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Scientific management of Mediterranean coastal zone: A hybrid ocean forecasting system for oil spill and search and rescue operations

A. Jordi [a,*], M.I. Ferrer [a], G. Vizoso [a], A. Orfila [b], G. Basterretxea [a], B. Casas [a], A. Álvarez [a], D. Roig [a], B. Garau [a], M. Martínez [a], V. Fernández [a], A. Fornés [a], M. Ruiz [a], J.J. Fornós [c], P. Balaguer [a], C.M. Duarte [a], I. Rodríguez [d], E. Alvarez [d], R. Onken [e], P. Orfila [f], J. Tintoré [a]

[a] *IMEDEA (CSIC-UIB), Institut Mediterrani d'Estudis Avançats, Miquel Marquès 21, 07190 Esporles, Illes Balears, Spain*
[b] *School of Civil and Environmental Engineering, Cornell University, 14853 Ithaca (NY), USA*
[c] *Departament de Ciències de la Terra, UIB, Crta. Valldemossa, km 7.5, Palma de Mallorca, Illes Balears, Spain*
[d] *Área del Medio Físico, Puertos del Estado, Antonio Lopez 81, Madrid E-28026, Spain*
[e] *Institute of Coastal Research, GKSS Research Centre, Max-Planck-Strasse 1, 21052 Geesthacht, Germany*
[f] *D.G. Emergències, Conselleria d' Interior del Govern de les Illes Balears, Spain*

Abstract

The oil spill from *Prestige* tanker showed the importance of scientifically based protocols to minimize the impacts on the environment. In this work, we describe a new forecasting system to predict oil spill trajectories and their potential impacts on the coastal zone. The system is formed of three main interconnected modules that address different capabilities: (1) an operational circulation sub-system that includes nested models at different scales, data collection with near-real time assimilation, new tools for initialization or assimilation based on genetic algorithms and feature-oriented strategic sampling; (2) an oil spill coastal sub-system that allows simulation of the trajectories and fate of spilled oil together with evaluation of coastal zone vulnerability using environmental sensitivity indexes; (3) a risk management sub-system for decision support based on GIS technology. The system is applied to the Mediterranean Sea where surface currents are highly variable in space and time, and interactions between local, sub-basin and basin scale increase the non-linear interactions effects which need to be adequately resolved at each one of the intervening scales. Besides the Mediterranean Sea is a complex reduced scale ocean representing a real scientific and technological challenge for operational oceanography and particularly for oil spill response and search and rescue operations.

Keywords: Oil spill; Risk assessment; Operational oceanography; Currents; Search and rescue; Mediterranean Sea

1. Introduction

Marine pollution was highlighted on November 2002 by the *Prestige* tanker accident off the northwest Spanish coast. This incident was preceded by similar ecological disasters such as the *Exxon Valdez* in USA (1989), the *Aegean Sea* in Spain (1992) and the *Erika* in France (1999). The Mediterranean Sea has kept relatively free from those accidents, although some accidents like the oil spills from the tankers *Haven* and *Lyria* and the *Eshkol* power station caused several damage (Guidetti et al., 2000; Ezra et al., 2000). However, accidental oil spills only account for a 5% of total oil pollution hiding the regular pollution in frequented sea routes generated by oil drillings or illegal discharges (Alpers and Huhnerfuss, 1988; Pavlakis et al., 2001). The Mediterranean is an important traffic

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[*] Corresponding author. Fax: +34 971611761.
E-mail address: vieaajb@uib.es (A. Jordi).

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zone for oil tankers allowing access to Southern Europe, North Africa, The Middle East and The Black Sea. Besides a high number of oil-related sites (pipeline terminals, refineries, offshore platforms, etc.) concentrate along the coastal zone. Furthermore, moderate pollution of petrogenic source has been detected in harbors of the Mediterranean Sea, probably also caused by oil spills (De Luca et al., 2004). As a result, the Mediterranean Sea is a particularly vulnerable area due to the different types of potential spills and to its semi-enclosed nature. Therefore, new scientifically based tools for adequate response and coastal management are specially needed.

