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Operational Oceanography System applied to the *Prestige* oil-spillage event

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Abstract

This contribution describes the procedure used during the *Prestige* oil-spillage event, by means of an Operational Oceanography System, and the behaviour of the present prediction tools (hydrodynamic and dispersion models) applied to it. The accuracy of these tools is estimated by a reanalysis of field data transmitted by a sea surface drifting buoy, released at the time of the oil spill. The numerical models applied were the Regional Ocean Modeling System (ROMS), fed by the available six-hourly NCEP atmospheric information, together with a Lagrangian Particle-Tracking Model (LPTM). ROMS has been used to estimate the current fields for the Bay of Biscay, whilst the LPTM has provided the oil spill trajectories. The results demonstrate that the accuracy of the numerical models depends upon the quality of the meteorological input data. In this case, the current fields at the sea surface, derived by ROMS, have been underestimated by the wind fields of the NCEP reanalysis data. An efficient calibration of these wind fields, with data provided by the Gascony buoy (fixed oceanic and atmospheric station), achieves more realistic looking results; this is reflected in the comparison between the buoy trajectory predicted numerically and the tracked movements of the drifting buoy.

Keywords: Bay of Biscay; Dispersion; Oil spill; Operational Oceanography; Prestige

1. Introduction

Operational Oceanography Systems (Behrens et al., 1997; Flemming et al., 2002; Dahlin et al., 2003) are procedures used to study and control the spatio-temporal evolution of a specific phenomenon at sea or, simply, to provide information on the circulation patterns in an area of interest. These systems, generally working at 100% in a marine emergency, where atmospheric and sea conditions are extreme, use measuring instruments (current meters, drifting buoys, meteorological stations, etc.) and numerical tools (mainly hydrodynamic models, feeding Eulerian or Lagrangian dispersion models), in order to provide information of the fundamental variables which control the event and forecast its evolution.

With respect to the numerical tools that can be used in Operational Oceanography Systems, a wide variety of Lagrangian Particle-Tracking Models (LPTM), linked to hydrodynamic models, has been developed in order to analyse the dispersion process of specific phenomena (e.g. García and Flores, 1999; Brickman and Frank, 2000; Huggett et al., 2003; Parada et al., 2003; Pedersen et al., 2003; Ferrer et al., 2004; North and Houde, 2004).

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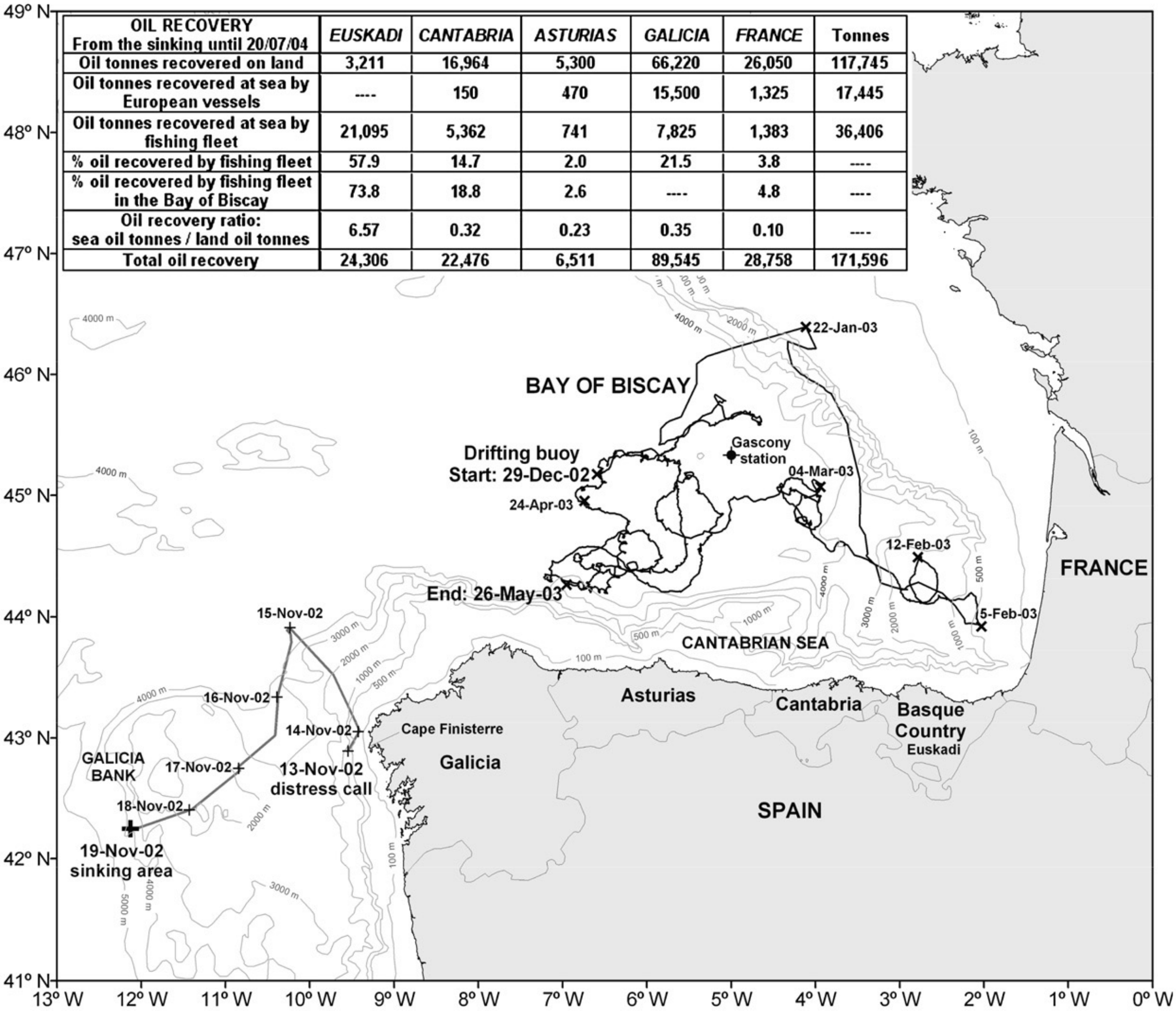

