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The Mediterranean Decision Support System for Marine Safety dedicated to oil slicks predictions

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ABSTRACT

In the Mediterranean sea the risk from oil spill pollution is high due to the heavy traffic of merchant vessels for transporting oil and gas, especially after the recent enlargement of the Suez canal and to the increasing coastal and offshore installations related to the oil industry in general. The basic response to major oil spills includes different measures and equipment. However, in order to strengthen the maritime safety related to oil spill pollution in the Mediterranean and to assist the response agencies, a multi-model oil spill prediction service has been set up, known as MEDESS-4MS (Mediterranean Decision Support System for Marine Safety). The concept behind the MEDESS-4MS service is the integration of the existing national ocean forecasting systems in the region with the Copernicus Marine Environmental Monitoring Service (CMEMS) and their interconnection, through a dedicated network data repository, facilitating access to all these data and to the data from the oil spill monitoring platforms, including the satellite data ones, with the well established oil spill models in the region. The MEDESS-4MS offer a range of service scenarios, multi-model data access and interactive capabilities to suite the needs of REMPEC (Regional Marine Pollution Emergency Response Centre for the Mediterranean Sea) and EMSA-CSN (European Maritime Safety Agency-CleanseaNet).

1. Introduction

Traditional shipping and oil transportation routes are more exposed to the impacts of oil-polluted discharges from tankers and other vessels than other areas. Oil discharges may be accidental or

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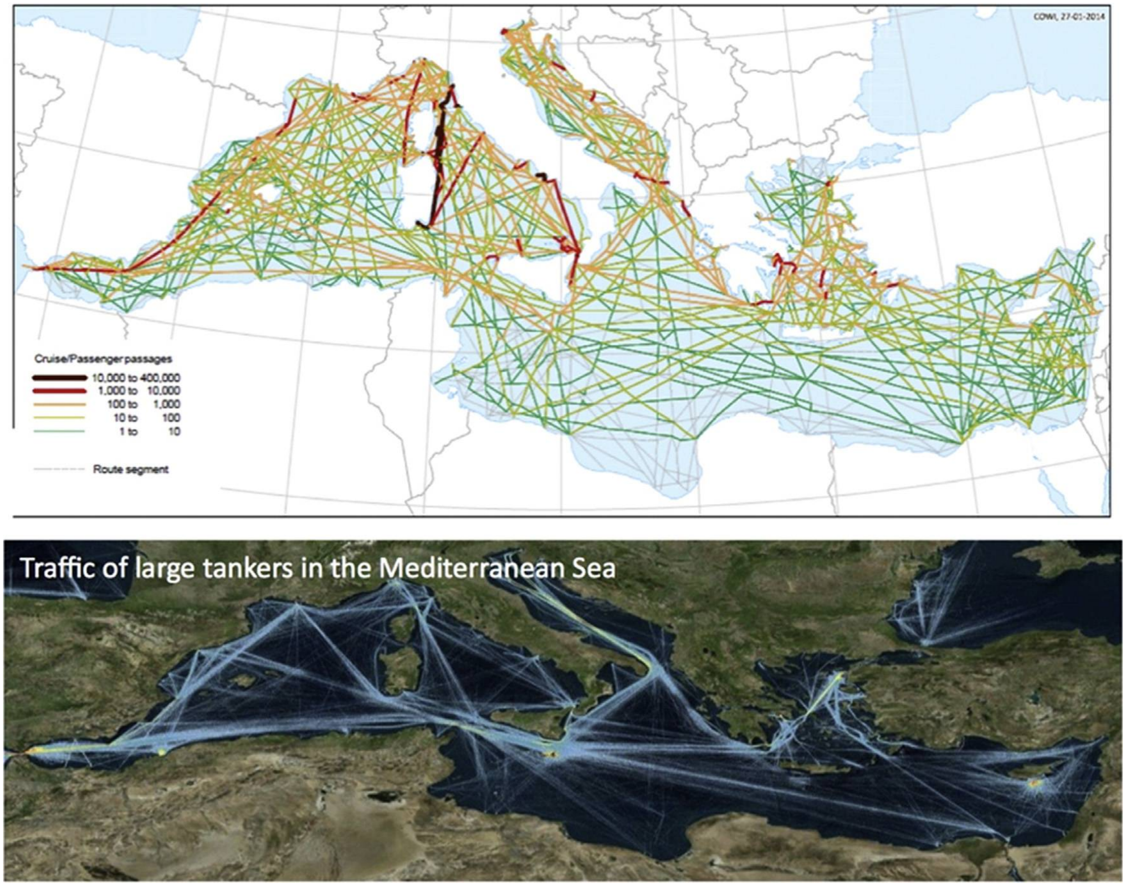

Fig. 1. Ship traffic density in the Mediterranean Sea (a and b; COWI 27/1/2014).

in many instances vessels intentionally discharge illegal wastes despite foreign and domestic regulation prohibiting such actions. The risk from oil spill pollution in the Mediterranean is high due to the heavy ship traffic (Fig. 1a), and in particular of merchant vessels for transporting oil and gas (Fig. 1b) and to the increasing coastal and offshore installations related to the oil industry in general.

Oil spills in the ocean, particularly in offshore and coastal waters are a matter of concern due to the damaging effect they can have on various resources and industrial installations and the marine vegetation and wildlife in general. To mitigate such damages as much as possible, it is common to combat a spill by deploying equipment such as booms and skimmers or to spray chemical dispersants. In order to make optimal use of such devices and to assist the response agencies and the decision makers, it is recommended to employ dedicated numerical models to predict where the spill will most likely move to, in particular which resources are threatened, and how soon it will get there. Such models often also predict the expected state of the oil when it arrives, that is, how much will have evaporated, the degree of emulsification of the remainder, how much will remain be on the surface and how much will be dispersed as fine droplets throughout the water column, and so on. The oil spill models require the location and the time of the observed oil slick, the type of oil and its characteristic, the wind fields, the sea state, the sea surface temperature and the sea currents as input data. Therefore, in order to assist the response agencies to protect the marine environment from oil spill accidents, it is necessary to offer an efficient estimate of the oil spill predictions, using quality controlled forecasting data, such as those provided by the Copernicus marine service and the downscaled ocean forecasting systems of MONGOOS (Mediterranean Oceanographic Network for Global Ocean Observing System). The Copernicus marine service provides the regional Med-MFC (Mediterranean Monitoring and Forecasting Centre) forecasting data at a lower spatial and temporal resolution, while the downscaled ocean forecasting systems of MONGOOS provide a variety of high spatial and temporal resolution at sub-regional and coastal domains.

1. Integration of the different well established oil spill models in the Mediterranean with the ocean data provided by the low spatial resolution Copernicus Med-MFC (Mediterranean Monitoring and Forecasting Center) and the high spatial resolution downscaled national ocean forecasting systems of MONGOOS (Mediterranean Oceanographic Network for Global Ocean Observing System) network (Table 1a; www.mongoos.eu);
2. Connection of the existing oil spill monitoring platforms in the region, such as EMSA-CSN (European Maritime Safety Agency-CleanSeaNet) and REMPEC (Regional Marine Pollution Emergency Response Centre for the Mediterranean Sea) to the integrated multi-model oil spill prediction system of MEDESS-4MS (Mediterranean Decision Support System for Marine Safety); and
3. Allow the backward predictions of the oil slicks, in order to assist the response agencies to implement the EC Directive 2005/35 facilitating the identification of the ship that has potentially originated the spill.

The Mediterranean decision support system for marine safety project was aiming to fulfill the above main requirements and to set up an integrated multi-model operational oil spill prediction service for the entire Mediterranean, dedicated to the EU members

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Table 1a
The hydrodynamic models (14 in total), the corresponding domains and horizontal resolutions.

HYDRODYNAMIC FORECASTING SYSTEM	PROVIDE	GEOGRAPHIC COVERAGE	RESOLUTION
POSEIDON Aegean Model	HCMR	Lon.[19.5 30]°E; Lat.[30.4 41] °N	~3.5 km
POSEIDON Mediterranean Model	HCMR	Lon.[-7 36]°E; Lat.[30.25 45.75]°N	~10 km
CYCOFOS CYPPOM (Aegean-Levantine)	OC-UCY	Lon.[20.00 36.20] °E; Lat.[30.70 41.20] °N	~2 km
CYCOFOS (Levantine Basin)	OC-UCY	Lon.[29.98 36.20] °E; Lat.[31.01 36.91] °N	~ 1.8 km
Copernicus Med-MFC (previously known as Mediterranean Forecasting System – MFS)	INGV	Lon. [-6 36.25] °E; Lat. [30.25 46] °N	6.5 km
AFS	CMCC-INGV	Lon.[12.2 20.78]° E; Lat. [39 45.82]° N	~ 2.2 km
SCRM	CNR(IAMC	Lon.[8.95 17.1]°E; Lat.[30 39.5]°N	~ 3,5 km
WMED	CNR(IAMC	Lon.[3 16]°E; Lat.[36.5 44.5]°N	~ 3,5 km
Copernicus IBI-MFC	PdE	Lon.[-9 5]°E; Lat. [35 44.5]°N	~ 3 km
SAMPA	PdE	Lon.[-7.5 -3]°E; Lat. [35 37.1]°N	~ 2 km
ALERMO	IASA	Lon.[20 36.4]°E; Lat.[30.7 41.2] °N	~3.5 km
WMOP	UIB-	Lon.[-6 9]°E; Lat.[35 44.5] °N	~1,5 km
PREVIMERMENOR	IFREMER	Lon.[0.00 15.99994] °E; Lat.[39.5 44.5] °N	~ 1.2 km
ROSARIO II Malta Shelf Model	UOM	Lon. [13.805 14.945]°E; Lat.[35.430	~ 1.5km

and non-EU members response agencies and to the key users, such as REMPEC and EMSA-CSN, but also national actors like Coast Guards from each Mediterranean riparian country. The multi-oil spill modeling system of the MEDESS-4MS service is coupled with the low resolution met-ocean data from the Copernicus Med-MFC and the higher resolution met-ocean data from the associated national downscaled ocean forecasting systems of the MONGOOS and the oil slick data from existing monitoring platforms in the Mediterranean, such as REMPEC and EMSA. The latter European agency has set up a web portal back in 2007, known as the CleanSeaNet (CSN), which provides to the member state's response agencies warnings for oil spill accidents and satellite data detecting possible oil spills.

The purpose of this work is to describe the Mediterranean decision support system for marine safety and to highlight the main features of this novel downstream service dedicated to integrated multi-model oil spill predictions. Section 2 presents the state-of-the-art background for the MEDESS-4MS service, Sections 3–6 present the main components of the MEDESS4-MS systems (i.e., the oil spill models, the met-ocean data, the Network Data Repository and the web User Interface), Section 7 offers a discussion about the accomplishments and capabilities of the MEDESS-4MS tool and Section 8 presents some conclusions.

2. The state-of-the-art background for a multi-model oil spill predictions service in the Mediterranean Sea

The implementation of MEDESS-4MS service is based upon the gained expertise in the past years

a) during real oil spill pollution emergencies in the Mediterranean, most well-known is the Lebanese oil pollution crisis in summer 2006 (Lardner et al., 1988; Zodiatis et al., 2007; Coppini et al., 2011), which is so far considered as the biggest oil pollution incident in the Eastern Mediterranean,
b) the inter-comparison of the oil spill prediction simulations exercises carried out during EU projects, such as ECOOP, MERSEA-IP, MyOcean, and NEREIDs (Brostrom et al., 2010; Coppini et al., 2011; De Dominicis et al., 2013b; Alves et al., 2014, 2015),
c) in the frame of pilot projects between EMSA-CSN and MONGOOS members experts in oil spill modeling and
d) in the frame of an agreement between REMPEC and MONGOOS.