Prediction of oil spill trajectories is essential to manage adequately the response in the coastal zone. A review of numerical models used to simulate the movement and fate of oil released into the sea was carried out by the National Research Council (NRC, 2003). Theses models are usually based on a pollutant dispersion model forced by winds provided by an atmospheric model and currents provided by an ocean circulation model. Spaulding et al. (1996) integrated the spill modeling with a wide variety of supporting models (ocean coastal circulation, meteorological, biological effects, tactical response) to provide real time support during actual spill events. It is important that these models adequately reproduce the interactions between large-scale circulation and coastal currents in order to lead to realistic forecasts. During the *Prestige* accident, good forecasting of the spread of the oil spill was only obtained when the general circulation near the Spanish coast (*Navidad* current) was adequately resolved (Garcia-Soto, 2004).

The interaction between scales is especially relevant in the Mediterranean Sea, where several temporal and spatial scales (basin, sub-basin and local) interact to form a highly variable general circulation (Fernández et al., 2005). The Mediterranean Sea is a complex and variable ocean system, where the circulation is strongly affected by frontal dynamics through mesoscale features that can give rise to a wide range of ocean variability. Currents are of the order of one quarter to half knot, mostly driven by density differences located over the slope areas. Theses coastal currents are strongly affected by frontal dynamics through mesoscale features that can give rise to transient currents of opposite direction and speeds higher than one knot (Orfila et al., 2004). In addition to this buoyant forcing, the ocean–atmosphere interaction mechanisms are very intense both at the synoptic and the slowly varying atmospheric variability scales (Korres et al., 2000). Thus, the ocean prediction problem in the Mediterranean Sea at short and medium time scales requires the modeling of the large spatial and long time scales, as well as the local and short scales. The in-depth knowledge of oceanographic phenomenology, circulation and variability in the Mediterranean Sea acquired at IMEDEA during the last two decades is a pre-requisite for adequate forecasting of the ocean state (Orfila et al., 2004).

The objective of this paper is to describe a new hybrid ocean forecasting system that was initially developed during the *Prestige* accident and its application to the Mediterranean Sea. The system adequately addresses the different physical processes affecting the drift of spills and more generally drifting objects, which opens the possibility of supporting a wide range of scientific and operational services and applications (oil spill monitoring, marine safety, search and rescue operations, etc).

2. Description of the system

The structure of the hybrid forecasting system for oil spill or search and rescue operations is presented in Fig. 1. The system is based upon three main components: (1) an operational circulation sub-system to predict wind, currents and waves; (2) the analysis of the drift of objects and spills, including the interaction with sensitive coastal areas; (3) a GIS-based risk assessment module. Each subsystem is composed by one or more modules that interact between them.

2.1. Operational circulation sub-system

The goal of the operational sub-system is to provide, in near-real time, reliable information and forecasts for marine environmental conditions, to support all kind of activities at sea. We next present the three main modules that compose this sub-system.

2.1.1. Coastal ocean forecast

The coastal ocean forecasting module is based on a hierarchy of numerical models and a set of forecasting tools (Fig. 2). The numerical part is composed of several nested models that can be applied at different scales (from the overall basin to near-shore scales) to adequately solve the processes that determine the circulation in the Mediterranean Sea. The different numerical models are based on well established applications carried out at different scales ranging from basin, sub-basin, local and near-shore in the last 10 years at IMEDEA (Table 1). This module is directly connected at basin scale to the Mediterranean Forecasting

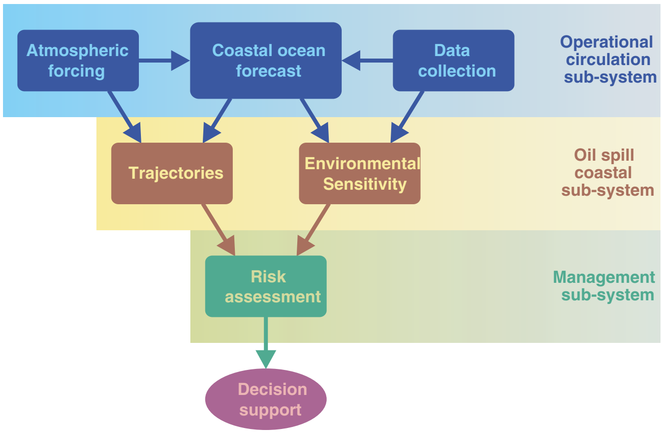

Fig. 1. Structure of the hybrid forecasting system for oil spill or search and rescue operations.

