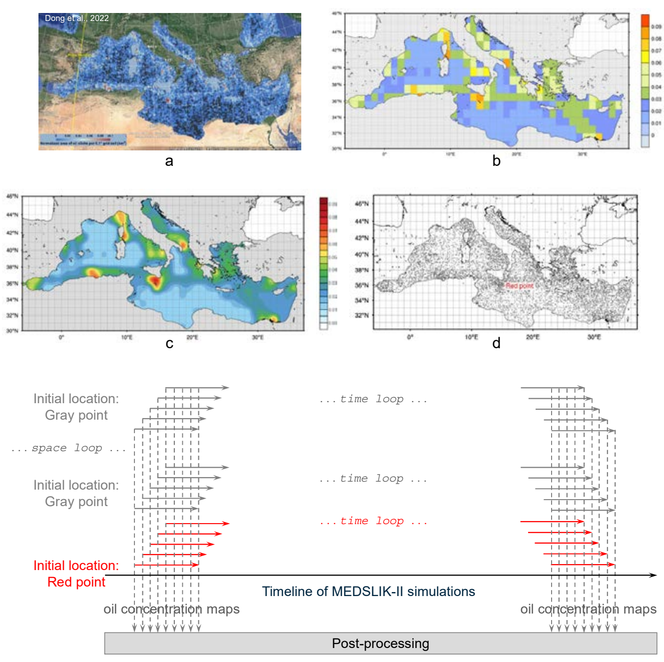

Figure 2 – Workflow elements for the MEDSLIK-II stochastic simulations: seeding algorithm (a–d) and two primary loops: over the time 2018–2021 and in space covering all the initial locations generated in (d).

The map (Fig. 2a) is digitized manually into a 1° resolution map (Fig. 2b) followed by re-gridding to a 1/24° resolution by optimal interpolation (Fig. 2c). This map is used for stratified sampling the initial spill locations (Fig. 2d). Running MEDSLIK-II in batch mode, we perform two basic loops: through the time 2018–2021; and in space, covering all the initial spill locations depicted in Fig. 2d as an example (Fig. 2e).

Among others, our approach has inherited a critical limitation from the radar-derived detection methodology, which states that the optimal wind speeds for oil slick detection range from ~1.5 to 10 m s^{-1}.

We assume that the resulting bias is not very big since the NCEP wind speed statistics in the Med shows that the mean ± STD occurrence frequencies of the low wind speeds (< 1.5 m s^{-1}) are 0.09 ± 0.09 and of the high wind speeds (> 10 m s^{-1}) are 0.08 ± 0.07 [13].

Ironically, the major oil spills in the Mediterranean, such as the *HAVEN* and *ULYSSE*/*VIRGINIA* (the NW Mediterranean, 2018) incidents, *JIYYEH* Power Plant (Lebanon, 2006) and *BANIYAS* (Syria, 2021) Power Plant oil spills started exactly under the low-wind conditions, in contrast to the Atlantic oil spills. So that, the early stages of those spill developments could be hardly visible to radars.

The simulation results are represented by a sample composed of a huge number of virtual spills constituted of the hourly oil concentration fields. In accordance with [8], we impose on them a threshold of 0.1 ton km^{-2} to separate the hazardous sea surface oil concentrations from the non-hazardous ones. Then, to obtain hazard indices in probabilistic terms we normalize the resulting distribution to the total number of virtual spills. Hazard indices clearly range between 0 and 1, where 1 indicates maximum hazard and 0 no hazard.

Results and Discussion: reconstruction of the *HAVEN* oil spill

A common assumption is that computed oil pathways tend to accumulate errors over longer distances and time due to intrinsic model simplifications. Restarting MEDSLIK-II with updated observational patterns, we believe that the effects of hindcast error growth could be implicitly accounted for and minimized.

Generally, the model realistically represents the oil drift in the SW direction with significant stretching along the coastline from Genoa to Fréjus (Fig. 3).

This movement is mainly controlled by the Northern Current with the peak velocities of 0.6÷0.8 m s^{-1} in front of Imperia. However, we could not improve the MOTHY[4]-based simulations of slick trajectory [19] despite the expected progress related to the enhancement in the resolution of currents, both spatial (4 km *vs* 6.5 km) and temporal (daily *vs* monthly). Moreover, MEDSLIK-II could not represent the backward movement of oil on 29th April 1991 (Fig. 3, 4). Underlaying model-based hydrodynamics shows a complicated cascade of short-lived mesoscale eddies (mainly anticyclonic) generated on the continental slope. But probably, these eddies are falling short in capturing the complexity of observed oil drift. The main reason might be related to the existing drift model parameterizations, which are to a

[4] http://www.meteorologie.eu.org/mothy/index.html (Accessed online: May 2024).

large degree based on laboratory measurements that are not always representative of field conditions.