From the point of view of multi-oil spill models approach, a few well established models have been used for many years by the members state agencies and response services in the Mediterranean (MOTHY, POSEIDON-OSM, MEDSLIK, and MEDSLIK-II), of which MEDSLIK got a broader use by response institutions from Israel, Cyprus, Italy, Malta, Spain, and Tunisia, especially after its successful predictions of the Lebanese oil pollution crisis, in 2006, while MOTHY was used for the Erika (Daniel et al., 2001) and the Prestige oil spill incidents and MEDSLIK–II was used during the Costa Concordia emergency in 2012 (De Dominicis et al., 2014).

MEDESS-4MS did not aim at developing new met-ocean and oil spill forecasting systems, but was built from existing ones; accordingly, a particular effort was carried out to have an integrated multi-model approach, both at the technical level and at user's level. In MEDESS-4MS, all the activities were carried out in terms of sustainability; consortium and partners expertise, end users and areas of responsibility. MEDESS-4MS consists from 4 oil spill models and uses met-ocean forecasting data from 28 different forecasting modeling systems (currents, waves, and winds), all harmonized, so each of the MEDESS-4MS oil spill model can uses met-ocean forecasting data from any of the 28 forecasting modeling systems, via a NDR (Network Data Repository). The equivalent in concept but not multi-model service existed prior to MEDESS-4MS in Europe for the Baltic Sea, where only the SeaTrack oil spill model is used with dedicated met-ocean forecasting data. Multi-model ensemble was found to be important in reducing errors from individual models in the operational forecast of the

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Deepwater Horizon oil spill trajectory in the Gulf of Mexico (Liu et al., 2011a, 2011b). That was the first time multi-model ensemble had been used in an operational oil spill trajectory forecast for a major oil spill incident (Liu and Weisberg, 2011). Many valuable lessons have also been learned (Liu et al., 2011a, 2011c), such as initializing the oil trajectory models with satellite imager-derived oil slick locations.

MEDESS-4MS was built on the experience gained through the interaction with REMPEC and EMSA (their requirements were fully implemented) and the demo implementations carried out previously in the frame of EC projects related to ocean forecasts, by establishing for the first time an integrated structured operational multi-model oil spill forecasting service for the entire Mediterranean, using both, the Copernicus Med-MFC data, as well as those from the downscaled ocean forecasts of the MONGOOS.

With regard to satellite SAR data became available to responsible governmental agencies in 2007 via the EMSA CSN service. Such service offers to all EC coastal member states, a near real time marine oil spill detection service by using radar satellite imagery by the Envisat (until April 2012), Radarsat and Sentinel (after February 2014) SAR satellites and COSMOS. The EMSA-CSN (European Maritime Safety Agency-CleanSeaNet) service, which is integrated within the national and regional oil pollution surveillance and response chains, aims at strengthening operational response for accidental and deliberate discharges from ships as well as assisting the coastal member states to locate and identify polluters in areas under their jurisdiction. The analyzed satellite imagery is available to the relevant coastal member states operational contact points within 30 min after satellite overpass. In the case of a detected possible oil slick, an alert message is delivered to the operational contact point of the relevant concerned coastal member state. Each coastal member state has access to the EMSA-CSN service through the dedicated CSN Browser. Towards the establishment of the MEDESS-4MS service, the MEDESS-4MS partners are collaborating with EMSA in pilot projects to test the capability of the prediction system to be integrated with EMSA-CSN satellite monitoring data, as well as with other satellite imageries (Zodiatis et al., 2010, 2012). In parallel, the MEDESS-4MS partners are collaborating with REMPEC setting an Emergency Response Officer to provide operational support to REMPEC's request. These actions represent important test of interacting between the key users (EMSA and REMPEC) and the forecasting systems and is the basis of the system that was implemented in MEDESS-4MS service.

The main components of the MEDESS-4MS are as follows:

a) the harmonized met-ocean data (currents, sea surface temperature, winds, and waves) provided from 28 in total different operational forecasting systems;
b) the oil spill data from existing monitoring platforms, such REMPEC and EMSA-CSN;
c) the 4 well established oil spill models in the region adapted to use, upon the request, the data from the 28 different forecasting systems;
d) the Network Data Repository (NDR), handling the flow of the met-ocean and oil spill data to the oil spill models and the interconnection with the user interface.
e) the user interface used to activate an oil spill simulation and for the visualization of results.

3. The Meteo-oceanographic data

From the oil spill prediction aspects, before the development of the operational oceanography, climatological currents or limited coastal in-situ observation were used. However, the flow, wind and wave fields varies on the time scales of hours and days and climatology does not allow a sufficiently accurate of the oil spill transport. The past 10–15 years, the Lagrangian dispersal models has started individually to integrate the analyses and the operational met-ocean forecasts in near real time for the oil spills predictions. MEDESS-4MS has set common input and output files dedicated to oil spill prediction and integrated via a NDR (Network Data Repository) the Copernicus Med-MFC products and the downscaled ocean forecasting systems of the MONGOOS network, with the well established oil spill fate and dispersal models in the Mediterranean (MEDSLIK, MEDSLIK-II, MOTHY, and POSEIDON-OSM), thus providing an innovative and multi-modeling system for oil spill predictions for the entire region.

For the hydrodynamics, the Copernicus Med-MFC and 14 downscaled systems of the MONGOOS network provide every day forecasts (from 4.5 days up to 10 days) of temperature and sea currents, as well as sea state from 7 wave forecasting systems and winds from 7 atmospheric forecasting systems (Fig. 2a–c) in a variety of temporal and spatial resolution (Tables 1a–1c). These data are available to the MEDESS-4MS service via a dedicated Network Data Repository (NDR) that was developed during the project. Since year 2002, in the framework of MFSPP-Mediterranean Forecasting System Pilot Project and MFSTEP – Mediterranean Forecasting System Towards Environmental Prediction project, the Mediterranean member state institutions (founders of the MONGOOS network in 2004) have elaborated a suite of downscaling ocean forecasting systems. These downscaled models correctly bring the information from the course Med-MFC regional model to the coast with high spatial and temporal resolution. Each MONGOOS member state offers now up to 1 km resolution sea current and temperature forecasts in near real time and every day. Thanks to MEDESS-4MS, these downscaled systems now work in an integrated way to support the multi-model oil spill prediction system for any part of the Mediterranean sea. In the past years, the MONGOOS members, responsible for operational ocean forecasting in the Mediterranean, have signed a Data Exchange Agreement that supports and ensures the exchange of data between its members. This legal framework, already available, ensures that the basic environmental data for the MEDESS-4MS service is available for the service sustainability.

The MEDESS-4MS hydrodynamic, atmospheric and sea state data are available to the service in daily basis through nine (9) different providers in the Mediterranean Sea. In Tables 1a–1c information regarding the boundaries and the resolution of the 28 meteorological, hydrodynamic and sea state MEDESS4-MS forecasting products are given, whereas in Figs. 2a–c the geographical coverage of each model is presented. A short description of the forecasting systems that are provided by MEDESS-4MS partners and are connected to the MEDESS-4MS system is presented hereafter.

The POSEIDON System has been established by Hellenic Center for Marine Research (HCMR; (Nittis et al., 2005) and provides hydrodynamic forecasting products to the MEDESS4-MS system for the whole Mediterranean and the Aegean Sea, under the following configuration: the Mediterranean forecasts are released through the implementation of the 10 km spatial resolution and 24 vertical sigma layers implementation of the Princeton Ocean model (POM; Blumberg and Mellor, 1987) which covers the entire Mediterranean basin (Table 1c) and provides 5-day forecasts. The Aegean Sea hydrodynamic model is also based on the POM; (Korres and Lascaratos, 2003; Table 1a), with 24 sigma layers along the vertical with a logarithmic distribution near the surface and the bottom. Boundary conditions at the western and eastern open boundaries of the Aegean model are provided by the POSEIDON Mediterranean model. The Aegean Sea model is re-initialized from the HCMR Mediterranean model analysis once every week. Meteorological

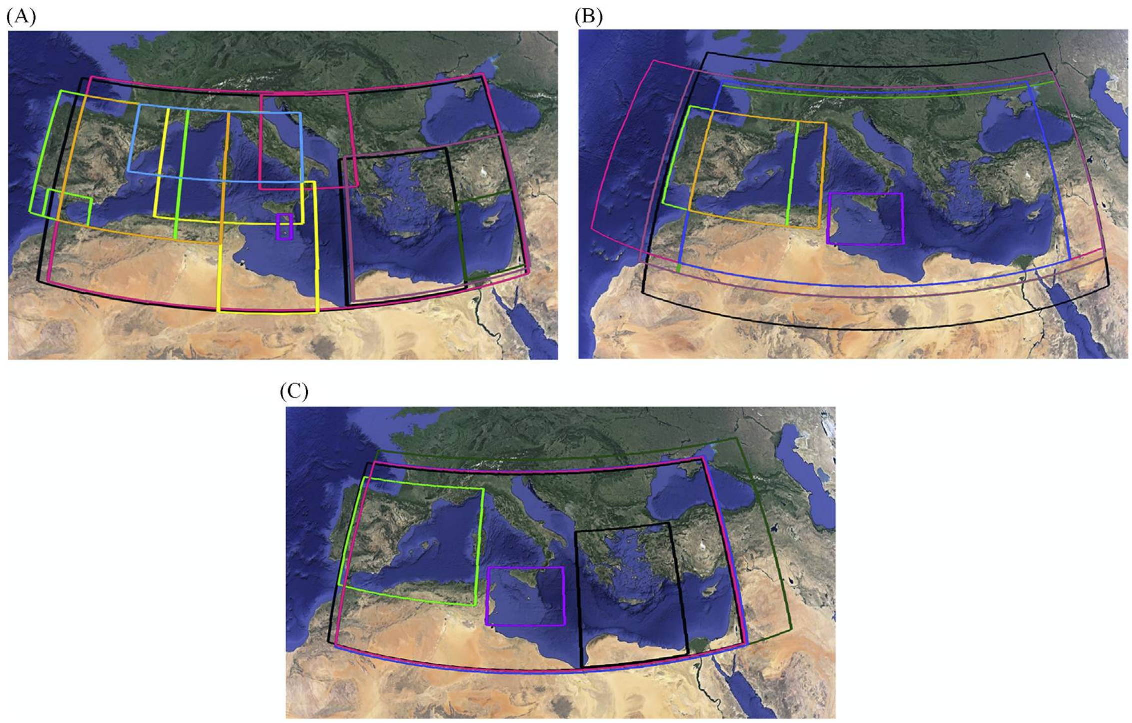

Fig. 2. (a) The Copernicus Med-MFCand the associated national downscaling hydrodynamic model domains of the MONGOOS network (14 in total), integrated with the MEDESS-4MS oil spill models.The basin scale Copernicus Med-MFC model resolution is approximately 6.5 km, while the regional/coastal scale, resolution ranges between 1 and 3.5 km. (b) The MONGOOS network atmospheric model domains (7 in total) integrated with the MEDESS-4MS oil spill models.The basin scale models resolution ranges between 5 and 25 km, while the regional/coastal scale, resolution is approximately 5 km. (c) The MONGOOS wave model domains (7 in total) integrated with the MEDESS-4MS oil spill models in order to take into account the Stokes drift. The basin scale models resolution ranges 5–10 km, while the regional/coastal scale, resolution ranges between 3.5 and 5 km.

Table 1b
The atmospheric models (7 in total), the corresponding domains and horizontal resolutions.

	ATMOSPHERIC FORECASTING SYSTEM	PROVIDER	GEOGRAPHIC COVERAGE	RESOLUTION
	POSEIDON	HCMR	Lon. [-10 42] °E; Lat.[26 50] °N	~5 km
	Skiron Non-Hydrostatic	OC-UCY	Lon. [-6 42] °E; Lat.[29 47] °N	~5 km
	ECMWF	INGV	Lon. [-19 42] °E; Lat. [30 48] °N	~25 km
	AEMET	PdE	Lon. [-9.5 5.5] °E; Lat. [35 44.5] °N	~15 km
	ARPEGE	Meteo-France	Lon. [-6 37]°E; Lat.[30 47.5]°N	~ 10 km
	SKIRON	IASA	Lon. [-11 42]°E; Lat.[29 48]°N	~ 10 km
	MALTA/Maria ETA Model	UOM	Lon. [10 18] °E; Lat. [33.75 38.25]°N	~ 4 km

Table 1c
The wave models (7 in total), the corresponding domains and horizontal resolutions.