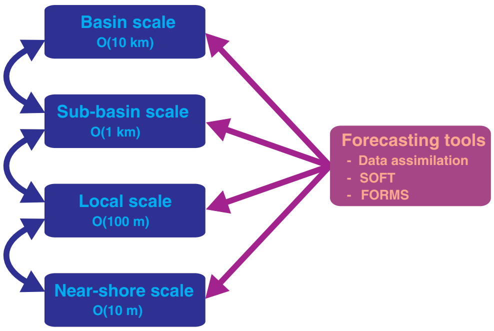

Fig. 2. Structure of the coastal ocean forecast module.

System (MFS, that currently produces ten-day ocean forecasts for the whole Mediterranean Sea once a week, Pinardi et al., 2003) and to the operational wave forecasting system of *Puertos del Estado* (Carretero et al., 2000). The references cited in Table 1 show that the mean large-scale circulation is modified at sub-basin scale and gives rise to highly variable mesoscale structures that interact with the slope circulation and topographic structures such as canyons or capes. They also show that successful applications at local and near-shore scale need to include the importance of see breeze and near-shore currents for water quality control.

The forecasting tools include capacities for near-real time data assimilation together with new tools for initialization and/or assimilation of satellite data based on genetic algorithms and feature-oriented strategic sampling. SOFT is a Satellite Ocean Forecasting Tool developed at IMEDEA based on non-linear prediction techniques like genetic algorithms that has been successfully used to forecast future states of ocean currents at the specific sub-basins of Alborán, Ligurian, and Adriatic Seas (Álvarez et al., 2004). The assimilation of these satellite based forecasts into the numerical models improves the forecasting skill of such models. Also, an important part of this module is a generic and portable methodology to initialize and/or to update fields for a coastal ocean model called FORMS for Feature-Oriented Regional Modeling Sampling. This approach is developed via observations of the synoptic structures in the region objectively analyzed with appropriate background climatology to generate the combined circulation variability (Gangopadhyay and Robinson, 2002).

2.1.2. Ocean observations

Ocean observations are mostly based on sensors and observing platforms (Fig. 3) that monitor the ocean variability. These data are required by any ocean forecasting module to correct deviations between model prediction and real ocean evolution due to the non-linear nature of the ocean. Spatial and temporal resolution of ocean observations depends on the observing platform employed. Table 2 shows the different applications carried out in the last years at IMEDEA at different scales. New ocean observing platforms able to carry out ocean measurements at high spatial and temporal resolutions have been developed. These platforms include Gliders, Autonomous Underwater Vehicles (AUVs), Autonomous Surface Vehicles (ASVs) and buoys, and their continuous use will represent a major breakthrough in ocean observation in the forthcoming years.

2.1.3. Atmospheric forcing

Improvements in numerical weather prediction models have given access to surface fluxes with high temporal and spatial resolution and sufficient quality to use them as forcing terms in ocean models. We use the 6 h operational analyses from the European Center for Medium-Range Weather Forecasting (ECMWF) and from Instituto Nacional de Meteorología (INM). An air–sea interaction sub-model computes air–sea fluxes of momentum, heat and water from the atmospheric forcing. The spatial resolution of atmospheric forcing ranges from 0.05° to 0.5°. Higher resolution atmospheric data are of great interest in particular to monitor adequately the variability at sub-basin and local scales.

2.2. Oil spill coastal sub-system

This sub-system incorporates the information associated with the response to oil spills and is composed of two

Table 1
Numerical models used and applications at different spatial scales

Scale	Area	Model	Resolution	Application
Basin	Western Mediterranean Sea	MOM	~15 km	Alvarez et al. (1994)
	Mediterranean Sea	DieCAST	~12 km	Dietrich et al. (2004)
	Mediterranean Sea	DieCAST	~12 km	Fernández et al. (2005)
Sub-basin	Blanes Canyon	Wang	~1.6 km	Ardhuin et al. (1999)
	Palamós Canyon	Wang	~1 km	Jordi et al. (2005b)
	Balearic Sea	HOPS	~2.1 km	Onken et al. (2005)
	Tunisia-Sardinia-Sicily Region	HOPS	~1.5 km	Onken et al. (2003)
Local	South of Mallorca	FUNDY	~300 m	Werner et al. (1993)
	Santa Ponça Bay	FUNDY	~50 m	Basterretxea et al. (2005)
	Port of Cabrera	FUNDY	~50 m	Orfila et al. (2005b)
Near-shore	Magalluf beach	Lynett	~10 m	Basterretxea et al. (2004)