OIL RECOVERY From the sinking until 20/07/04	EUSKADI	CANTABRIA	ASTURIAS	GALICIA	FRANCE	Tonnes
Oil tonnes recovered on land	3,211	16,964	5,300	66,220	26,050	117,745
Oil tonnes recovered at sea by European vessels	----	150	470	15,500	1,325	17,445
Oil tonnes recovered at sea by fishing fleet	21,095	5,362	741	7,825	1,383	36,406
% oil recovered by fishing fleet	57.9	14.7	2.0	21.5	3.8	----
% oil recovered by fishing fleet in the Bay of Biscay	73.8	18.8	2.6	----	4.8	----
Oil recovery ratio: sea oil tonnes / land oil tonnes	6.57	0.32	0.23	0.35	0.10	----
Total oil recovery	24,306	22,476	6,511	89,545	28,758	171,596

Fig. 1. Ship trajectory from distress call to the sinking area, movement of a drifting buoy released at the time of the oil spills, and oil recovery, at sea and on land, from the sinking date until 20/07/04.

Oil spills, algal blooms, and the early life stages of fish (eggs and larvae), amongst others, are the most common marine phenomena which can be tracked using a Lagrangian approach. Following this approximation, the phenomenon analysed can be described by a set of particles with different characteristics (concentration, age, length or size, etc.) and with specific initial values.

The task of describing the particle behaviour with mathematical models in the sea is very complex, especially with highly non-uniform velocity fields (heavy seas and near coastal or river-influenced zones), due to a large number of interacting factors. Prior to the application of hydrodynamic and dispersion models in an Operational Oceanography System, these have to be calibrated and validated for different conditions, with standard databases, such as the mathematical solutions of test cases. Likewise, with a large amount of field data, in order to provide accurate predictions. On the other hand, real-time field data required as input to the models are commonly scarce, of poor quality in the event of a specific phenomenon, or non-existent.

This contribution describes the procedure used during the *Prestige* oil-spillage event, by means of an Operational Oceanography System, and the behaviour of the present prediction tools (hydrodynamic and dispersion models) applied to it. In this case, the magnitude of the problem caused the establishment of an Operational Oceanography System for the Bay of Biscay with data analysis of *in-situ* tracked buoys, satellite and visual observations of the oil, combined with numerical