	SEA STATE (WAVES) FORECASTING SYSTEM	PROVIDER	GEOGRAPHIC COVERAGE	RESOLUTION
	POSEIDON WAM Cycle 4 Mediterranean	HCMR	Lon.[-7 36]°E; Lat.[30.25 45.75] °N	~10 km
	POSEIDON WAM Cycle 4 Aegean	HCMR	Lon.[19.5 30]°E; Lat.[30.4 41]°N	~3.5km
	CYCOFOS WAM4Mediterranean	OC-UCY	Lon.[-6 42] °E; Lat.[30 47] °N	~ 5 km
	PdE-WAM	PdE	Lon.[-6.8 9]°E; Lat.[35.2 44.5]°N	~8 km
	PREVIMER-MENOR-WW3	IFREMER	Lon. [-6.00 36.50]°E; Lat. [30.00 46.00]°N	~10 km
	MALTA/Maria WAM1	UOM	Lon.[10.25 18]°E; Lat.[33.75 38.25]°N	~12.5 km
	Copernicus Med-MFC WWIII	INGV	Lon.[-6 36.25]°E; Lat.[30.1875 45.9375]°N	~ 6.5 km

forecasts are also provided to the service by the POSEIDON weather forecasting system (Papadopoulos et al., 2002) which covers an area broader than the Mediterranean basin (Table 1b). The sea state forecasting products are provided also for the Mediterranean and Aegean/Ionian Seas through the implementation of WAM Cycle 4 on a spatial resolution of 10 km and 3.5 km respectively (Table 1c).

Forecasting products from the Med-MFC, initially called Mediterranean Forecasting System (MFS; Pinardi et al., 2003; Pinardi

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and Coppini, 2010) and the high resolution Adriatic Forecasting System (AFS; Oddo et al., 2005, 2006; Guarnieri et al., 2008) are available to the MEDESS4MS through Istituto Nazionale di Geofisica e Vulcanologia (INGV). The Med-MFC is based on the NEMO Ocean General Circulation Model (OGCM) that it is implemented on a model domain of 6.5 km spatial resolution that covers the entire Mediterranean area (Table 1a), providing 10-days forecast on daily basis. The OGCM is coupled with an implementation of Wave Watch III (Tolman, 2002; Clementi et al., 2013) for the entire Mediterranean Sea and at the same resolution of the hydrodynamics. Med-MFC gives the initial and lateral boundary conditions for temperature, salinity and velocity to the Adriatic Forecasting system (AFS) model to produce the high resolution (2.2 km) forecasting products for the Adriatic Sea with ECMWF forcing.

Ocean forecasting for the Sicily Strait area and western Mediterranean Sea around Sardinia are delivered to the MEDESS4MS by CNR-IAMC, originated from two hydrodynamic sub-regional models, the Sicily Channel sub-Regional model (SCRM; Sorgente et al., 2011) and the sub-regional Western Mediterranean Model (WMED; Cucco et al., 2012) whose geographical limits and spatial resolutions are described in Table 1a. Both forecasting systems of the marine circulation at sub-regional scale (about 3 km) of the Sicily Strait area and of the seas of the Western Mediterranean around Sardinia are based on the three- dimensional primitive equation, finite difference hydrodynamic model named POM (Blumberg and Mellor, 1987). Actually, they produce a daily forecast, valid to maximum +120 h, forced at the sea surface by the high resolution weather forecast SKIRON (Kallos et al., 1997), through an interactive air-sea module. It provides daily 5-day forecast of atmospheric parameters at high frequency (hourly fields) with a horizontal resolution of 5 km. The atmospheric parameters include hourly fields of mean sea level pressure, air temperature at 2 m, wind speed and direction at 10 m, convective and accumulated precipitation, cloud cover, sensible and latent heat fluxes, incoming and outgoing shortwave and long-wave radiation fields and evaporation. At the open boundaries the two sub-regional models are nested with the forecast daily mean fields from the coarse resolution Med-MFC (Tonani et al., 2014), that are driven by conditions from the forecast fields of temperature, salinity and total velocity downscaled and optimized with VIFOP (Gabèrsek et al., 2007).

Forecasting products for the Eastern Mediterranean are available for the next 5 days by the Aegean Levantine Eddy Resolving Model (ALERMO; Korres and Lascaratos, 2003) which is operated by IASA. The ALERMO model consists of a high-resolution implementation of the POM applied in the Aegean–Levantine basins (Table 1a) with a horizontal resolution of 1/30° and 25 sigma levels in the vertical logarithmically distributed. Open boundary conditions are defined one-way nested with the Copernicus Med-MFC (Tonani et al., 2014). ALERMO is one-way coupled with the SKIRON weather forecasting system and it is initialized from the Copernicus Mediterranean model on a weekly basis. IASA supplies also atmospheric data to the service, which are produced by the SKIRON/Eta forecasting system (Kallos et al., 2005) at 10 km resolution for the Mediterranean (Table 1b).

The Cyprus Coastal Ocean Forecasting and Observing System products (CYCOFOS; Zodiatis et al., 2003, 2008, 2013, 2016) are delivered to the MEDESS-4MS service. Hydrodynamic data are provided from the CYCOFOS ocean model for the Levantine Basin and from the CYCOFOS high resolution system for the Aegean sea and the Levantine. The CYCOFOS model for the Levantine basin is based on the POM and is run daily on a $(1/60)^\circ \times (1/60)^\circ$ horizontal grid (~1.8 km resolution; Table 1a) with terrain following sigma levels. The model is nested to the Copernicus Med-MFC, while atmospheric forcing comes from the ETA atmospheric model used in the SKIRON system (Kallos et al., 2005). Oceanographic data regarding the wide area of Aegean–Levantine basin (see CYCOFOS CYPPOM in Table 1a) are also provided to the MEDESS-4MS service with $1/50^o \times 1/50^o$ resolution. Meteorological data produced by SKIRON non-Hydrostatic forecasting system in 5 km horizontal resolution are also supplied as well as wave data by CYCOFOS WAM4 for the Mediterranean in the same resolution (Table 1c).

Forecasts for the Western Mediterranean and for the Gibraltar Strait are generated from the Copernicus Iberian Monitoring and Forecasting Center IBI-MFC and the high resolution SAMPA ocean forecast system for the Gibraltar Strait area and they are delivered to the MEDESS4MS service by Puertos del Estado (PdE). The Copernicus IBI-MFC system is based on an eddy-resolving NEMO model application running at 1/36° horizontal resolution (Sotillo et al., 2015). A specific subset of this core IBI-MFC product, covering part of the western Med (Table 1a), is preprocessed and provided in the agreed formats and standards by PdE for MEDESS-4MS. The Copernicus IBI – MFC run is forced every 3 h with atmospheric fields provided by European Center for Medium Weather Forecasting (ECMWF). The SAMPA service is a local ocean forecast service operationally delivered by Puertos del Estado in daily basis for the Gibraltar Strait area. The SAMPA model system (Sánchez-Garrido et al., 2013) is based on the MITGCM model (Marshall et al., 1997). The model domain, centered in the Gibraltar Strait, covers the Alboran Sea and part of the Gulf of Cadiz (Table 1a). The model horizontal resolution varies with the maximum resolution of 400–500 m in the Strait of Gibraltar which gradually decreases to 8–10 km towards the open boundaries. The model is nested into the Copernicus IBI-MFC forecast products. PdE is also providing meteorological data for the Western Mediterranean produced by AEMET (ONR) (Table 1b). Wave data are distributed by PdE WAM wave forecasting model at 8 km resolution in the western Mediterranean domain (Table 1c).

Oceanographic forecasts for the Western Mediterranean are also available through WMOP (Western Mediterranean sea /Balearic operational system), the forecasting subsystem component of SOCIB-IMEDEA, the new Balearic Islands Coastal Observing and Forecasting System. The hydrodynamic forecasting component is based on a regional configuration of the Regional Ocean Modeling System (ROMS; Shchepetkin and McWilliams, 2005) and covers the geographical area from Gibraltar strait to Sardinia Channel (Table 1a) with a spatial resolution varying from 1.8 to 2.2 km and a vertical grid of 32 stretched sigma levels. The model is nested to the Copernicus Mediterranean Forecasting System.

Products of the PREVIMER Observation and Forecasting System are also delivered on a daily basis to the MEDESS-4MS by IFREMER. The oceanographic forecasts are provided by the PREVIMER-MENOR model which covers the northern part of the Western Mediterranean Sea (Table 1a) on 1.2 km spatial resolution and 60 sigma levels refined near the surface. Boundary conditions are provided by the Copernicus Med-MFC model. This configuration, based on a primitive equation model dedicated to regional and coastal modeling, is used for both operational purposes or academic research (Garreau et al., 2011; Schaeffer et al., 2011) Wave data for the whole Mediterranean (Table 1c)are also distributed to the MEDESS-4MS service, by PREVIMER-MENOR-WW3 at 10 km spatial resolution based on a Wave watch III configuration (Magne et al 2010). Both model are forced by the atmospheric model of the French Metoffice : ARPEGE.

Forecasting products for the Central Mediterranean region are delivered to the MEDESS-4MS service from ROSARIO II Malta Shelf Model, operated by UOM. It is an eddy-resolving primitive equation sigma level shelf-scale numerical model based on POM. It is run at two spatial resolutions $1/64^\circ \times 1/64^\circ$ and $1/96^\circ \times 1/96^\circ$ with a grid ratio of 1:2 with respect to the regional model in both cases, but to the MEDESS-4MS service are only provided data of 1/

$64^{\circ} \times 1/64^{\circ}$ ($\sim$1.5 km) spatial resolution. The Malta shelf model is forced at the surface by hourly high resolution forecast fields from the SKIRON atmospheric model, running operationally on a daily basis and released by the University of Athens. The ROSARIO II runs in the Malta Shelf Area (Table 1a) nested to the SCRM from CNR IAMC. Atmospheric and wave forecasting data are also distributed to the MEDESS-4MS service by UOM, produced by MALTA/Maria ETA Model (Table 1b) and MALTA/Maria WAM1 (Table 1c) for the central Mediterranean region.

Finally, Météo-France is contributing to the service with atmospheric outputs of the ARPEGE system for the entire Mediterranean basin (Table 1b). The numerical model ARPEGE is a global and spectral general circulation model. It has been developed for operational numerical weather forecast by Météo-France in collaboration with ECMWF (Reading, U.K.) (Deque et al., 1994). The initial conditions of the ARPEGE model are based on a 4 dimensional variational assimilation (4D-Var).

4. The oil spill models (OSMs) system component

From the point of view of oil spill models, few well established models have been used for years by member state agencies in the Mediterranean during major real oil spill incidents and they are all implemented in establishing the MEDESS-4MS service. They are as follows: MEDSLIK, MEDSLIK-II, MOTHY and Poseidon-OSM. These models are all Lagrangian particle models (the oil slick is discretized by numerical particles), but have very different numerical schemes and parameterizations for effects of waves, winds and in general the transformation of oil due to physical processes in the water. For the first time these models are consistently used in parallel and inter-compared as well as harmonized in data exchange. Furthermore, the MEDESS-4MS service offer the four of them (multi-model approach) to the users, coupled with different (from regional, sub-regional to coastal) operational ocean models, but harmonized in data exchange to suit the needs of the MEDESS-4MS service.