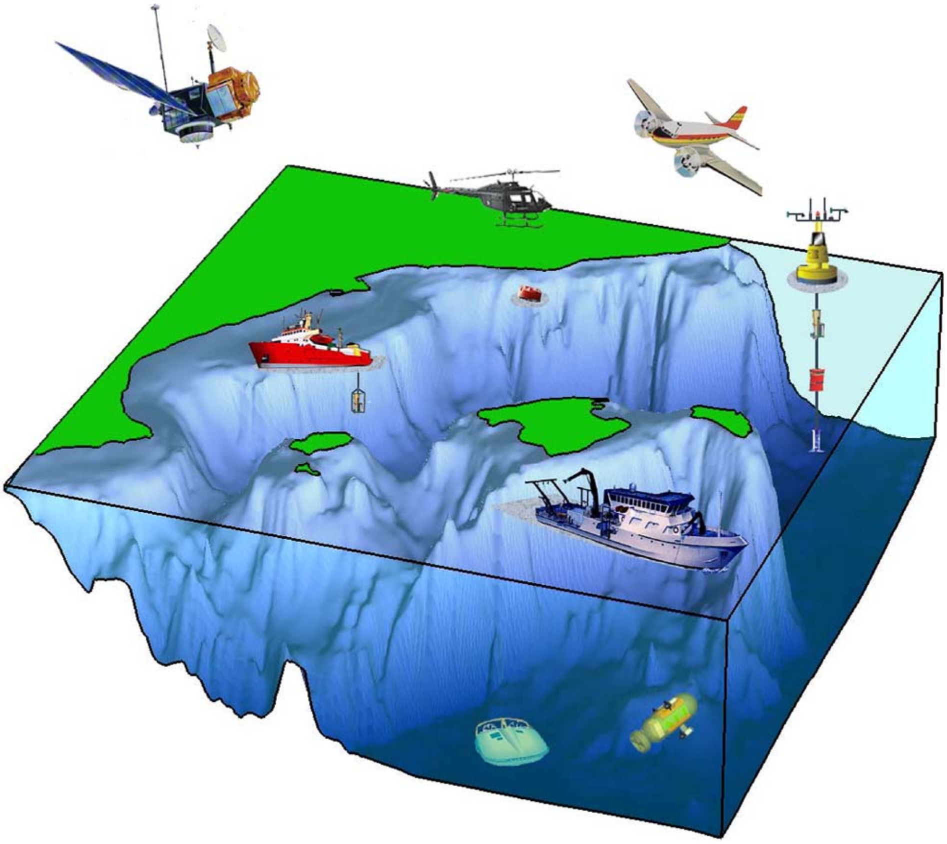

Fig. 3. Schematic view of the observing platforms used by the hybrid ocean forecasting system.

Table 2
Observing platforms used and applications at different spatial

Scale	Area	Platform	Sensor	Application
Sub-basin	Palamós Canyon	Ship	CTD	Álvarez et al. (1996)
	Catalan and Gulf of Lion shelves	Moorings	Currentmeters and pressure gauges	Jordi et al. (2005a)
	Ligurian Sea	Satellite	SST and SLA	Orfila et al. (2005a)
	Alborán Sea	Ship	CTD, ADCP	Rodríguez et al. (2001)
	Balearic Sea	Ship and aeroplane	CTD, ADCP and AXBT	Pinot et al. (1995)
Local	Santa Ponça Bay	Moorings	Currentmeters and biological sampling	Basterretxea et al. (2005)
	Port of Cabrera	Moorings	Currentmeters and termistor chain	Orfila et al. (2005b)
Near-shore	Magalluf beach	Moorings	Wave recorder and topographic leveling	Basterretxea et al. (2004)

modules. The first one predicts the spill trajectory taking into account the physical and chemical processes affecting the oil. The second evaluates the coastal zone vulnerability combining physical, biological, geological and socio-economic parameters of the coastline into a single environmental sensitivity index related to oil spills.

