THE ARPA FVG SUPPORT TO OIL SPILL EMERGENCY RESPONSE IN THE GULF OF TRIESTE

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Abstract – Maritime transport has characterized the human activities since the beginning of the mankind history and it has increased over time its impact on the environment. Nowadays, almost all the seas are interested by shipping lanes where the density of the ships per unit time is very high, and that results in a non-negligible probability of pollutant release in the sea, besides the accidental collisions between ships.

In this work, we focus the attention on the North Adriatic area, in particular the Gulf of Trieste, where two important harbours operate, namely Trieste and Monfalcone, whose activities have increased fast in the last decade, with the perspective to rise further in the next future. In addition, a third port, Porto Nogaro, is located inside the Marano and Grado Lagoon and, even if it has a limited ship traffic in comparison with the two main terminals, it is set inside an important ecosystem included in the NATURA2000 sites [15] (code: IT3320037).

According to the above frame, it is extremely important to be able to react promptly to an oil spill emergency, in order to avoid that the pollutant spreads over the limited area of the gulf and the lagoon, possibly reaching the shores. ARPA FVG [1] gives support to the local authorities in managing the oil spill emergency in the Gulf of Trieste, so it has been developing and operationally implementing environmental services that are ready to be part of the decision chain, which is activated in case of accidental releases of oil in the sea. Here we present an operational service that integrates weather and marine forecasts into a numerical model that simulates the dispersion of the oil slick. A description of the computational chain implementing the environmental service is presented, together with applications of the model during simulated ship collisions or accidental released along the routes.

Introduction

The oil spill occurrence is one of the worst hazards for the seas, in particular for the marine and coastal ecosystems. Furthermore, it creates societal problems, including impacts on health of individuals, well-being of communities, and their economic activities [9]. The hazard of oil spill along the ship routes, or in the harbours, may be caused by adverse weather and sea conditions, besides to be function of the density of potential sources of pollutants. Furthermore, the oil dispersion over the sea surface is directly related to the atmospheric conditions and to the surface marine currents.

The Adriatic Sea is a closed, very shallow sea in the northern part of the Mediterranean, communicating with the remaining part through the Otranto strait. Besides

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the ecological intrinsic importance of the sea, as all the seas and oceans of our world do have, the Adriatic coast is an environment hosting a rich biodiversity that is witnessed by the number of NATURA 2000 [15] sites. In addition, plenty of human activities [16], which have a large economic value, populate the shores; among them, worth of mention is the bathing tourism during the warm season.

The Adriatic is also relevant for marine transport, because of its geographical position, so the ship routes develop along the sea extension connecting several important harbours with the world maritime transport network [7]. The possibility of collisions between ships sailing on the ship lanes, or of accidental releases of pollutants from ships when they are at the anchor, before entering the harbour, has a probability that is not negligible [14]. Since one of the factors magnifying the probability of such oil spill events is the number of vessels present per unit area and time [30] [22], the current workload rapid increase of the northern Adriatic ports, i.e., Trieste [17], Monfalcone [20] and Venice [18], rises the oil spill hazard too.

Keeping in mind these evidences, it is straightforward the need for an operational forecast service that supports the emergency response to oil spill events, aiming to limit the impacts of the pollutants on the sea and especially on the shores. In fact, once the oil spill occurs, the size, the shape and the drift of the oil slick have to be contained, to prevent its impact on vulnerable areas and to ease the pollutant reclaim.

In this paper, we present the oil spill forecast service, developed by ARPA FVG [1] as the Agency operational support to the local authorities involved in the oil spill emergency response. The service is based on the oil spill model GNOME [27], which requires forecasts of sea surface currents and winds as mandatory inputs, in turn provided by state-of-the-art atmospheric and oceanographic numerical models. The combination of multiple weather and marine forecast outputs minimizes the probability that the GNOME inputs are not updated when they are needed, that is during emergencies, and this results in a service available 24 hours a day, seven days per week.

The details of the service are described together with the validation procedure and the results of its application during coordinated exercises, which have been conducted according the local Coast Guard offices exercitation plan. In addition, the contribution given by the set of instruments that ARPA FVG deploys in the field during the emergencies, for the identification of the oil type and the real time validation of the model forecasts, is described with the aim to underline that it is the synergy among information collected in situ and simulations of the spill evolution that makes the service efficacy high.