MOTHY is a 3D pollutant drift model implemented by Météo-France for the Mediterranean and the Black Sea, whereas the pollutants can be oil or floating objects. (Daniel, 2009, 1996). It has been operated since 1994 in the marine forecast section at Météo-France, and has been extensively used for the Erika and the Prestige incidents (Daniel, 2010). About 500 interventions each year are conducted with an averaged time response of 30 min. The geographical coverage includes the Mediterranean and Black Sea area, and the provided forecast length is 2 or 3 days for the most cases but probabilistic forecasts up to 10 days are also available. MOTHY does not use wave data to calculate the physical displacement of the oil parcels. Current in the mixed layer is computed using a combination of a shallow water model driven by the wind and the atmospheric pressure, coupled to an analytical turbulent viscosity model, so as to represent vertical current shear, and a background current provided by an oceanic model. A continuous profile from surface to bottom describes the water column. Additional oil spill model capabilities can also be supported such as beaching, sedimentation, backtracking, as well as the double choice for the definition of the pollutant as oil or a floating object.

MOTHY has been validated during major real oil spill incidents such as the Erika (1999) (Daniel et al., 2001) and the Prestige (2002). Furthermore the model has been used in several intercomparison exercises in a number of European funded projects.

MEDSLIK-II, implemented at INGV in Bologna (Italy), is designed to predict the transport and weathering of an oil spill, using a Lagrangian representation of the oil slick (De Dominicis et al., 2013a) and is an open source code version of MEDSLIK. It simulates the transport of the surface slick governed by the water currents and by the wind in the entire Mediterranean Sea. Oil particles are also dispersed by turbulent fluctuation components that are parameterized with a random walk scheme. In addition to advective and diffusive displacements, the oil spill particles change due to various physical and chemical processes that transform the oil (evaporation, emulsification, dispersion in water column, adhesion to coast).

MEDSLIK-II includes a proper representation of high frequency currents and wind fields in the advective components of the Lagrangian trajectory model, the introduction of the Stokes drift velocity and the coupling with the remote-sensing data.

The geographical coverage of MEDSLIK II implementation includes the entire Mediterranean Sea.

MEDSLIK-II performance has been validated both during real incidents (the Lebanese oil pollution crisis in summer 2006, Coppini et al., 2011) and validation exercises using drifters, remote sensing data and in situ data acquired during several cruises organized in the framework of European and Italian funded projects, like the Serious Game exercise in the Tuscan Archipelago in May 2014 for the project MEDESS-4MS, described in De Dominicis et al. (2016).

MEDSLIK-II has also been used to forecast the possible spill of the 2500 tons of oil from the Costa Concordia, assuming a continuous oil release. Every day, until the unloading operations had run out, a bulletin with the forecast scenario for the next 72 h has been released to the competent authorities (De Dominicis et al., 2014).

MEDSLIK-II is a freely available community model and can be downloaded from the following website: http://medslikii.bo.ingv.it.

The *POSEIDON Oil Spill Model* has been implemented at the Hellenic Centre for Marine Research (HCMR) and it is used operationally for the Aegean and Ionian Seas (Polani, 2001, Perivoliotis, 2011). It is a fully 3D oil spill model capable to simulate the movement, spreading and aging of the oil particles in the 3-D space. The entire mass of the oil is represented by a large number of material particles or parcels, each of which represents a group of oil droplets of like size and composition. The oil transport is described by two modules, the circulation module and the wind generated waves module. The horizontal displacement due to advection and the vertical transport of the oil are calculated using the output of the oceanographic model. The net current speed caused by linear waves (Stokes drift) is calculated using the wave model output.

The POSEIDON-OSM is capable to simulate several process of the oil spill weathering transformation in the marine environment such as the evaporation, the emulsification, the beaching and the sedimentation. POSEIDON OSM is a standard module of the POSEIDON Operational Oceanography System that has been implemented and operated in the Greek Seas since 2000. The POSEIDON OSM was the forecasting component of MARCOAST integrated oil spill service which is operationally provided in the Aegean Sea during three years period (2006–2008). This later service was an integration of the oil spill detection processes that was applied on satellite based SAR images together with the forecast of oil spill evolution which was provided by the HCMR oil spill system. The core user of this service was the Marine Environment Protection Division (MEPD) of the Greek Ministry of Mercantile Marine, which is the responsible authority for the surveillance of the Greek Seas. The user received near real-time (in one hour after satellite overpass) synthetic information concerning the oil spill detection and the relevant forecasts in the Aegean Sea through a dedicated web site and was alerted by e-mail/fax/telephone of new information posted to the site

MEDSLIK is the oil spill model, which is implemented and operationally used by the response agencies in Cyprus, Israel and

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Malta in the frame of contingency plans (Lardner et al., 1998). MEDSLIK oil spill and trajectory model is a 3D model that predicts the transport, fate and weathering of oil spills (http://www.oceanography.ucy.ac.cy/medslik/). The model is currently used in operational mode in the Levantine Sea although it is also implemented in a pre-operational mode in the rest part of the Mediterranean and the Black Sea. The oil spill movement is simulated by MEDSLIK using a Monte Carlo method. The pollutant is divided into a large number of Lagrangian parcels of equal size. At each time step, each parcel is given a convective and a diffusive displacement. Furthermore, the oil is considered to consist of a light evaporative component and a heavy non-evaporative component. Emulsification is also simulated, and the viscosity changes of the oil are computed according to the amount of emulsification and evaporation of the oil. The model simulates slick transports and takes into account the movement of the surface slick is governed by currents, waves (Stokes drift) and wind, while the diffusion of the slick is simulated by a random walk (Monte Carlo) model. The oil may be dispersed into the water column by wave action but the dispersed oil is moved by currents only. Mechanical spreading of the initial slick is also included. The forecast length varies from few hours up to 3 weeks, but using the 'restarting' facility of the model the forecast length can be extended further depending on the end user application requirements and the forcing availability.

The MEDSLIK model has been extensively validated along the Mediterranean sea both in real oil spill incidents (i.e., the Lebanese oil pollution crisis in 2006 and through EMSA-CSN warning reports and satellite images SAR (Zodiatis et al., 2007, 2012). Also, the model has been used in different model inter-comparison exercises where observations from drifters (ARGOSPHERE and SVP) were used. MEDSLIK-II is an open source code version of MEDSLIK.

5. Network Data Repository system component

A Network Data Repository (NDR) is a core component of the MEDESS-4MS oil spill prediction system. Its main function is the integration of the oil spill models with the different met-ocean data providers. Its secondary function is to catalogue the different oil spill events using the system for historical needs. All the data from the different type of modeling and observing systems of the MEDESS-4MS are managed through the NDR, using the harmonized data formats for all the 28 met-ocean forecasting systems of MONGOOS network providing data to MEDESS-4MS, as well as harmonized data formats for input and outputs of oil spill modelling into an integrated data warehousing facility (Fig. 3). All developments based on state-of-the-art technologies such as OPeNDAP and NetCDF standards, which are in wide use in operational oceanography. Use of such standards in MEDESS-4MS allow to be at the forefront of technological developments years after the lifetime of the project. This facility allows for the storage/archive of data but also for its search, discovery and visualization through the User Interface (UI). Such a capability allows users, involved in oil spill monitoring and forecasting for operational or emergency management purposes, to have unified access to all necessary data concerning their operations.

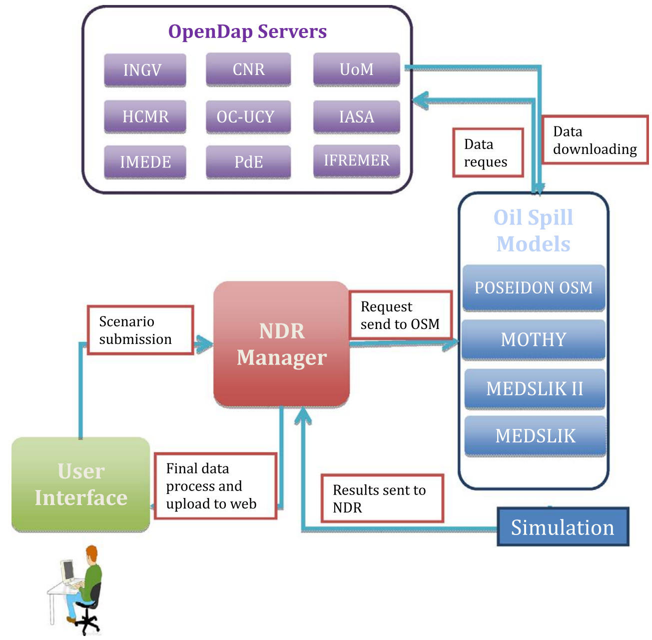

Fig. 4. MEDESS-4MS Network Data Repository.

The NDR manager is the central facility that integrates the different parts of the NDR. It connects to the UI to interact with the user, communicates with the data and oil spill model servers to transfer data, initiate the oil spill forecasting and download the results. The description of the workflow of the NDR is provided in the Appendix A and graphically illustrated in Fig. 4.

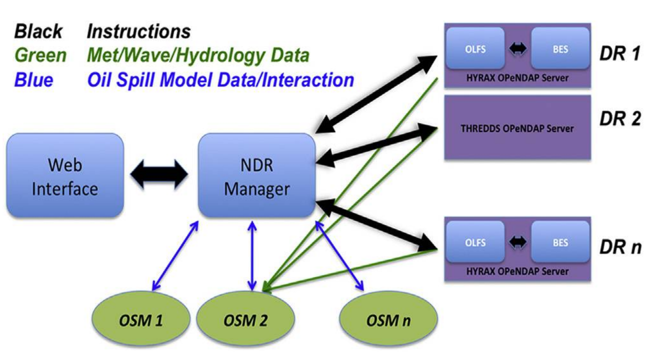

Fig. 3. Flow schematic of NDR showing different components, and paths of data flow (OSM: Oil Spill Models, DR: Data Repository, BES: Back-End Server, and OLFS: OpenDAP Lightweight Frontend Servlet).

6. User interface system component

The NDR is connected to the UI, the web portal of MEDESS-4MS service, which provides to the user different service scenarios, multi-model data access and interactive capabilities including a multilayer operational Geographical Information System. The UI allows real time activation of the MEDESS-4MS in emergency situations through automatic simulations following reported spills (via satellite image or reports), or in delayed mode with simulations using archived environmental data for processing past oil spill observations and for hazard-risk assessment purposes and contingency planning.

The MEDESS-4MS service can provide different services in order to assist operational response agencies—

(1) The real time automatic service provides oil spill forecasts, starting from oil slick observed by satellite. This service concerns the operational monitoring and forecasting of the Mediterranean Sea, in order to connect timely detected oil slicks to oil spill models, and provide rapid predictions of the movement of spilled oil. This service is designed for the users with operational responsibility. In the case of service (1) the activation of the MEDESS-4MS system is automatic upon the receipt of the satellite information.