2.2.1. Trajectories

The trajectories module predicts the drift on the ocean surface and is based on the General NOAA Oil Modeling Environment (GNOME), which uses the standard Eulerian/Lagrangian approach to pollutant modeling with the regional ocean characteristics simulated as Eulerian fields within which the pollutant's Lagrangian elements move (Beegle-Krause, 2001). The model includes processes affecting the oil and other hydrocarbons into the sea such as turbulent diffusion, weathering, wave stress, wave compression, Stokes drift, dispersion, over-washing, surface drift, and Langmuir circulation, see the review of Reed et al. (1999) for detailed description. There are six product types and one non-weathering type for oil spill simulation. Initial spill distribution can vary in space (point, line, or sprayed distributions) and in time (point and line sources simulate instantaneous spills or spills over time). The model tracks the mass balance of the floating, beached and evaporated oil, as well as the uncertainty associated with the trajectories.

2.2.2. Environmental sensitivity

Environmental Sensitivity Index (ESI) identifies vulnerable coastal locations to the effects of an oil spill, so that protection priorities can be established and cleanup strategies identified. It is determined by the relationship between the physical make up of the shore, biological resources, geological characteristics and areas of socio-economic importance. The physical characteristics are comprised of the relative exposure to waves, climate conditions and the water residence time of semi-enclosed areas. The biological resources are ranked according to their sensitivity to the oil spilled (*Posidonia oceanica* meadows or wetland vegetation), the use of the shoreline by oil-sensitivity animals, the presence of rare and endangered species and special status areas (natural parks, marine reserves). The geological characteristics include different coastal environments (rocky shores, sandy beaches, etc.), the sediment type, the natural persistence of oil, and the ease of cleanup. The areas of socio-economic importance are the regions that support high intensity recreational use like touristy beaches, cultural and archaeological sites, commercial areas, etc.

2.3. Management sub-system

The management sub-system is based on a geographical information system (GIS) for oil spill crisis management. GIS are a useful tool for storing, analyzing and displaying data in order to support decisions about use and management of marine resources, such as organization of the spill recovery and for short term environment protection planning. GIS have been increasingly used in conjunction with oil spill modeling tools as a means of integrating and processing spatial data inputs to the numerical modeling and for assessing about potential impacts of the oil spill on the coast. This sub-system therefore, incorporates all the available information and identifies resources at risk, establishes protection priorities and identifies appropriate response.

3. Application to the Bay of Palma

In this section we present an application of the system to the Bay of Palma, an area of high socio-economic interest and strong dependence on tourism located in the southern shelf of Mallorca in the Balearic Islands (Fig. 4). The Bay of Palma is a frequent route for oil shipments which supply with hydrocarbon products the population of Mallorca and as a result, we have examined the potential impact on the coast of an accidental spill.

Before describing the different forecasting models used it is important to establish the major oceanographic conditions in the area and their variability, conditions that always need to be adequately considered prior to any modeling study. We do not reproduce here details about these conditions, but they can be found at local scale Werner