The organization of the dispersion model and the input availability for running simulations on a common laptop, which allows the environmental technicians to execute the simulations wherever their expertise is required, completes the presentation of this cutting edge service, that can be easily exported in other local realities since it has been developed to be sharable.

ARPA FVG is the Regional Environmental Agency of Friuli Venezia Giulia Italian Region [1].

Materials and Methods

An oil spill forecasting system requires a model that simulates the oil release from a source and the dispersion of the pollutant in the sea according to the boundary conditions of the considered area, namely the bathymetry and the coast shape, in addition to models that provide forecasts of the driving forces of the transport, that is the sea currents, the sea state and the atmosphere at the sea surface. Furthermore, if pollutant evolution has to be considered, the oil spill model is required to simulate the wind and the sun effect on the oil.

In the framework of the oil spill emergency response, the model chosen by ARPA FVG is GNOME. GNOME (General NOAA Operational Modeling Tool) [27] is an oil spill model developed by the U.S. NOAA (National Oceanographic and Atmospheric Administration), which predicts the trajectory and the fate of the oil released in the marine environment. It belongs to the class of Lagrangian models, where the oil is represented by a large amount of individual particles (also known as Lagrangian elements, LEs for short), each one independently moving and undergoing biophysicochemical transformations. Lagrangian oil spill models are widely adopted, mainly because of their suitability with different large spatial scales and their effectiveness for operational use.

In GNOME, the oil movement is driven by three main actions, namely the sea currents, the wind field at the sea surface, and the turbulent diffusion. The result of these physical actions on the pollutant depends on a set of user-customizable parameters, among which the windage, i.e., the degree of influence of the wind on the oil trajectory, plays a relevant role. The biophysicochemical transformations of the oil due to different natural processes, which together go under the name of weathering, are also included in the model. These transformations are highly dependent on the oil type, which indeed is one of the model variables. Lastly, GNOME contains beaching and refloating algorithms, to simulate the oil fate when it approaches the shore.

Running a GNOME simulation requires different inputs. Besides the spill details, data of sea currents and sea surface winds have to be provided as input to the model. Furthermore, static boundary conditions, such as coast lines, are also required, in order to simulate the oil behaviour on the shoreline. The accuracy of all these input data clearly influences the reliability of the forecasted oil trajectory, thus it is important for them to be up-to-date and to have a suitable spatiotemporal resolution. In order to minimize the probability that GNOME inputs are not available when needed, it is also important to have a plethora of weather and marine forecasts to be used as input data for the model.

GNOME is provided in different versions: a 2-dimensional GUI version, GNOME Desktop [26], and a 3-dimensional batch version, PyGNOME [28] [29]. GNOME Desktop, written in C++, can be directly installed on any PC and has a very user-friendly interface, which makes it easy to use for any trained user. Therefore, it is the version chosen by ARPA FVG for on-demand emergency response. PyGNOME integrates the C++ code underlying GNOME Desktop with Python code, and it currently represents the up-to-date version of the model. In comparison with GNOME Desktop, PyGNOME is more suitable for use on a HPC infrastructure; indeed, in ARPA FVG, it runs on the HPC cluster serving the FIRESPILL project [5].

Taking advantage of their complementary features, the above two versions of GNOME model have been used by ARPA FVG to provide two different emergency response services, which are available 24/7 and cover the whole Adriatic Sea: on-demand simulations via GNOME Desktop, to be carried out when an emergency occurs, and simulations of once-an-hour releases at fixed hotspots via PyGNOME, which provide ready-to-consult outputs. Since they constitute the main object of the present paper, an extensive description of these services is postponed to the Results section.

In order to evaluate the effectiveness of the services offered, ARPA FVG has been carrying out a validation of the models through tests with the use of Stokes drifters. The Stokes drifter is a low-profile surface current tracking buoy that provides real-time surface current data. It is equipped with GPS positioning by means of Iridium satellite telemetry, which enables the buoy to transmit geo-positional location data in real-time. These features make it the ideal tool for oil spill monitoring and validation of operational oil spill trajectory forecasts. The objective of ARPA FVG's drifter tests is to assess the differences between the spreading of the drifters and the trajectories forecasted by the operational Lagrangian oil spill model.