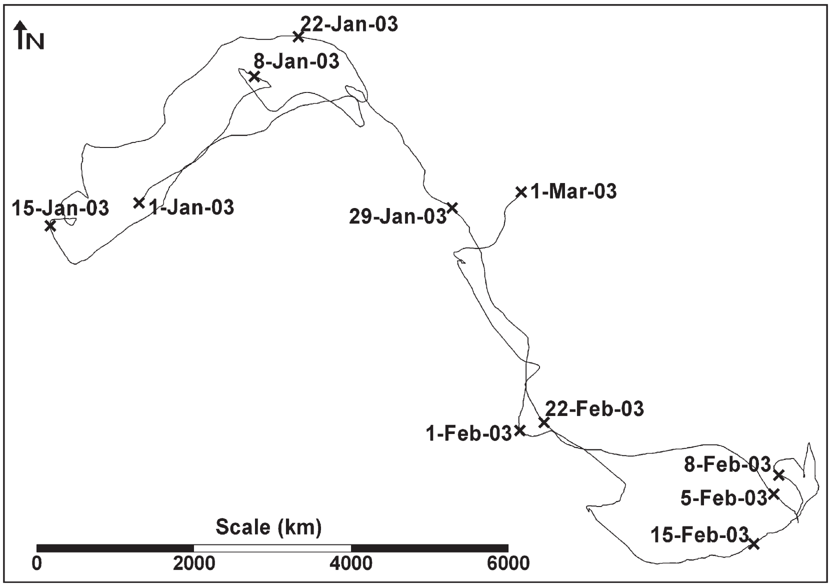

Fig. 2. Progressive wind vector derived from the Gascony station data, between January and March 2003.

model forecasts. The accuracy of the prediction tools is estimated by a reanalysis of field data transmitted by a sea surface drifting buoy, released at the time of the oil spill.

The numerical tools used have been: (1) the Regional Ocean Modeling System (ROMS), described by Shchepetkin and McWilliams (2005). The current fields for the Bay of Biscay were estimated using this hydrodynamic model, fed by atmospheric NCEP reanalysis data; and (2) a Lagrangian Particle-Tracking Model (Ferrer et al., 2004), fed by the output derived from ROMS, which provides oil spill trajectories. The comparison between the trajectory followed by the drifting buoy at the sea surface and that predicted numerically has provided information on the accuracy of the models. This information is very useful for improving, both the accuracy of the input data and the physical schemes used in the models, in order to predict a specific phenomenon in an emergency case with guarantee of success.

2. The sinking of the *Prestige*

On the 13th November 2002, a distress call was sent out by the *Prestige* oil tanker (with 77,000 tonnes of heavy fuel), offshore of Cape Finisterre, on the Atlantic coast of Galicia, to the northwest of Spain. In heavy sea and strong wind conditions, the vessel broke up and started leaking its load, some 28 miles off the coast. Partial evacuation of the crew was undertaken and attempts were made to tow the oil tanker with tug boats. These attempts failed initially and the *Prestige* was eventually taken in tow by a salvage vessel, on the 14th November. On the 19th November, six days after the distress call, the vessel broke in two (at 42°15′N and 12°08′W) and sank in 3500 m depth, in the southwestern flank of the Galicia Bank (Fig. 1), after spilling about 19,000 tonnes of oil (Balseiro et al., 2003).

The associated oil slick, prior to and during towing and following the sinking of the ship, reached rapidly the adjacent coastline of Galicia, in response to the rough seas and strong wind conditions, and, progressively, the western and northern coastlines of the Iberian Peninsula and the Atlantic coast of France. This fact made the general public fully aware of the problem. The surface drifting of the pollutant from the sinking area to the different affected regions, was the outcome of the combination of a large number of interacting factors: local wind stress, acting directly on the fuel oil patches or indirectly through the Ekman layer; the density-driven circulation; and the development of mesoscale structures such as surface eddies and fronts (Álvarez-Salgado et al., 2006; González et al., 2006; Ferrer et al., 2007).

The arrival of *black tides* on the coasts of Galicia, Asturias, Cantabria and the Basque Country emphasised the absence of any operative system, both at sea and on land, to track/follow the spatio-temporal evolution of the oil spill. Initially, a standard approach was adopted, involving the deployment of oil recovery vessels and oil containment booms (González et al., 2006). Subsequently, the local and regional fishing fleets were utilised