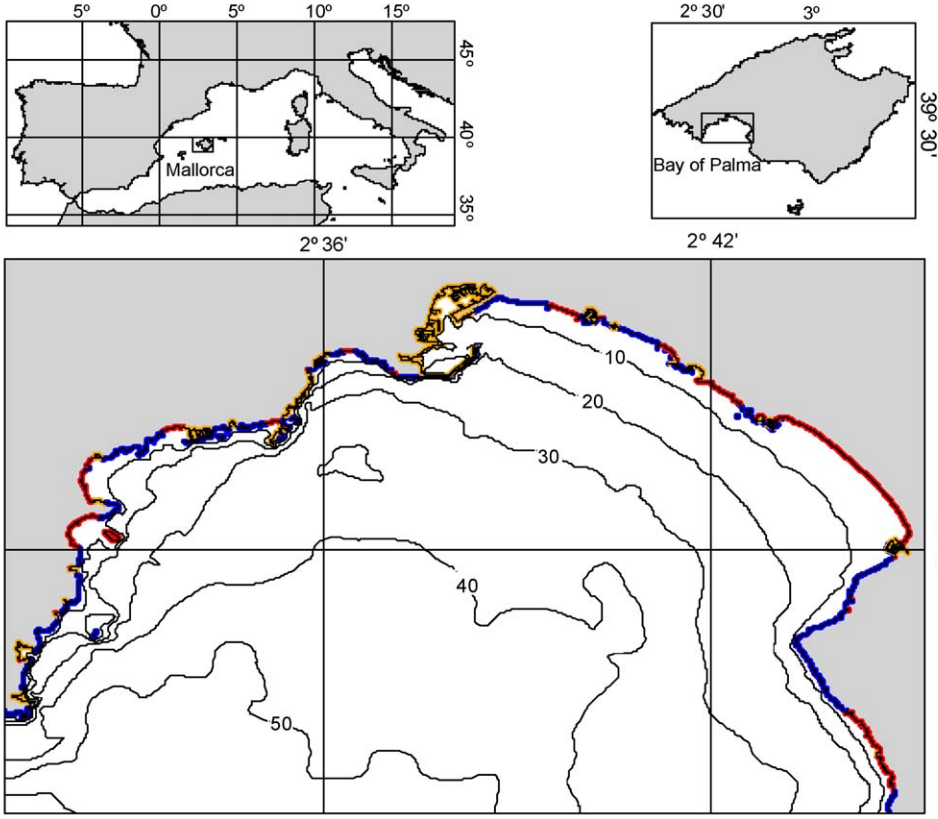

Fig. 4. Bathymetry (m) of the Bay of Palma showing the environmental sensitivity index.

et al. (1993) and Ferrer et al. (in preparation), and at sub-basin scale in Pinot et al. (2002).

The operational circulation sub-system (Fig. 1) is set-up for this region for research and operational purposes (Ferrer et al., in preparation). The sub-system incorporates three nested models covering the overall basin, the sub-basin and the local scale (Bay of Palma). The model at local scale includes real atmospheric forcing from operational analyses and the assimilation of CTD observations from March 1 to 15, 2002. This operational sub-system is used to demonstrate the need of adequately addressing and therefore resolving each one of the physical processes that determine the circulation in the Mediterranean Sea at basin, sub-basin and local scale.

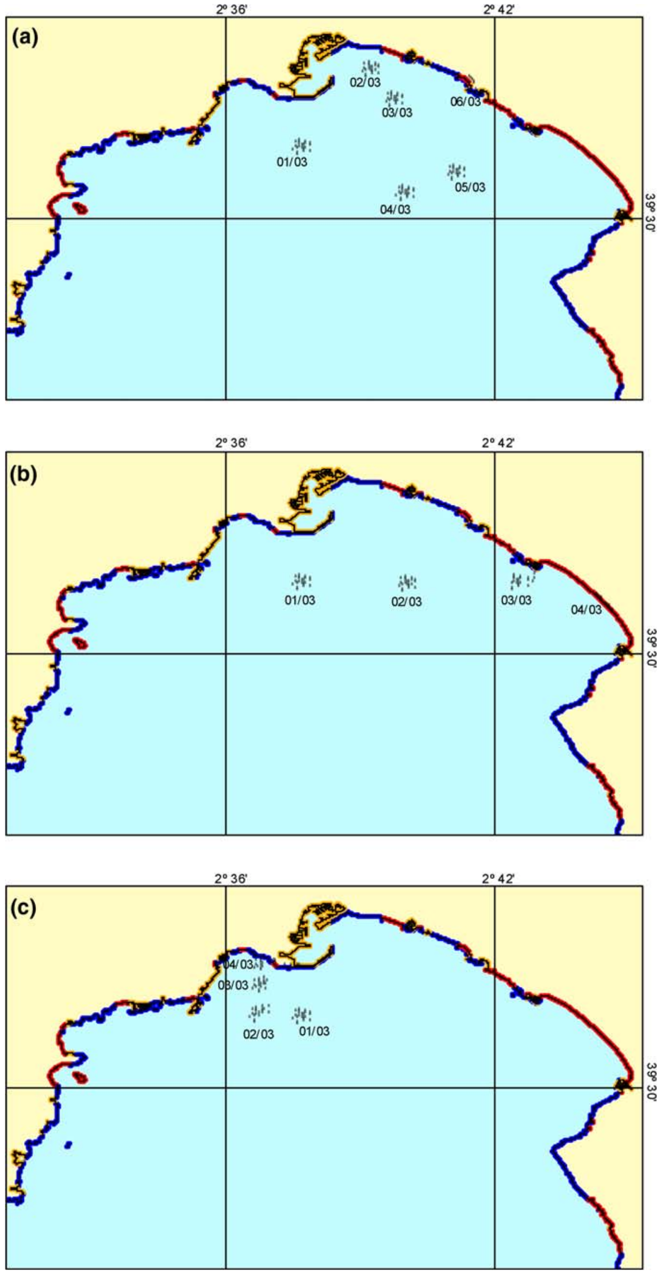

Fig. 5. Modeled spreads of spilled oil in the Bay for Palma for wind drift only (a), for wind drift and climatic sea currents (b), and for wind drift and modeled sea current with data assimilation (c).