In order to get a measure of the model accuracy, the Skill Score Index, first introduced by Liu and Weisberg [21], has been used. The Skill Score (SS) is calculated from the Separation Index (S) defined as:

$$S = \frac{\sum_{i=1}^{N} d_i}{\sum_{i=1}^{N} l_{oi}}$$

where $\sum_{i=1}^{N} d_i$ is the sum of distances between the endpoints of each trajectory segment of simulated and observed drifters, and $\sum_{i=1}^{N} l_{oi}$ is the cumulative length of the observed trajectory at time step i. N is the number of time steps since the beginning of the simulation. The Skill Score (SS) is then defined as:

$$SS = \begin{cases} 1 - S/n & \text{if } S \leq n \\ 0 & \text{if } S > n \end{cases}$$

where n is a user-selected tolerance threshold. Typically, n is set to a value of 1, meaning that the error should not exceed the magnitude of the cumulative movement.

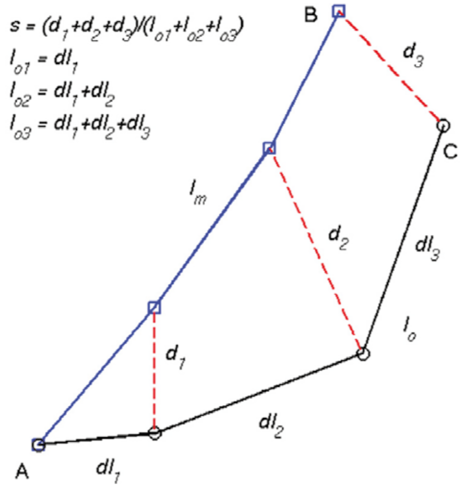

Figure 1 – Example showing the quantities involved in the calculation of the Skill Score Index, where l_o and l_m are the lengths of the observed and modelled paths, respectively. Source: [21].

In the tests already carried out, the GNOME oil spill model was used, in combination with the WRF model as source of wind data, and with both the CMEMS and ROMS models as sources of sea currents data. As the GNOME simulations were run using 10^3 Lagrangian particles, in order to obtain the step-by-step trajectory of the oil, the ARPA FVG's choice was to calculate the centroid of the 10^3 Lagrangian elements and to compare the observed drifter trajectory with the trajectory extracted from the centroid at every time step.

Results

Two services for oil spill emergency response have been developed and tested by ARPA FVG. The first service is the daily preparation and supplying of forecast data of surface winds and sea currents, as well as the supplying of updated coast lines, to be used as inputs for on-demand simulations via GNOME Desktop. In the event of an oil spill emergency, these data can be downloaded from the service webpage and used to run simulations through the GNOME Desktop application installed on the user's PC. In particular, this allows any trained user to run the simulation on his/her own, thus obtaining in a few seconds the forecasted oil trajectory for the specific scenario.

Data are provided on three areas, namely the Gulf of Trieste, the North Adriatic, and the whole Adriatic Sea, at descending spatiotemporal resolution, respectively, with a temporal coverage of +72 h. Furthermore, in order to guarantee the redundancy of the data, which is needed to minimize the risk of non-availability of required GNOME inputs, data originated by multiple meteo-marine models are made available. GNOME inputs are provided in the form of compressed archives, each one containing forecast data of surface winds and currents from specific source models, and the relevant coast lines. Detailed information about data resolutions and sources is displayed in the table below, where each line refers to one of the released archives.