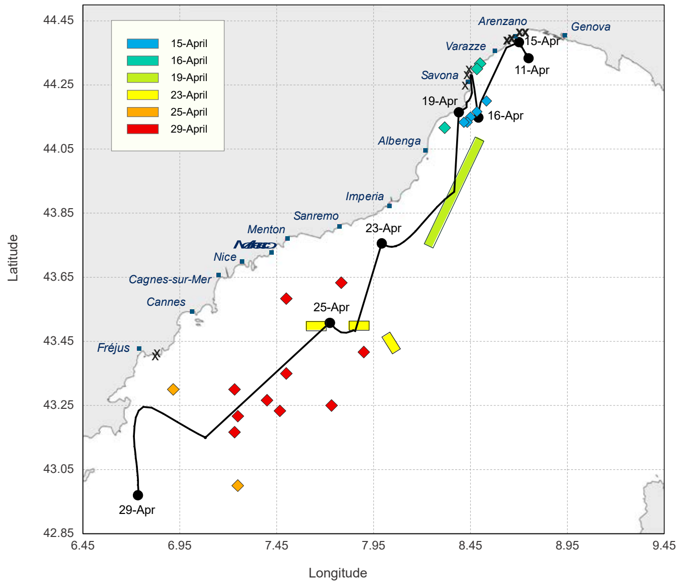

Figure 3 – Model-based oil drift (black curve) and the observations (colorful patterns); bold crosses show the massive oil beaching (>1 ton km^{-1}), while regular crosses depict the medium beaching (</= 1 ton km^{-1}).

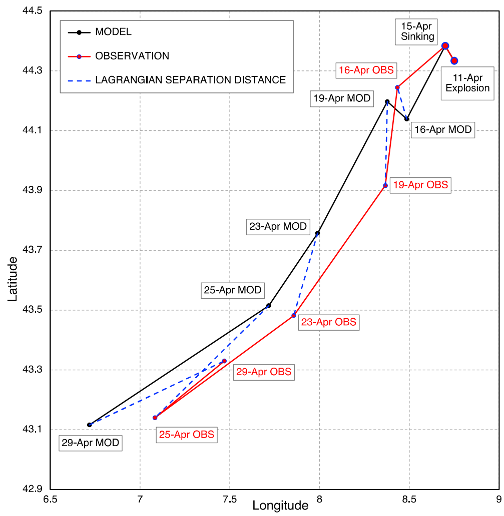

Figure 4 – Model (in black) and observation (in red) mass center trajectory, and the Lagrangian separation distances (in dotted blue segments).

Our simulations confirm a big quantity of oil arrived to the Arenzano beach as well as some oil accumulated ashore between Varazze and Savona (Fig. 3).

On the other hand, the modelled slick too quickly approaches towards the coastline causing the excessive beaching (e.g., east of Fréjus), which was not confirmed by observations.

Lagrangian separated distances applied to the center mass trajectory show quite large values, growing in time from ~12.5 km on April 16th to ~67.7 km on April 29th, (Fig. 4) and pretty poor Liu-Weisberg skill scores (0 ÷ 0.61).

Further efforts are needed to refine both underlying hydrodynamics and oil drift and weathering parameterization in MEDSLIK-II.

Results and Discussion: stochastic simulations of the *HAVEN* oil spill

We sample a great variety of virtual spill trajectories 2018–2021 (e.g., Fig. 5).