Considering the results from the operational sub-system which provide the oceans conditions, and assuming an oil spill on March 1, 2002 of 10,000 tones, the trajectories module of the oil-spill coastal sub-system is run to establish the drift under three different forcing scenarios. The first scenario only includes wind forcing from ECMWF. The second one incorporates the current forcing associated with oceanic climatological conditions of temperature and salinity from *Medar/medatlas II* database (http://modb.oce.ulg.ac.be/Medar). The third scenario includes currents from the assimilation of CTD observations and winds from the meteorological operational analysis. The Environmental Sensitivity module is applied to identify more vulnerable areas. Fig. 4 shows an ESI map of the Bay of Palma. An index value of 1 (red) is given to the most sensitive coastal area to oil spill in the bay; the second sensitive, a value of 2 (yellow); and the least sensitive, a value of 3 (blue).

Fig. 5 shows the modeled spreads of spilled oil in the Bay for Palma for the three mentioned scenarios: wind, wind and climatic currents, and wind and modeled current with data assimilation. Wind conditions are weak and variable as usual in the area and therefore, the trajectory of spilled oil is rather irregular impacting on the coast after 5 days of simulation. Taking into account the climatic currents, the oil moves directly eastward and is beached after three days. However, the trajectories with wind and modeled currents with data assimilation are directed to the west during the first day and then deviated northward until the oil reaches the coast at the third day of simulation.

4. Discussion and conclusion

The combination of operational oceanography systems and oil spill models has been realized with encouraging results for the last few years (Nittis et al., in press). The simulation of the oil spill from *Nakhodka* tanker in the Sea of Japan in 1997 showed that surface currents from a regional circulation model together with high resolution wind data were most important for realistic simulation of the oil spreading after the accident (Varlamov et al., 1999). During the *Prestige* accident, the MERCATOR system was used to provide long range currents to the MOTHY system with a clear contribution for long-term oil spill simulations (Daniel et al., 2004). Our results also show that it is important to address each one of the intervening processes, as indicated in the *Prestige* and *Nakhodka* tanker. Further, the installation of a management sub-system complementary to the operational circulation and the oil spill coastal sub-system is very useful to manage oil spill accidents especially in areas close to the coast. The management sub-system provides the appropriate information of the area, and allows the evaluation of the consequences, the determination of the extent and the region of the affected part of the adjacent area. This will obviously guide the actions to protect the environment.

One of the advantages of the system described is the rapid response capability in front of oil spill crisis or marine emergencies. A quick characterization of the area of interest is highly recommendable to improve the forecasting skill of the numerical models, especially if the area is not monitored permanently. Lagrangian buoys and airborne expendables bathythermographs (AXBTs) have demonstrated to be useful instruments for that purpose because they can be deployed from planes and helicopters. For example, an AXBTs survey of the Balearic Sea was carried out in only three days with a plane; note that the same survey with oceanographic ship was taken in approximately one month (Pinot et al., 1995). In addition, gliders, AUVs and ASVs are now able to carry out oceanographic campaigns continuously and in an autonomous way.

Although the system has been described for oil spills, it can be also used for other applications like search and rescue operations. In this case, the trajectories module is slightly different because drifting objects are not affected by processes that affect oil like spreading or weathering. The motion of the object is the net result of the forces acting upon it (mainly currents and wind). The immersed fraction of the object is a key parameter which is variable depending on the object (life raft, person in water, vessel, etc.). Another uncertainty usually involved in a search and rescue operation is the position and the time of the accident. As a consequence of these uncertainties, a search area is defined by computing an ensemble of trajectories with slight changes in the fraction immersed of the object, the initial position and the time of incident.

To improve the system described in this paper, extra effort is actually centered in the development of new ocean observing platforms (gliders, AUVs and ASVs) to provide, in real time, data to assimilate into numerical models. Surface currents and waves provided by coastal radar stations would be also extremely useful for this purpose. At the same time, the atmospheric forcing has to be improved with high resolution fields to monitor adequately the variability at sub-basin and local scales.

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