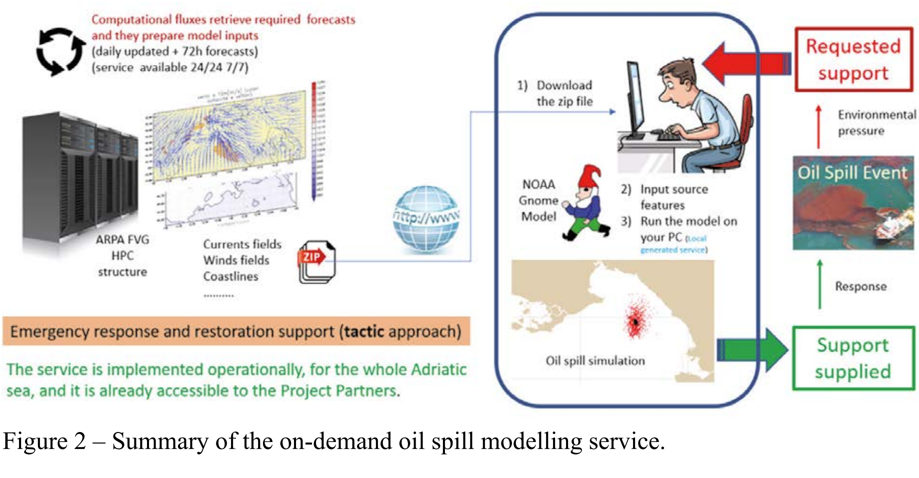

Figure 2 – Summary of the on-demand oil spill modelling service.

Table 1 – Description of meteo-marine input data for GNOME Desktop.

Domain	*Winds at 10 m*			*Sea surface currents*		
	Model	*Resolution*	*Source*	*Model*	*Resolution*	*Source*
Trieste Gulf	WRF[1]	2 km, 1 h	ARPA FVG	MedFS[2]	4 km, 1 h	CMEMS[3]
Trieste Gulf	WRF	2 km, 1 h	ARPA FVG	ROMS[4]	2 km, 3 h	ARPAE[5]
North Adriatic	WRF	2 km, 1 h	ARPA FVG	MedFS	4 km, 1 h	CMEMS
North Adriatic	WRF	2 km,1 h	ARPA FVG	ROMS	2 km, 3 h	ARPAE
Adriatic Sea	WRF	10 km, 3 h	ARPA FVG	MedFS	4 km, 1 h	CMEMS
Adriatic Sea	WRF	10 km, 3 h	ARPA FVG	ROMS	2 km, 3 h	ARPAE

In order for the on-demand service to be effective, the expertise of the operators involved in the emergencies clearly plays a relevant role. Therefore, ARPA FVG has organized a series of training courses on the use of GNOME Desktop via this service, mainly addressed to the personnel in charge of supporting the local authorities during emergency situations, but also to members of such authorities. The course material is publicly available at [2].

The second service developed by ARPA FVG for oil spill emergency response consists in a set of daily oil spreading simulations, carried out through PyGNOME, where the sources are located at certain hotspots, i.e., points or routes at high probability of oil spills, such as the Trieste and Monfalcone harbours. For each identified hotspot, one spill per hour from that fixed source is simulated, leading to a total of 24 simulations per day. The forecasting period of these simulations is usually set to +48 h or +72 h, but it can be effortlessly customized. The output is provided in the form of a GIF animation, which allows the user to have an immediate visualisation of the forecasted oil trajectory. Being the pilot area of ARPA FVG for the FIRESPILL project, the Gulf of Trieste is the main domain of these simulations. However, since the service has been developed to be shared among all project partners, any hotspot in the Adriatic Sea can be easily integrated in the service.

The purpose of the simulations on hotspots is to provide stakeholders, when facing an oil spill emergency in those areas, with an on-the-spot hint about the trajectory that the pollutant will follow, without the need to run a simulation on their own. In particular, this second service does not require any expertise with the oil spill model, hence it is addressed to a broad group of stakeholders.

Both the modelling services developed by ARPA FVG as support to oil spill emergencies, in the framework of FIRESPILL project, are daily updated and available to all stakeholders at the project website [5]. The archives containing forecast data of oil movers for on-demand simulations with GNOME Desktop can be downloaded by accessing the page "GNOME model driving forces" [3], which also contains useful links for the model use.

Graphical output of the daily simulations on hotspots can be viewed at the page "Daily oil spill simulations" [6], where every simulation is identified by an alphanumeric code containing all the information about its specific features.

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[1] Weather Research and Forecasting Model [25] [4].
[2] Mediterranean Forecasting System [8].
[3] Copernicus Marine Environment Monitoring Service [24].
[4] Regional Ocean Modeling System [12] implemented on the Adriatic domain.
[5] ARPA Emilia-Romagna.