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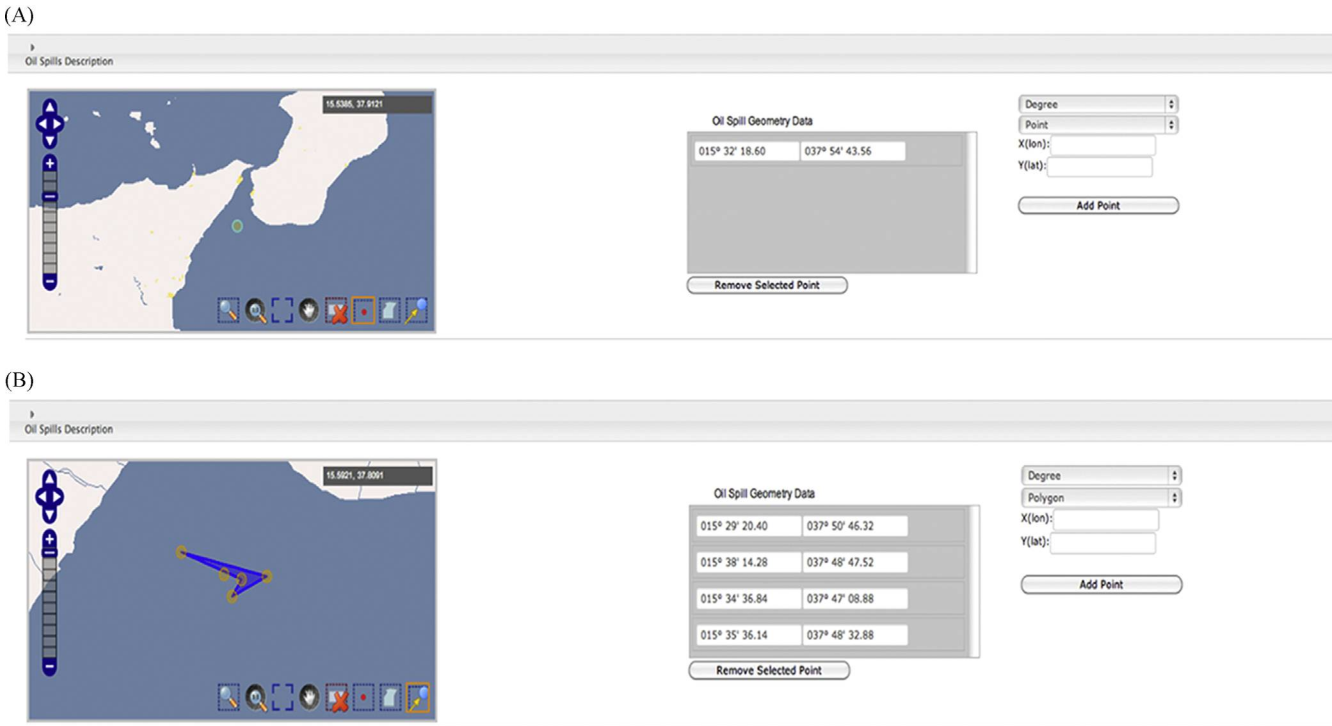

Fig. 5. MEDESS-4MS User Interface – input panel: insertion of input data for a point source (a) and a polygon source (b).

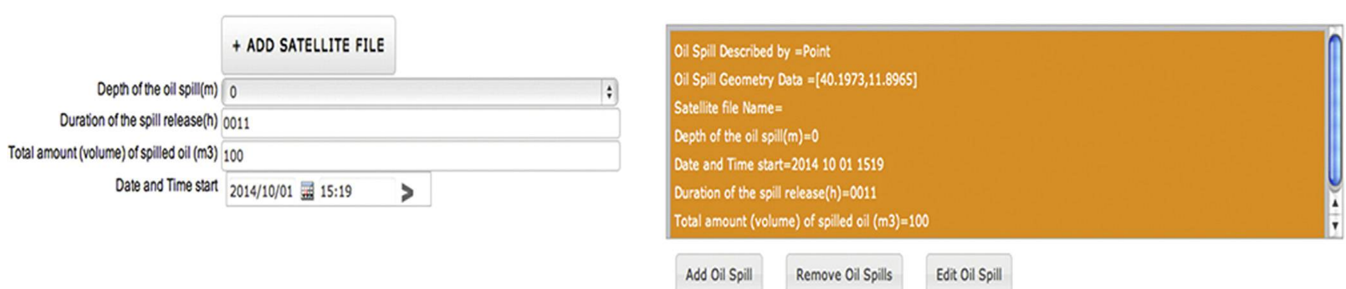

Fig. 6. MEDESS-4MS User Interface – input panel: insertion of oil spill descriptors (depth of the oil spill, time of start/observation, duration of release, volume).

(2) The delayed mode service allows oil spill simulations using historical met-ocean data. This service is mainly aimed at processing of past observations, performing a large number of simulations randomly varying the environmental data used to transport the oil. In the framework of this service, one can determine most likely spill paths for spills on a monthly and seasonal basis and simulate probabilities of oiling the water surface and shorelines. The service allows the hazard assessment of a particular site to oil spills. This solution is intended for the use of REMPEC or generic users interested in oil pollution risk/hazard assessment for specific areas.

(3) The real time management of emergency situations service allows any user to access the UI and to perform an oil spill simulation in real time. This service is mainly devoted to assist the decision makers involved in real time management of emergency operations. Through the UI of the service any user can launch a set of simulations using different oil spill models and met – ocean forecast data.

The description of the UI interface is provided in the Appendix B and illustrated in Figs. 5–11.

7. MEDESS-4MS capabilities and validation

7.1. MEDESS-4MS multi-model inter-comparison

The MEDESS-4MS unique capability of choosing among 28 different model data sets of various resolutions provides to the end user the opportunity to use the best available resolution for each case, and giving the essential elements of uncertainty estimation for the oil spill forecast.

Fig. 12a and b illustrates the oil spill evolution in the dynamic marine environment of the Alboran Sea, close to Gibraltar Strait, after a hypothetical accident of 10,000 tons on 28 May 2014, using the POSEIDON OSM under met-ocean forcing from 2 data sets with different horizontal resolution: the lower resolution case (ocean hydrodynamics from the Copernicus MED-MFC with 6.5 km horizontal analysis, atmospheric forcing from ECMWF winds with horizontal resolution of 25 km and waves from the Puertos del Estado WAM with 8 km resolution), and higher resolution (ocean currents from the Puertos del Estado SAMPA with 1 km spatial resolution, atmospheric forcing from AEMET with horizontal analysis of 12 km and waves from POSEIDON with 10 km resolution). It is evident that the higher resolution hydrodynamic model currents can describe better the mesoscale

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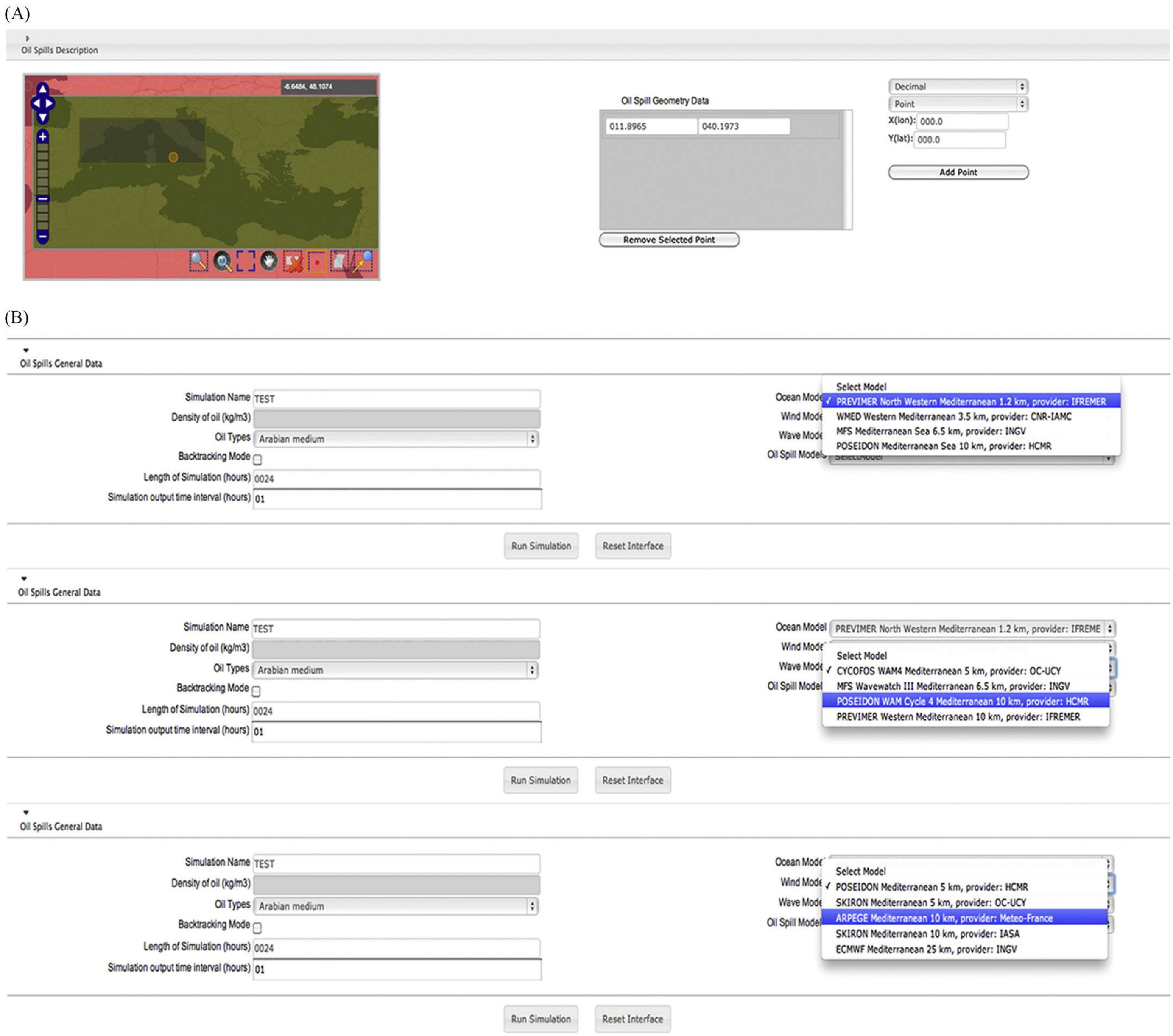

Fig. 7. MEDESS-4MS User Interface – input panel: automatic selection of the best available met-ocean models (a), drop-down menus for the user-defined selection of ocean model.

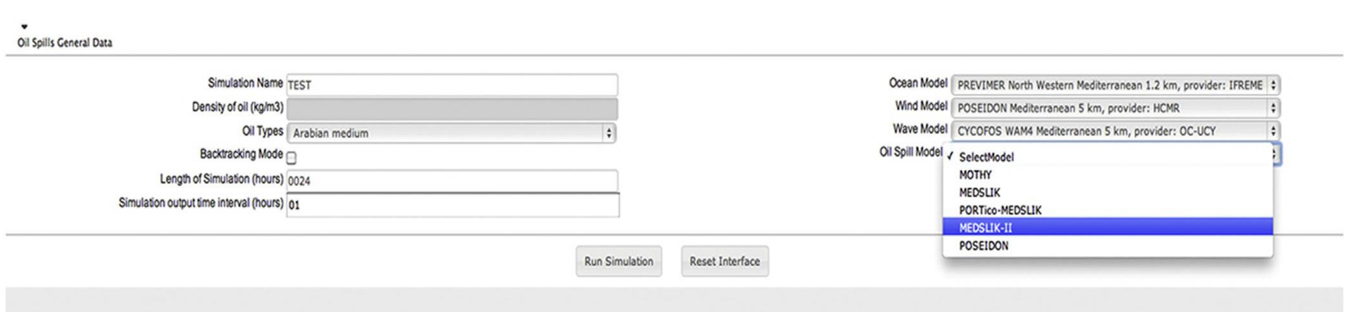

Fig. 8. MEDESS-4MS User Interface – input panel: selection of the oil spill model to be used.

activity, particularly when in-situ data are regularly assimilated, consequently providing a more realistic oil spill dispersion pattern. Nevertheless, if the hydrodynamical pattern of the area under investigation is not correctly forecasted, then the higher resolution model may give an even worse result. Therefore, the models have to be tested against the in-situ observations, in a way similar to Liu et al. (2014).