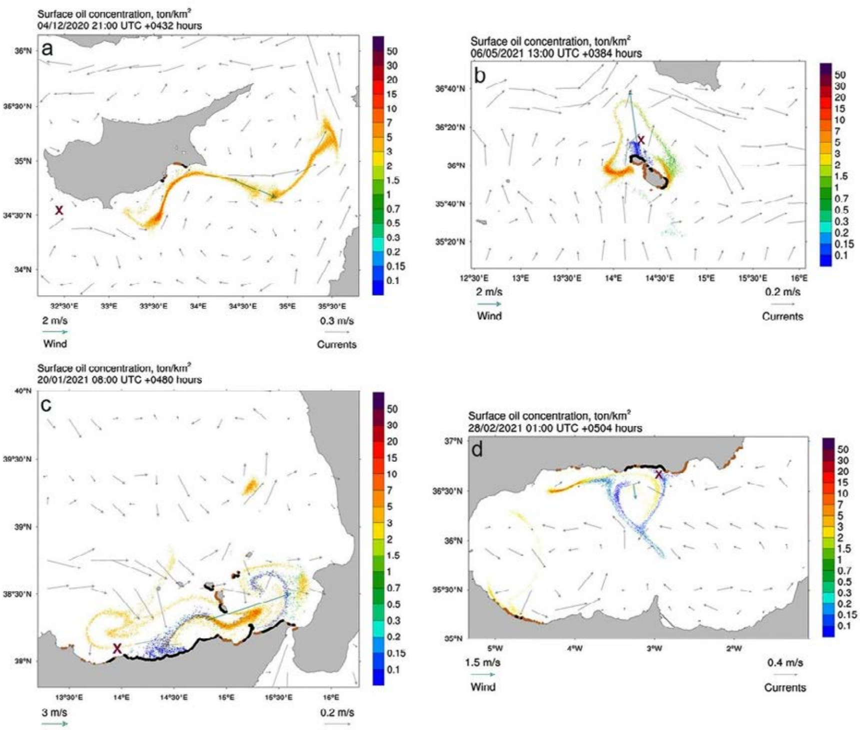

Figure 5 – Snapshots of some virtual spills started 04/12/2020 21:00 near Cyprus (a); 06/05/2021 13:00 in the Malta bunkering area (b); 20/01/2021 08:00 near Sicily (c); and 28/02/2021 01:00 in the Spanish coastal area (d). Pink crosses mark the start locations. The wind vector corresponds to the center of mass of the slick. Beached oil at concentration < 1 ton km^{-1} is depicted in brown, >/= 1 ton km^{-1} – in black.

Depending on currents and winds, the spill may cover large sea areas (Fig. 5a, d) or may develop locally (Fig. 5b, c). In the NE Levantine, a virtual spill is entrapped by a vortex dipole that is clearly visible in Fig. 5a. Genesis of such kind of structures seems to be typical of these waters [21]. In case of a slick seeded in the vicinity of the Malta bunkering area, the currents and wind are relatively weak. Therefore, almost the whole coastlines of the neighboring islands are contaminated by oil (Fig. 5b). Being driven by complicated coastal hydrodynamics, a virtual slick seeded near Sicily (Fig. 5c) reveals multiply re-suspensions and splitting into the small-scale patterns. In the Alboran Sea, a large spill can quickly contaminate both the northern and southern coastlines due to very energetic circulation (Fig. 5d).

Post-processing the acquired statistics allows us to map the pollution hazard indices at the Mediterranean surface.

Accomplishing the stochastic simulations, we should be confident that the number of virtual spills is large enough to obtain a reasonably accurate hazard map. Convergence of our method is based on the law of large numbers, which indicates that repeated sampling will result in the average outcome converging towards 'the true solution'. Remarkably, the optimal number depends on the basin geometry, meteo-oceanographic conditions, and initial distribution of spill sources. To determine this number we monitor the variability of hazard maps progressively increasing number of virtual spills. Initially, the maps showed many discontinuous patterns (Fig. 6a), but eventually the solution converge to a quite smooth hazard distribution, which is stable as the number of spills increased. We have found that ~1 200 000 virtual spills are enough to achieve stationary hazards that almost do not change with further number increasing.

Analyzing the final hazard map (Fig. 6b), we note that the hazard indices range up to 10^{-2}, which is typical of the smoothly distributed initial oil spill sources [5]. On the contrary, the hazard values asymptotically approaching 1 are usually obtained in case of a point-source associated, for example, with an oil production platform [7]. Spatial patterns of hazards over the Mediterranean tends to correspond to the initial spill sources (Fig. 2a–d). Distinctive 'hot spots', where the values of hazard indices exceed $5.6 \cdot 10^{-3}$, are clearly visible in the Algerian subbasin and the eastern Alboran Sea, in the Liguro-Provençal subbasin, and in the center of the Ionian Sea.

Conversely, the southern part of the Ionian, the areas east of Sardinia and west of Corsica, the Gulf of Lion, the northern Adriatic, and north-eastern Aegean Sea do not reveal high hazards. Intermediate values of hazard indices ranged $3.2 \cdot 10^{-3} \div 4.8 \cdot 10^{-3}$ are found in the Balearic Sea, in the northern Tyrrhenian, eastern Ionian and the entire Levantine. Interestingly, the shape of the largest hazard areas is following the climatological paths of the principal currents including the Algerian Current, Eastern Alboran Gyre, Northern Current, and the Atlantic-Ionian Stream. The connection with other sea surface currents is visible, e.g., with the Western Adriatic Coastal and Eastern South-Adriatic Currents, as well the Asia Minor Current.