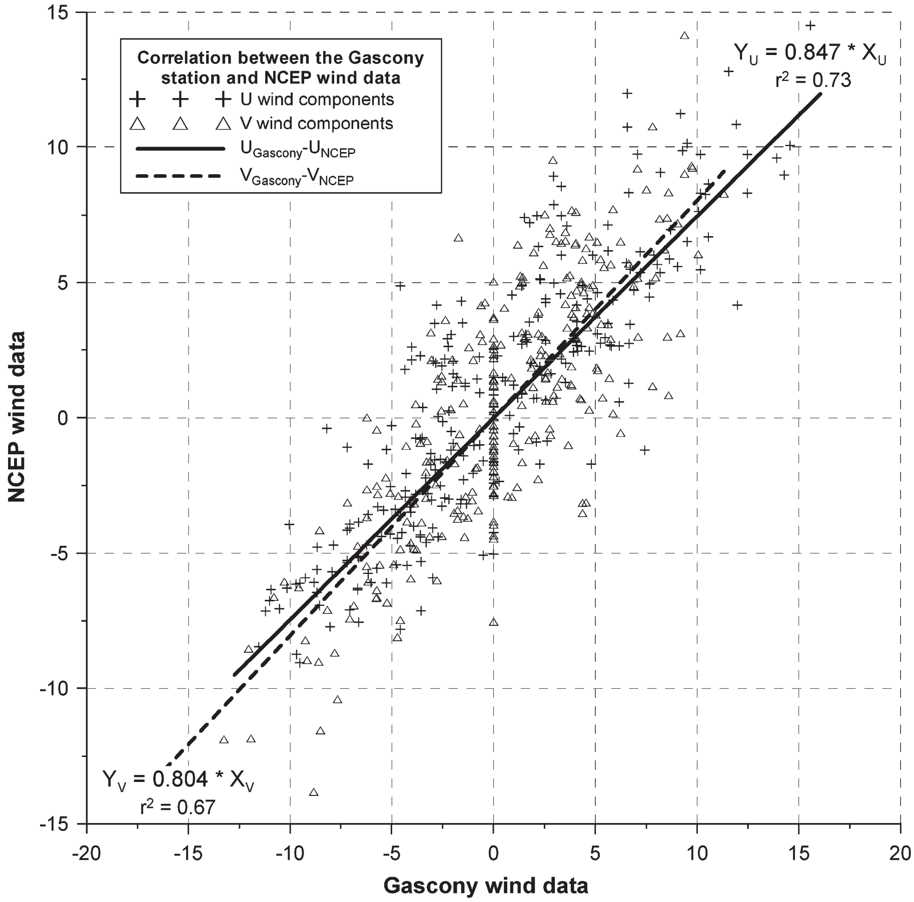

Fig. 3. Correlation between the NCEP wind data and those obtained by the Gascony station, for the time period over which the drifting buoy was providing information.

to contain the dispersed and fragmented slicks at sea, in the different areas. Their efforts were directed on the basis of the oceanographic output derived by institutions such as AZTI-Tecnalia, the University of Cantabria (Spain), and Le Cedre (France).

The local operational oceanography procedure established for the oceanic and coastal region of the Basque Country (Euskadi) included: (1) carrying out visual observations, by aircraft and vessels at sea and by experts and volunteers on land, in the different local coastal areas, to look for the presence of oil slicks and evaluate their dimensions and expected times of arrival at the coast; (2) informing and sending to the oil slicks at sea, vessels to recover the fuel, together with cleaning teams to the coastal areas affected by oil arrivals; (3) analysing satellite imagery and the data from transmitting buoys released at different times during the *Prestige* event, to monitor the movement of the surface waters and the associated slicks; and (4) run numerical models to predict the current fields and the trajectories of the observed oil slicks, which were not recovered or controlled at sea (González et al., 2006).

On the basis of the data sets obtained and the derived predictions, daily reports were provided to the local administrations, for decision-making regarding the deployment of the fishing fleet at sea (190 vessels, ranging in length from 9 m to 30 m, with approx. 1100 fishermen) and experts and volunteers on land for the oil recovery labour. Such a system, within the context of forecasting the pollution of certain areas and the absence of detection methods for small slicks, is consistent with the definition of *Operational Oceanography*, i.e. "the activity of systematic and long-term measurements of the seas and oceans and atmosphere, and their rapid interpretation and dissemination" (www.le-cedre.fr).