The values of the fate processes in the case of the lower resolution ocean forcing, 1 June 2014, after 96 h of simulations, is 21.2%

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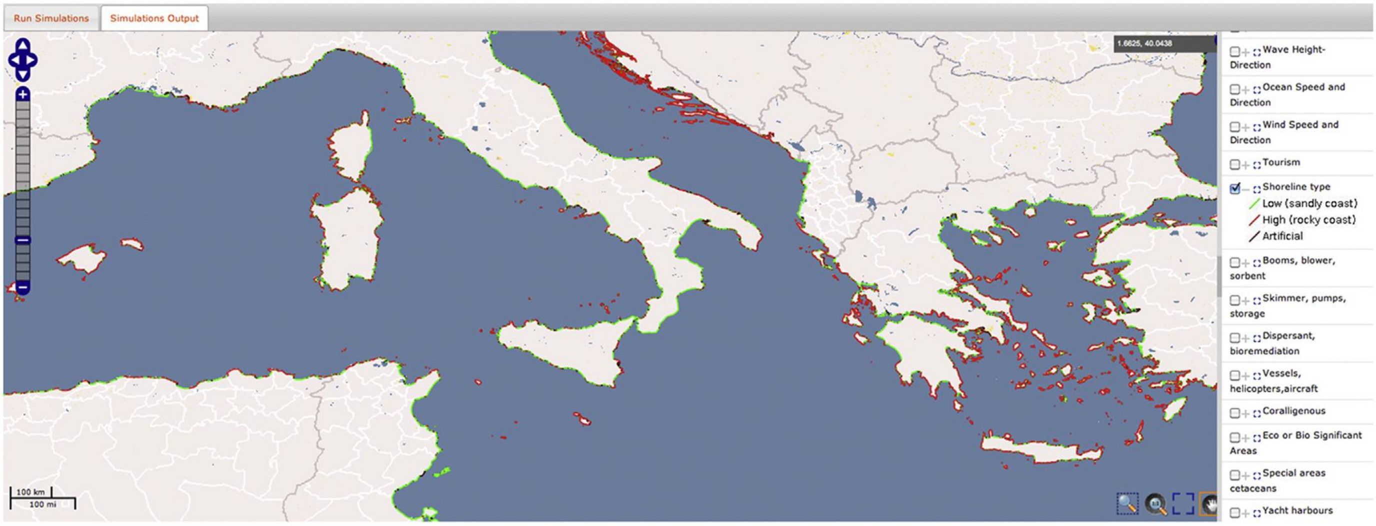


Fig. 9. MEDESS-4MS User Interface – output panel: shoreline types - sandy coast (green), rocky coast (red) and artificial coastline (black) (source of data ENI). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

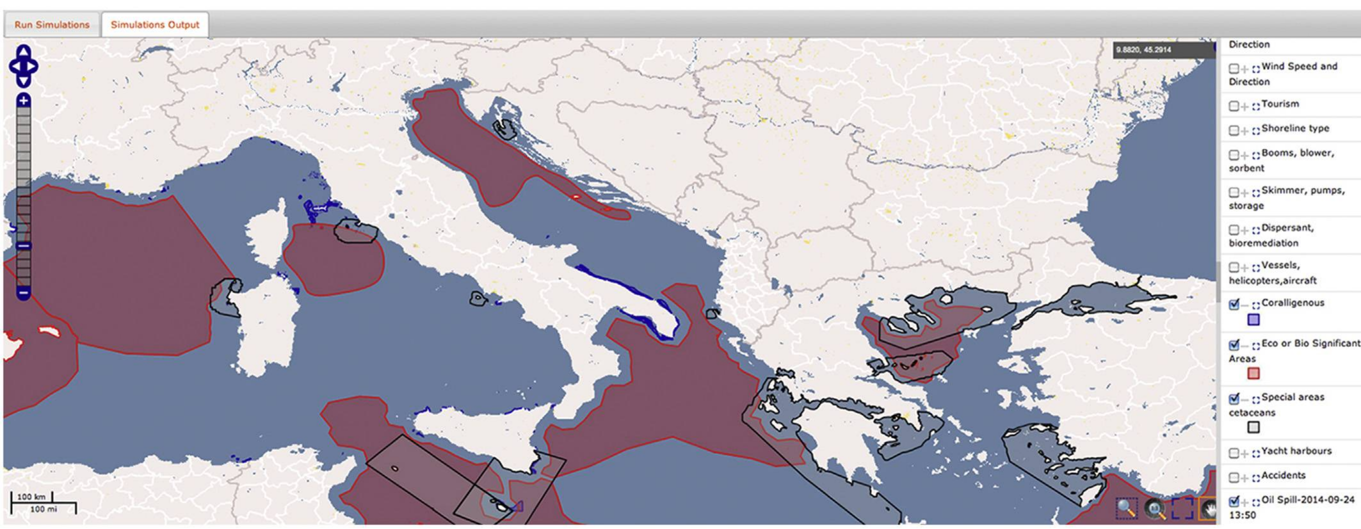


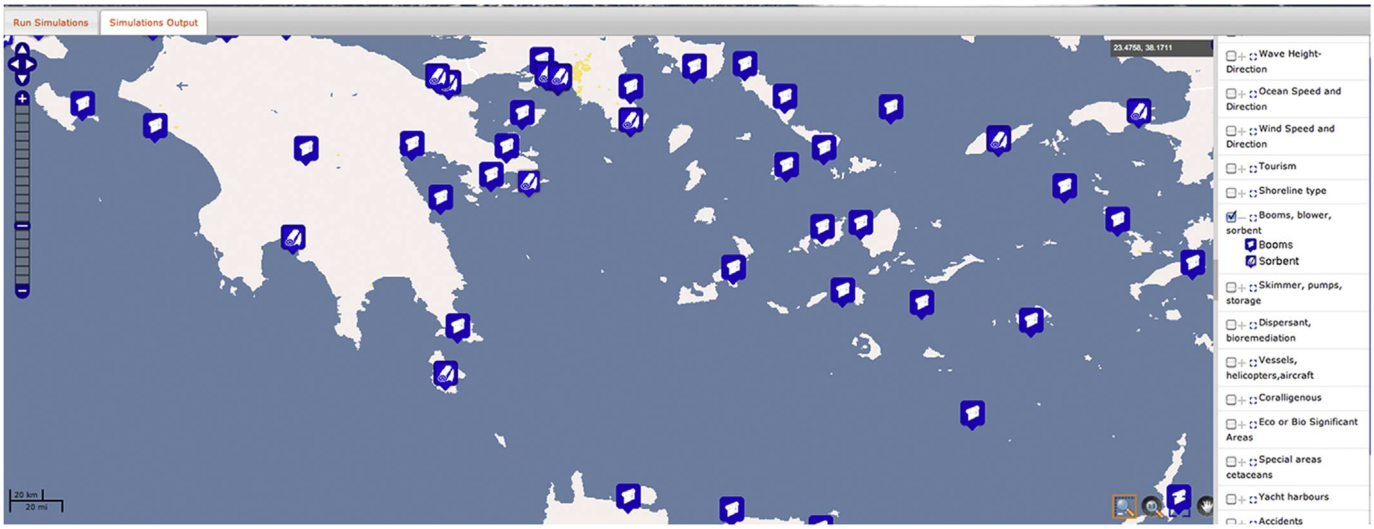
Fig. 10. MEDESS-4MS User Interface – output panel: coralligenous areas are marked in blue, ecological or biological significant areas are marked in red and special areas for cetaceans are marked in black (source of data SPA/RAC). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

for evaporation, 66.7% for emulsification and 78.8% for oil remained at sea surface, are almost the same with the relevant values obtained in the case of higher resolution ocean forcing, 21.3%, 66.6% and 77.7%, respectively.

Fig. 13a and b shows the oil spill fate in the Ionian Sea after a hypothetical accident of 10,000 tons released at sea during a period of 48 h on 28 May 2014, using 2 different oil spill models, the POSEIDON-OSM and MEDSLIK. Both models used the same met-ocean forcing: the low resolution ocean forcing from the Copernicus Med-MFC product with 6.5 km horizontal analysis, the atmospheric forcing from ECMWF winds with horizontal resolution of 25 km and waves from Copernicus Med-MFC Wave Watch III with horizontal resolution 6.5 km. It is evidently that both oil spill models after 148 of simulations show the oil spill to move in the same eastward direction, with the MEDSLIK to provide a smoother displacement of the dispersed oil spill, along the periphery of an anticyclonic vortex. Moreover, the values of the fate processes differs between the 2 cases: POSEIDON-OSM scores for the evaporation and emulsification are lower than MEDSLIK ones (25.6% and 66.7% compared to 35.8% and 70.8% respectively) and this results to higher amount of the oil remained at the sea, that is, 74.4% with POSEIDON-OSM and 63.5% with MEDSLIK. The above deviations in the estimated values are probably due to the different configuration of the oil spill numerical models (different formulas are used for the calculation of evaporation and emulsification, specific hydrodynamic processes are also described differently) and further examination is needed together with in-situ data in order to reach to a concrete conclusion, since such kind of analysis was beyond the aim of the MEDESS4MS project.

Fig. 14a and b shows the oil spill evolution in the complicate physiography of the central Aegean Sea (Cyclades), after a hypothetical accident of 10,000 tons on 28 May 2014, using the POSEIDON OSM under 2 different met-ocean forcing data sets with different horizontal resolution: the lower resolution case (ocean forcing from the POSEIDON Med product with 10 km horizontal analysis, atmospheric forcing from POSEIDON weather winds with horizontal resolution of 5 km and waves from the POSEIDON WAM Med with 10 km resolution), and higher resolution forcing (ocean currents from the POSEIDON Aegean with 3.5 km spatial resolution, atmospheric forcing from POSEIDON weather with horizontal

(A)



(B)

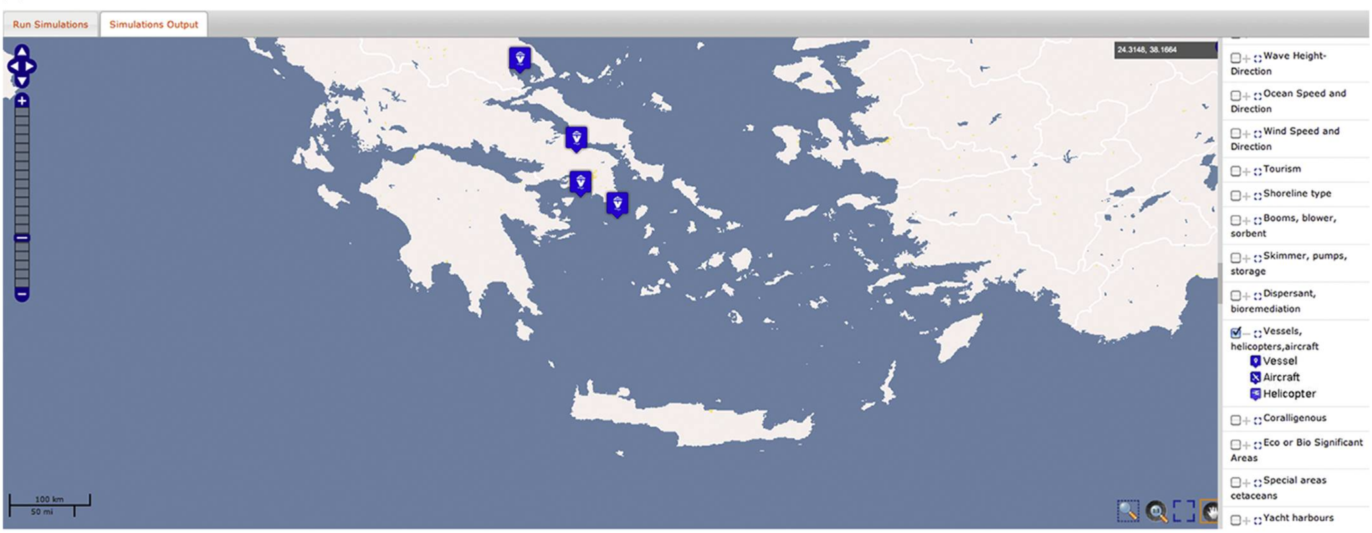


Fig. 11. MEDESS-4MS User Interface – output panel: booms, blower and sorbent (a), anti-pollution vessels, helicopters and aircraft (b).

analysis of 5 km and waves from POSEIDON WAM Aegean with 3.5 km resolution). It is evident that the higher resolution hydrodynamic model in areas with complicate coastlines, as for example in the Cyclades with many small islands scattered around, the higher resolution met-ocean data sets can describe better the local currents, and consequently the oil spill dispersion pattern. The values of the fate processes on the 1 June 2014, after 96 h, in the case of the higher resolution forcing, was 33.1% for evaporation and 66.4% for emulsification, while in the case of lower resolution forcing was 31.8% and 66.2% respectively, that is, the obtained values were close. However, in the case of the higher resolution forcing the oil spill predictions is considered more accurate, because the coastline is better resolved, therefore the beached oil was estimated to be 2.1% while in the lower resolution case the beached oil reached 10.7%.