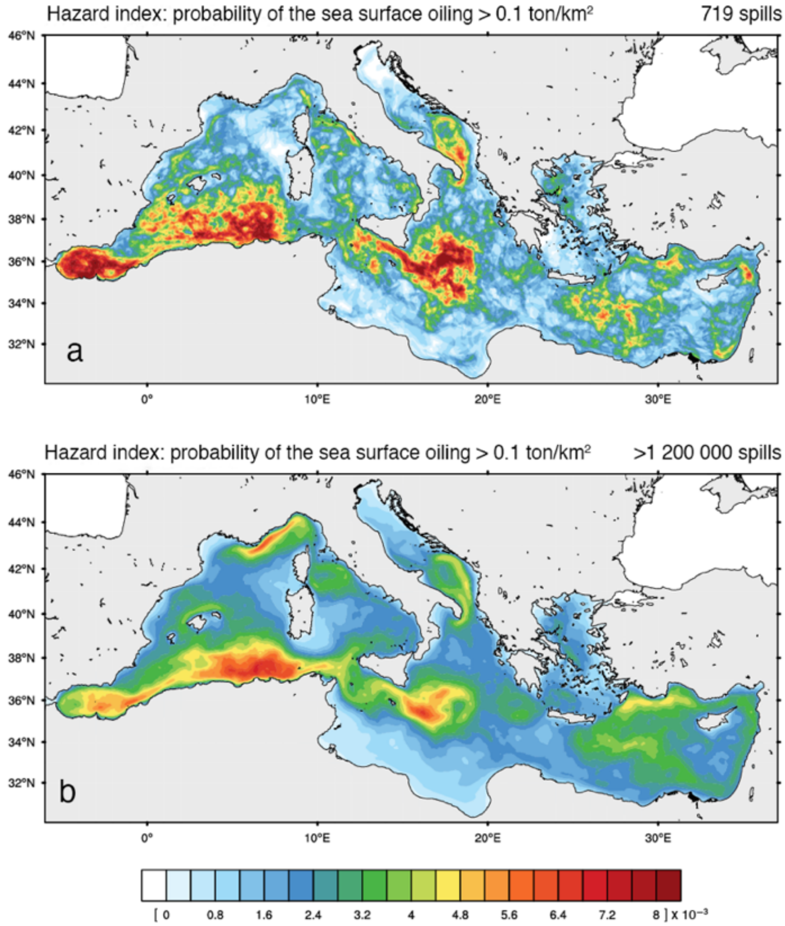

Figure 6 – Convergence to the stationary 'true solution': (a) hazard map acquired from 719 virtual spills; and (b) from > 1 200 000 ones.

Conclusion

In this work, we focus on the *HAVEN* oil spill occurred in April 1991 off the Genoa Port which is considered a 'high-impact low-probability' accident. The total cost of this disaster to the entire Mediterranean ecosystem may never be fully recognized.

We have reconstructed this historical spill with the Lagrangian oil spill model MEDSLIK-II forced by the contemporary high-resolution meteo-oceanographic datasets. Although we obtain quite a consistent general direction of the oil movement, we could not improve the results computed earlier with the MOTHY model suite [17]. This fact confirms that enhancing the hydrodynamic model resolution does not always lead to better performances in the coupled Lagrangian particle tracking [22]. Further efforts are needed to improve the MEDSLIK-II parameterizations.

Thereafter, we launch the stochastic oil spill simulations of the *HAVEN* spill scenario to map oil pollution hazard indices in case a similar large oil spill happens in the Mediterranean in the future. The hazard map obtained can be considered a multiyear product that will be delivered to the NECCTON project. This map is representative of future accidents as we can assume that the oil source distribution is representative of the present state and the used meteo-oceanographic datasets contain a realistic sample of possible weather and sea state conditions.

Hazard indices show the elevated values in the Algerian subbasin and the eastern Alboran Sea, in the Liguro-Provençal subbasin, and in the center of the Ionian Sea. Conversely, the southern part of the Ionian, the areas east of Sardinia and west of Corsica, the Gulf of Lion, the northern Adriatic, and north-eastern Aegean Sea do not display high hazards.

Hazard maps computed in this work are of relevance mainly to practitioners: agencies providing oil spill monitoring and organizations engaged in oil spill contingency and preparedness planning.

Acknowledgements

This work is performed in the framework of the NECCTON project (grant number 101081273).

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