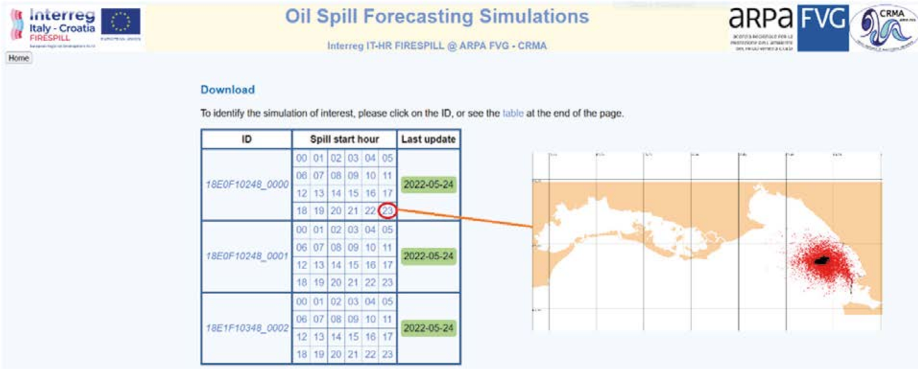

Figure 3 – Output of a PyGNOME simulation on hotspots, from the webpage of the service. In this case, the oil source is located near the Port of Trieste.

The page "GNOME course" [2] is the above-mentioned page containing training material for the on-demand service.

The operational implementation of the described services has been realised by means of the workflow manager ecFlow [13], which eases the execution of all the computational routines. This way, human intervention is limited to unordinary situations, thus enhancing the service operability.

In order to verify the results obtained through the GNOME model simulations, four different release days of the Stokes Drifters were organised between February and May 2022. All releases were carried out in the Gulf of Trieste and lasted from 24 hours to 60 hours.

Three different drifters were used on each test day. In particular, on one occasion, namely on 2022-02-28, the three drifters were released in three different positions in the Gulf of Trieste, while in the other three cases all of them were released at the same point. The choice of using a single release position was made in order to monitor the possible deviation of the drifters themselves after 48 h and, at the same time, to verify the sensitivity of the Skill Score index to slight deviations from the observed trajectory. In none of the releases there was a coastal stranding or any other event that could have affected the natural movement of the drifters.

Tables 2 and 3 present the results obtained in terms of the Skill Score and its standard deviation, respectively. The results are grouped by time bands. The first column takes into account 48 h from release, the second the first 12 h, while the last three columns present the results within 24 h. This representation was chosen in order to visualize how the value of the Skill Score is influenced by the relaxing simulation time. In fact, the value of the Skill Score shows an initial oscillation before reaching an almost constant value.

In the tests conducted by releasing the three drifters at a single position, the deviation of the three drifters among themselves never exceeded 2 km after 48 h. From the calculation of the Skill Score with the three drifter traces observed, only slight non-significant variations on the final value of the Skill Score were seen. Therefore, these preliminary tests provide a clear indication of how the Skill Score index is a robust and useful tool for quantifying the accuracy of the models and of the input data required by them.

From the results obtained, presented in Table 2, the Skill Score values exceeded 0.5 for both source of sea currents data, on all test days except 2022-04-11. This gives a clear insight into how the emergency response system adopted in ARPA FVG is able to provide a reliable forecast.

Table 2 – Summary of the Skill Score (SS) mean collected during the ARPA FVG tests in the period February – May 2022. Results of each set of inputs are presented, namely sea currents from CMEMS and ROMS modelling systems, with the same source for winds, that is WRF model.

Skill Score	48h		12h		24hfrst		24hsnd		24htrd	
Data	CMEMS	ROMS	CMEMS	ROMS	CMEMS	ROMS	CMEMS	ROMS	CMEMS	ROMS
28/02/2022	0.721	0.682	0.549	0.385	0.659	0.567	0.782	0.796	/	/
11/04/2022	0.496	0.442	0.316	0.248	0.383	0.347	0.607	0.536	/	/
18/05/2022	0.561	0.756	0.46	0.676	0.561	0.756	/	/	/	/
20/05/2022	0.756	0.835	0.68	0.759	0.707	0.763	0.791	0.874	0.783	0.899
MEAN	0.634	0.679	0.501	0.517	0.578	0.608	0.727	0.735	0.783	0.899

Table 3 – Summary of the Standard Deviation (SD) collected during the ARPA FVG tests in the period February – May 2022. Results of each set of inputs are presented, namely sea currents from CMEMS and ROMS modelling systems, with the same source for winds, that is WRF model.