7.2. MEDESS-4MS system validation trough exercises at sea: serious Games

The MEDESS-4MS functionalities were tested through a series of field experiments, called Serious Games, using drifters and oil slicks satellite observations in different areas of the Mediterranean Sea. Main scientific outcomes of these validation exercise are presented in De Dominicis et al. (2016), Sorgente et al. (2016), Capó et al. 2016 and Sotillo et al. (in this issue).

An additional exercise in connection with the RAMOGEPol exercise took place in Portoferraio north of the Elba island between 16 and 17 September 2014. The RAMOGEPol exercise is organised annually by the Italian Ministry of Environment in cooperation with the Government of France, Italy, Monaco and Spain in the framework of the trilateral RAMOGE Agreement with a view to evaluate the efficiency, organisation and coordination of the arrangements in place between the Parties to the Agreement (i.e., Italy, France and Monaco), in the field of preparedness for and response to marine pollution from ships. The Italian Ministry of the Environment kindly accepted to participate with ITCG, Cedre and INGV to test the tool developed under MEDESS-4MS project during the aforementioned real scale exercise. The fictitious scenario chosen for the exercise involved a collision between an oil tanker carrying Arabian crude and a container ship. During this phase, the Italian Ministry for the Environment activated the RAMOGEPOL Plan to seek assistance from neighbouring states in managing this event. Three OCEANIA Buoys Long Rang (LR), equipped with satellite transmission to track the oil spill on long

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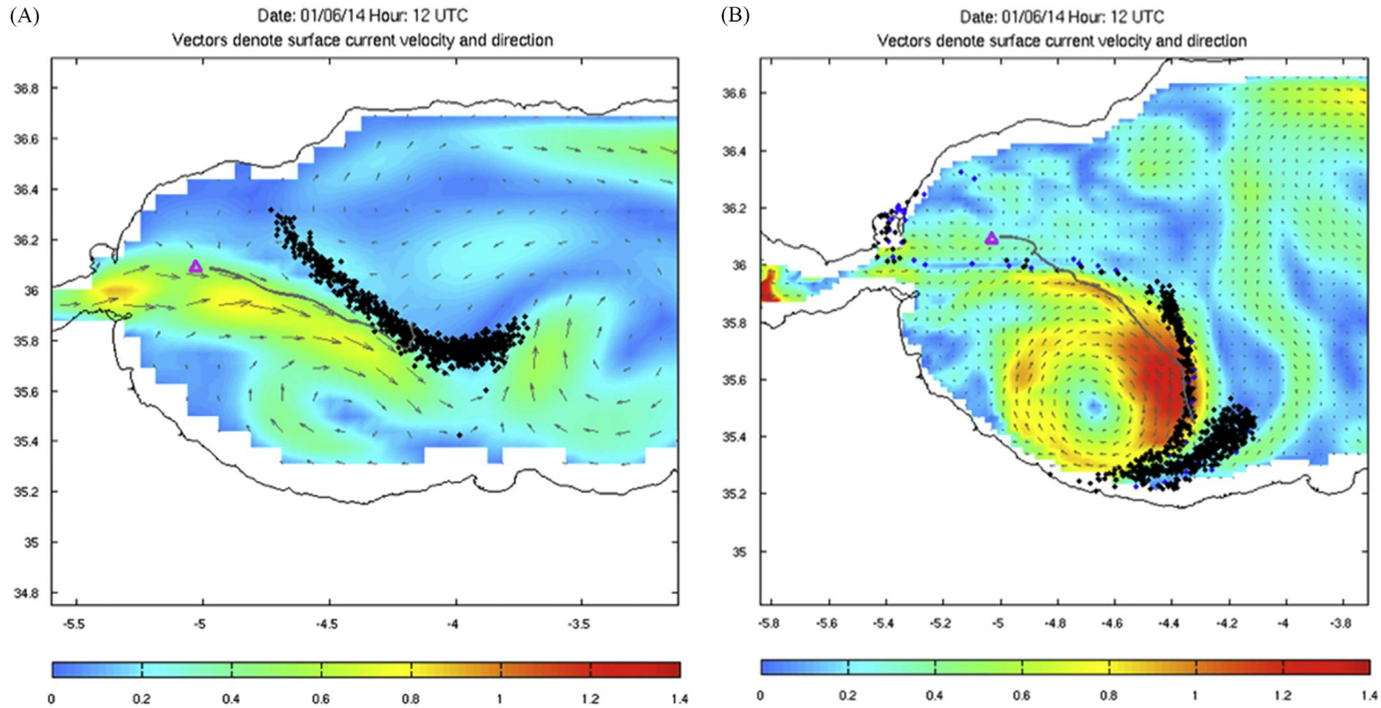

Fig. 12. Oil spill predictions in the Alboran Sea, date of hypothetical event 28 May 2014 using the POSEIDON-OSM for 96 hours of simulation with a) Lower resolution hydrodynmics data set (Copernicus Med-MFC) and b) Higher resolution hydrodynamics data set (SAMPA).

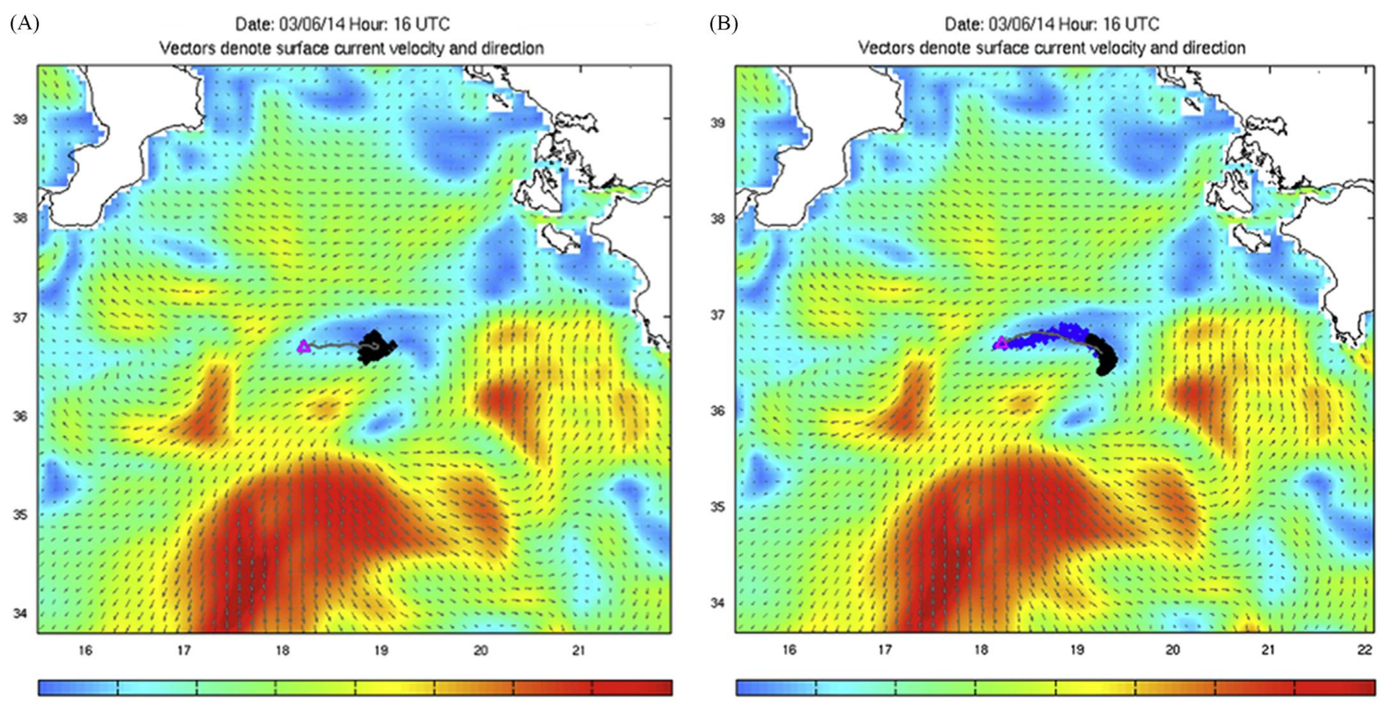

Fig. 13. Oil spill predictions in the Ionian Sea, date of hypothetical event 28 May 2014 using the same met-ocean forcing data set (Copernicus Med-MFC and ECMWF) with (a) POSEIDON-OSM and (b) MEDSLIK.

range at any distance, were released by the Cedre representative from the ITCG's vessel into a rice hulls, used as pollutant at the fictitious accident position.

The aims of this release were: to check on whether the buoys would behave as the pollutant-like substance by showing a similar drift and to follow on real time their positions and compare their trajectory with the predictions from the forecasting models. These exercise thus also tested the MEDESS-4MS oil spill forecasting capabilities, by using its oil spill forecasting tools based on met-ocean models available in the area as well as the MEDESS-4MS oil spill models. The satellite transmitting buoys showed a similar drift to the rice hull. All three buoys remained in the path of the pollutant-like substance throughout the duration of the exercise (6 h). These types of buoys thus reflected the reality of the rice hull

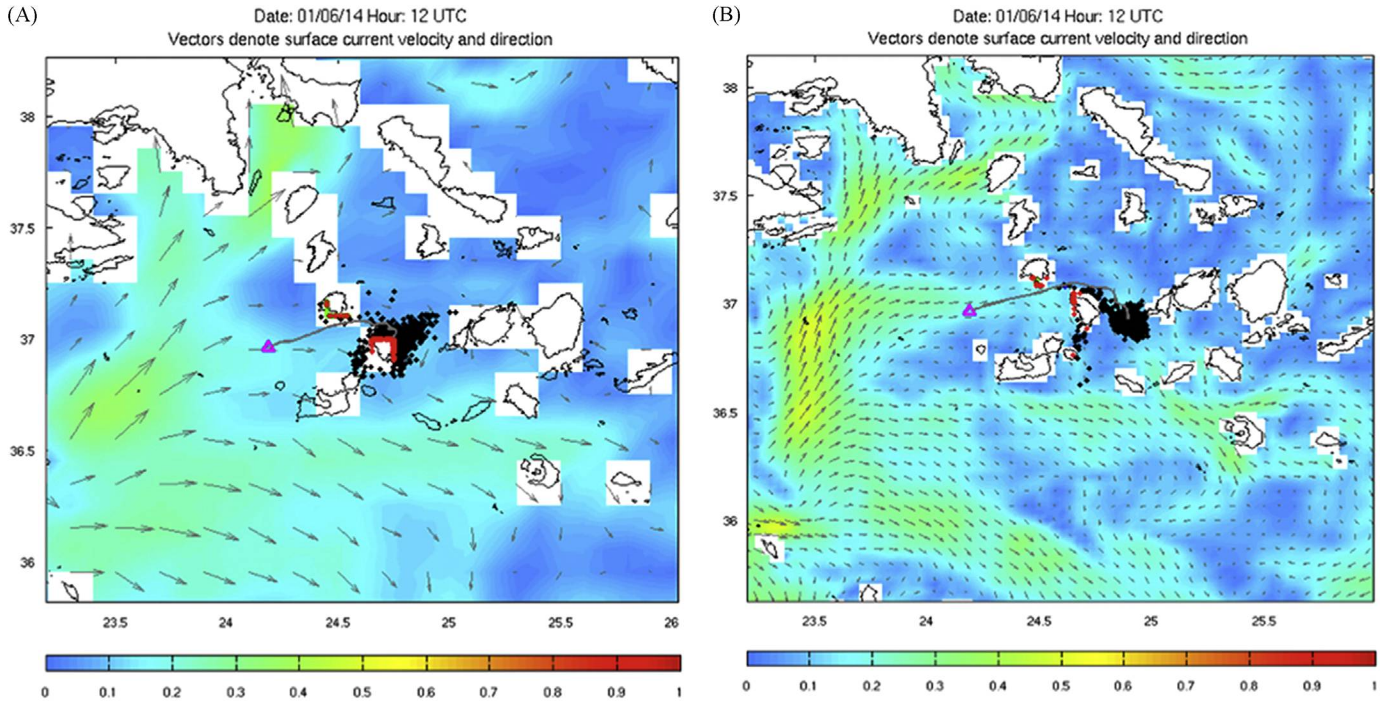

Fig. 14. Oil spill predictions in the Aegean Sea (Cyclades), date of hypothetical event 28 May 2014 using the POSEIDON-OSM for 96 h of simulation with (a) Lower resolution hydrodynamics data set (POSEIDON Med) and (b) higher resolution hydrodynamics data set (POSEIDON Aegean).

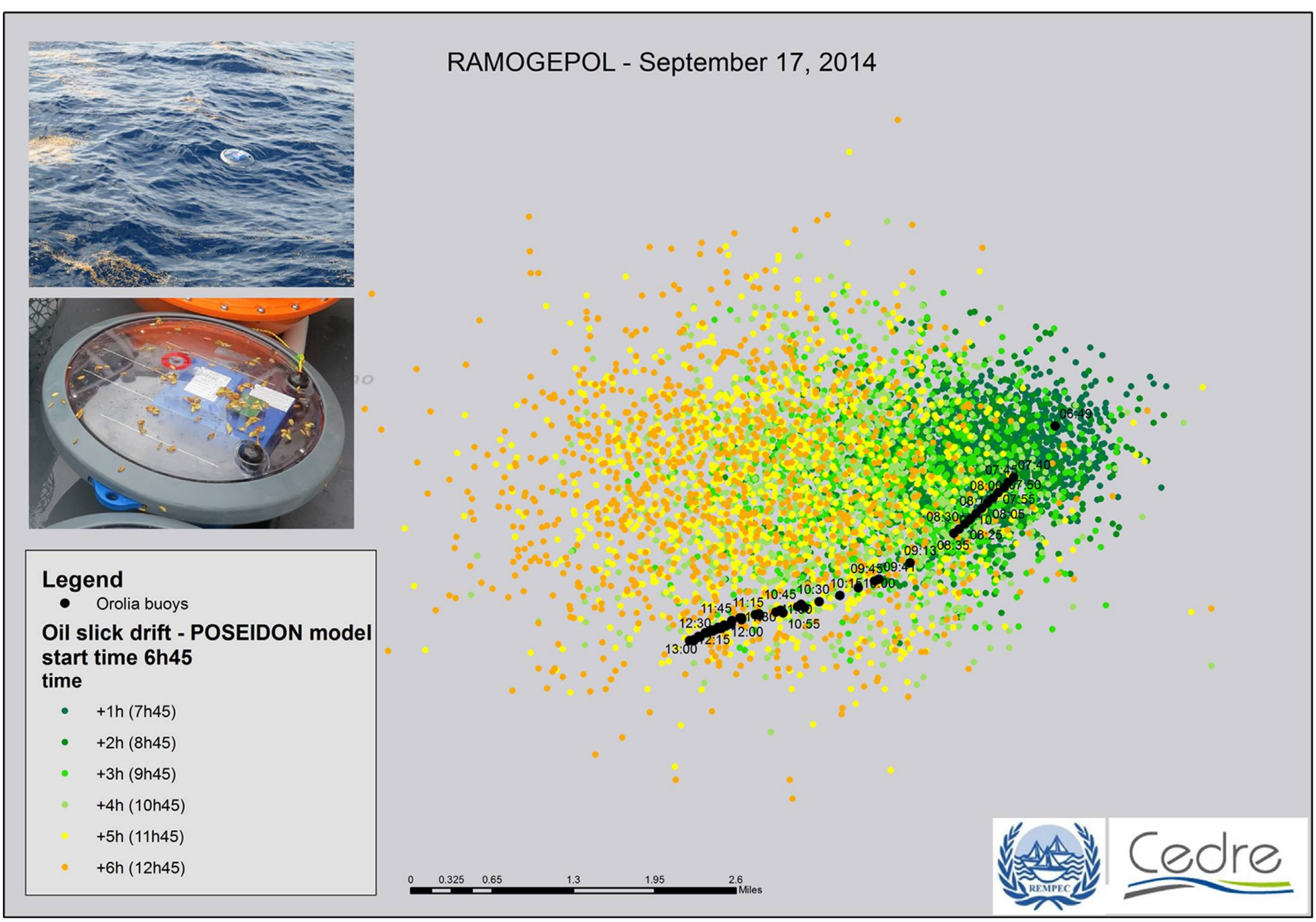

Fig. 15. Map representing the buoys trajectories from 17 September 2014 at 6:45 up to 12:30 compared with the MEDESS-4MS's predictions.

drift, and therefore could be considered to monitor the drift of a pollutant whose behavior is similar to the rice hull. The POSEIDON Oil Spill Model (POSEIDON-OSM) was chosen during the exercise through the MEDESS-4MS User Interface amongst the other oil spill forecasting models available in the system. The drift of the satellite transmitting buoys was compared with the drift of the trajectory provided by MEDESS-4MS-OSM. Both have similar south-westward trajectories as shown in Fig. 15. It can be assumed that MEDESS-4MS-OSM predicted in a correct manner the drift of the rice hull, the pollutant-like substance of the exercise.

8. Conclusions

MEDESS-4MS service is dedicated to the maritime risks prevention and strengthening of maritime safety related to oil spill pollution in the Mediterranean. MEDESS-4MS delivers an integrated operational multi-model oil spill prediction service in the Mediterranean, connected to existing monitoring platforms (EMSA-CSN and REMPEC), using the well established oil spill modeling systems (MEDSLIK, MEDSLIK-II, MOTHY, and Poseidon-OSM), the data from the Copernicus Med-MFC and the national operational oceanographic forecasting systems of the MONGOOS network. MEDESS-4MS provides 3 services scenarios to the key and general users; real time oil spill forecasting by authorized users; delayed mode by authorized users and Oil Spill Decision Support System, for selection of management strategies.

MEDESS-4MS addressed several challenges concerning the integration of operational ocean forecasts with the oil spill models, the operational access to the input and output data vise-versa and the user interface accessing the oil spill predictions in near real-time. The final interconnection of the four different oil spill models with the 28 forecasting systems along the Mediterranean was made possible by implementing common specifications for all the different modules of the system (common input/output files, common naming of the products and the available parameters, common format of the provided files, common protocol for data exchange, common rolling archive for keeping history of the results).

The several milestones that were accomplished in order the MEDESS-4MS service to be delivered are presented hereafter:

- Real time environmental data from the Copernicus Med-MFC complemented with best information from the downscaled national ocean forecasting systems of the MONGOOS network; all 28 different environmental data sets were gathered in the frames of the MEDESS-4MS project and are delivered in a daily basis through the service's OpenDap servers under the same common specifications.
- Unique access multi-model solution to oil spill prediction was set up; 4 different oil spill dispersion models were implemented to be capable of simulating the fate of oil spills using all the available Mediterranean environmental data under the common specified format.
- It was designed and implemented a unique web portal access point for end-users that allow the rapid exploitation of oil spill forecasting products. Support for non-EU countries which compose at least half of the riparian countries of the Mediterranean is now available for the first time ever.
- The NDR component was developed in order to provide the necessary connection and management of all the individual components of the system and bring the MEDESS-4MS network to service. The interconnection of all the different parts of the service is shown in Fig. 4.
- A series of field experiments were conducted in several regions of the Mediterranean Sea (Serious Games), offering valuable data for the validation of the service throughout a long period of testing (Targeted Operational Period).
- The connection between the EMSA's oil spill satellite detection and the MEDESS-4MS forecasting networks were developed, providing to the European Maritime Safety Agency a valuable tool; The oil dispersion forecasting service is directly linked to CleanSeaNet service and capable of making available in a short notice forecasting reports for the satellite detected oil spill's fate in the next critical hours.

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Appendix A

The workflow of the NDR

The NDR manager is built using the Python programming language, Mongo DB (Plugge et al., 2010) for the backend database, and Flask (Grinberg, 2014) to provide the web hooks to the UI. Connections to the forecasting data servers are achieved using the OPeNDAP protocol using routines implemented in Python. The workflow of the NDR is graphically illustrated in Fig. 4. When an oil spill forecast is requested via the UI, the NDR manager first checks the existence of the relevant meteo-oceanographic files on the OPeNDAP server. It then creates a list of the data files to be downloaded for the forecasting, copies it along with the input data file to the oil spill model server, and then initiates the forecast run. Communication to the oil spill server to copy data and start the simulation is done using the secure shell (SSH) libraries wrapped with Python routines. Once the forecasting is completed, the output file is copied to the NDR manager, and the results are converted to the NetCDF format for visualization using the UI. The run details and files are then archived in the database catalogue. If any part of the forecasting run fails, appropriate error messages are generated instead of the output file to be communicated back to the user so they make take appropriate action.

Appendix B

The description of the UI

The User Interface (UI) is composed of two main panels: the input and the output panel. For service (2) and (3) the activation of the service is manually carried out by a user and it is performed in three main steps. From the input panel, the first step to be accomplished by the user is the definition of the oil spill geometry: single or multiple points, single or multiple polygons (areal source of oil, e.g., in the case of aerial observation of the oil slick), mixed source (multiple/single points or polygons). The above choices can be done by using a clickable map by manually inserting in an editable box the coordinates of the point(s) or the vertexes of the polygon(s) composing the slick (Fig. 5).

The second step is the specification of some oil spill descriptors: depth of the oil spill, time of start/observation, duration of release, volume and type of oil (Fig. 6).

Once the first two steps have been accomplished the oil spill is fully described and the MEDESS-4MS system automatically selects the best ocean, wind and wave models that are available for the given oil spill positions. The best guess is made by localization and accuracy (higher resolution models are chosen) of the models (Fig. 7a).

The user can also change the ocean, wind and wave models, that were automatically selected by the system (Fig. 7b).

At this stage only few parameters regarding the simulation settings have to be specified: the simulation name, the type of the requested simulation (forward or backward), the simulation duration (for how long the user wants to have the forecast) and the requested time step (interval between the output images) and finally the oil spill model to be used has to be chosen by the user (Fig. 8). The backward mode provides useful qualitative information for the possible identification of the source of the oil pollution towards the identification of the responsible of the pollution through the estimation of the date and position of the origin of the oil spill.

Finally, when the user click on the Run simulation button, the information are forwarder to the NDR, and from there to the Oil Spill Models (OSM) servers. From the output panel, the user can follow the progress of the simulation. Once it is completed the user can visualize the evolution in time of the oil spill position and concentration together with additional met-ocean information (wave height and direction, the ocean currents and its intensities, wind speed and direction). In order to evaluate the impact on the marine environment and coastal human activities the oil propagation can be overlaid with socio-economic and environmental data: touristic areas, type (Fig. 9), coralligenous, ecological or biological significant areas (Fig. 10), special areas for cetaceans.

For specific users it also allowed to access the information on the location of response equipment: booms, blower, sorbent, skimmer and pumps storages, dispersant and bioremediation storages, anti-pollution vessels, helicopters and aircraft (Fig. 11a and b)

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