Skill Score	48h		12h		24hfrst		24hsnd		24htrd	
Data	CMEMS	ROMS	CMEMS	ROMS	CMEMS	ROMS	CMEMS	ROMS	CMEMS	ROMS
28/02/2022	0.160	0.167	0.243	0.257	0.208	0.216	0.023	0.027	/	/
11/04/2022	0.131	0.129	0.051	0.070	0.095	0.123	0.016	0.011	/	/
18/05/2022	0.154	0.120	0.153	0.120	0.154	0.120	/	/	/	/
20/05/2022	0.067	0.075	0.107	0.088	0.086	0.069	0.010	0.012	0.004	0.006
MEAN	0.1280	0.1228	0.1385	0.1338	0.1358	0.1320	0.0163	0.0167	0.0040	0.0060

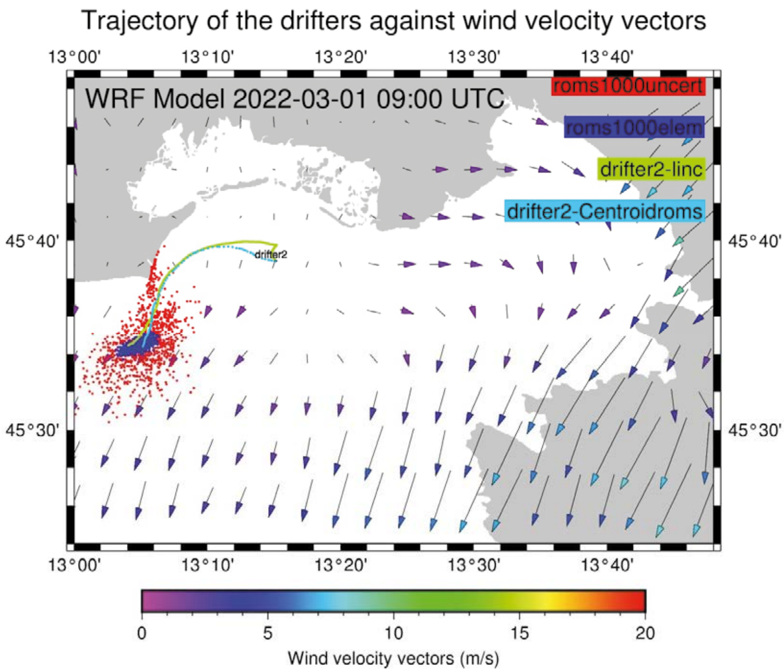

Figure 4 – A snapshot of the simulated (green) and observed (light blue) trajectories. The deterministic prediction by the GNOME model is represented in blue, while the probabilistic one is shown in red. Model inputs are wind velocities from ARPA FVG – WRF model and sea currents from ROMS model. Wind vectors are plotted in the domain, too.

Figure 5 – Picture of a drifter released in the water during a model validation test.

The oil spill forecasting system developed by ARPA FVG was also tested during an anti-pollution and fire-fighting exercise coordinated by the Monfalcone Port Authority on 2021-11-25. In case of an oil spill event, ARPA FVG is indeed one of the authorities committed to organize the intervention groups of the Emergency Response System, with the task of giving support to the authorities in charge of the emergency management, such as the Port Authority, the Fire Brigade, or the Civil Protection. For instance, the presence of ARPA FVG in the accident site is required in order to establish the type of pollutant, both through on-site measurements and through sampling and subsequent laboratory analyses. Besides the on-field teams, ARPA FVG also provides support via its modelling tools, in particular the above-mentioned services for oil spill emergencies.

The exercise, where a ship accident leading to a leak of 5 m^3 of fuel oil within the Port of Monfalcone was simulated, showed the important role of the oil spill forecasting system in addressing the emergency management operations. At the same time, it exposed the need for improvement of the services, in particular when the oil spill occurs very close to the coast. For further information about the observed limits and the planned solutions, see the Discussion section.

Discussion

The services developed by ARPA FVG for oil spill emergencies have proved to be an import tool to support the authorities in the emergency management, providing them with useful information about the oil spreading evolution, as it has emerged from the exercise coordinated by the Monfalcone Port Authority.

The complementary features of the two services presented in this paper make the ARPA FVG's oil spill forecasting system useful and beneficial for a large class of stakeholders. The system has been mainly tested on the Trieste Gulf and the Marano-Grado Lagoon, i.e., the FIRESPILL pilot area of ARPA FVG, but it has actually been developed for the whole Adriatic Sea, in order to be sharable with all project partners. Therefore, any stakeholder in the Adriatic area can benefit from this work.

The validation campaign through drifter tests has confirmed the reliability of the adopted system, including both the oil spill model and the meteo-marine models. This has been highlighted by the results on the Skill Score, whose mean values were greater than 0.5 in all but one test, even with different sources of data of sea currents. Recall that 0.5 is the value which is usually considered the threshold between low and high performance of the trajectory model.

However, the validation has also allowed to understand the current limits of applicability of the services, in particular within lagoon environments or within harbours. The coastal local variations are not captured with sufficient spatial accuracy, and sometimes the inputs time resolution does not allow to capture transient meteorological phenomena, which however considerably influence the results. As a consequence, in correspondence of river mouths, or when strong tidal excursions or rapid changes in the seabed occur, the results obtained in such critical areas are uncertain or unreliable. In addition, the lack of data of sea currents close to the shoreline, due to the resolution of the adopted models, leads the Lagrangian elements to be moved only by the wind field, with a subsequent decrease of the oil spill model performance.

For this reason, a new high-resolution hydrodynamic forecast system, focused on the Trieste Gulf and the Marano-Grado Lagoon, has been designed and is in the implementing phase. It is based on the shallow water model SHYFEM [19], which is driven by means of the Mediterranean basin scale sea state forecasts provided by CMEMS [24] and of the ARPA FVG meteorological forecasts, operationally generated via the WRF model [4]. The quality evaluation of the high-resolution fields has already been performed and the best parameters configuration has been identified.

Furthermore, the implementation of another oil spill model, MEDSLIK-II [10] [11] [23], is in progress and close to be ready for operational purposes. The basic model has been adapted to take as input the same data of driving forces used for GNOME, and a more detailed local cartography than the default one has been added to the model. By adding new forecasts of the oil trajectory and fate to the already existing ones, this will allow to improve the oil spill forecasting system. In particular, the use of this new model, together with the full exploitation of the recent 3D features of PyGNOME, should capture the entire 3D evolution and not only the 2D oil trajectory on the sea surface, as is currently the case.

Finally, in order to keep and improve the service efficiency, the training of the personnel involved in the emergency response has to be maintained constant and updated with the new system features. Only this way the oil spill forecasting system can be used promptly and efficiently, as it is needed during an emergency situation.

Altogether, this set of improvements is expected to allow ARPA FVG to overcome the current limits of the oil spill response services, which anyway are already at a good level of reliability, as shown by the above results.

Conclusion

Oil spill events pose a serious threat to the marine and coastal environment, in particular in an area such as the Adriatic Sea, and more specifically the Gulf of Trieste, where the marine traffic has been constantly increasing in the last years. Among the vulnerable subjects, it is worth mentioning the human activities, such as marine transport, tourism, fishing, fish and mussel farming, besides the entire ecosystem, in which many vulnerable species live. Last but not least, also the historical and cultural heritage sites are vulnerable to the oil spill threat.

This highlights the importance and usefulness of a forecasting system to support the authorities in the management of oil spill emergencies. The services described in this work exactly aim at providing such an efficient and reliable operational system, focused on the Gulf of Trieste and the Adriatic Sea, with the ability of being employable by different users. Public availability is one of the important features of these services, which have indeed been developed to be sharable.

The oil spill forecasting system of ARPA FVG has been under continuous validation, which has shown, together with on-field experiences like the participation in a Coast Guard exercise, its value and reliability. Of course, some limits of the services have also emerged, requiring further development and improvement, on which ARPA FVG is currently working.

The beneficiaries of this work are various, including all the stakeholders related to the above-mentioned vulnerable subjects, and the public entities in charge of managing the marine emergencies, like the Port Authorities, or the society safety, such as the Civil Protection.

Acknowledgments

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