With respect to the oil recovery labour, the following patterns could be identified: (1) a peak in the amount of oil reaching Galicia in late January 2003 (at around 500 tonnes), resulting from the original discharge of oil; (2) low levels (50 tonnes) in Asturias, as the initial oil

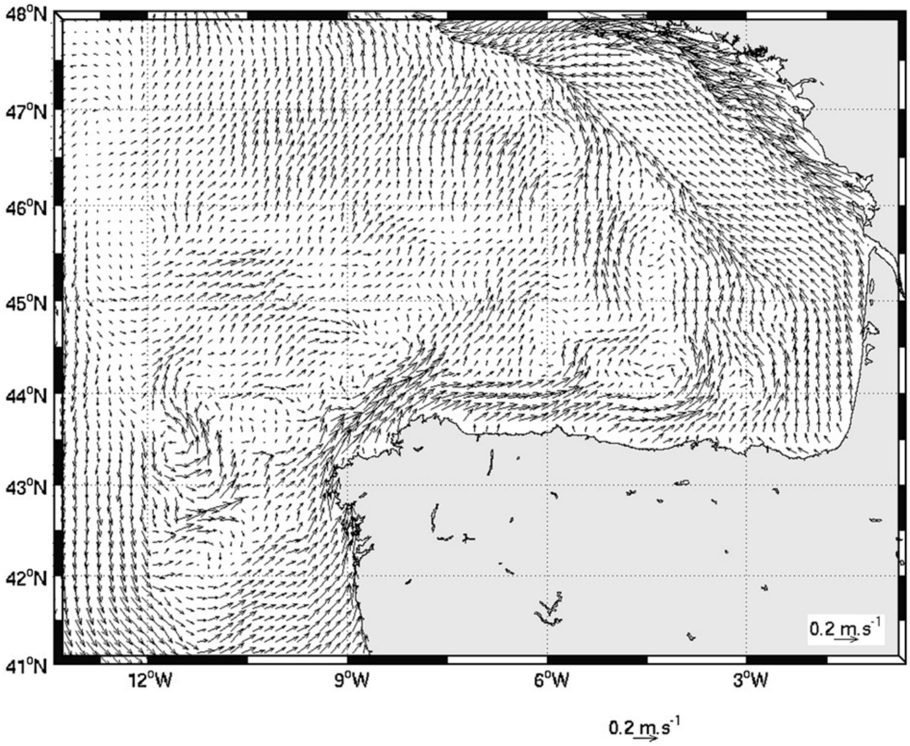

Fig. 4. Sea surface current map for the Bay of Biscay, derived by ROMS, for April 13th 2003.

spill trajectory reached this section of the coastline; (3) a Cantabrian peak (600 tonnes), which occurred in early February 2003; (4) medium levels in the Basque Country (330 tonnes), but slightly later to the Cantabrian peak; and (5) in mid-February 2003, along the western coast of France, a peak of 2000 tonnes. In total, approx. 21,000 tonnes of fuel were retrieved at sea by the Basque fishing fleet, representing a ratio of 6.6 tonnes recovered at sea per tonne on land (González et al., 2006). The recovery of polluted material, at sea and on land, from the sinking date until 20th July 2004, is summarised in Fig. 1.

3. Regional water circulation

The Bay of Biscay is part of the Atlantic Ocean, and is limited by the northern and western coasts of Spain and France respectively, extending over approximately 250,000 km^2. Following the *Prestige* event, important efforts have been directed, by marine research institutes, to analyse the effects on the ecosystem; this, in turn, is related to the high economical importance of the fisheries sector in the Bay of Biscay. Thus, numerous studies have been undertaken in recent years, involving physical aspects of the oceanography, such as: hydrological sampling; current meter and drifter deployments; air and sea surface temperature measurements; satellite data analysis; and numerical modelling (e.g. Álvarez-Salgado et al., 2006; Fontán et al., 2006; González et al., 2006, Ferrer et al., 2007).

As a result of these studies, an improved description of the Bay of Biscay physical system is now available, whilst the understanding of many important processes has significantly progressed (Borja and Collins, 2004). The aim of this section of the contribution is to produce a general description of the regional water circulation in the Bay of Biscay. More specifically, identify the characteristic patterns of the surface water dynamics for the period corresponding to dispersion of the *Prestige* oil spills. Likewise, extract key processes which affected the evolution of the different pollutant patches.

The general oceanic circulation in the Bay of Biscay is weak and variable (Koutsikopoulos and Le Cann, 1996). The main feature is the frequent presence of cyclonic and anticyclonic eddies, which are the result of the continental margin currents instabilities interacting with the bottom topography. Pingree and Le Cann (1992a) called these structures “SWODDIES” (Slope Water Oceanic Eddies), because their core is principally slope water. These structures (100 km diameter, 500 m width centred at 200 m depth) move slowly (2 km/day)

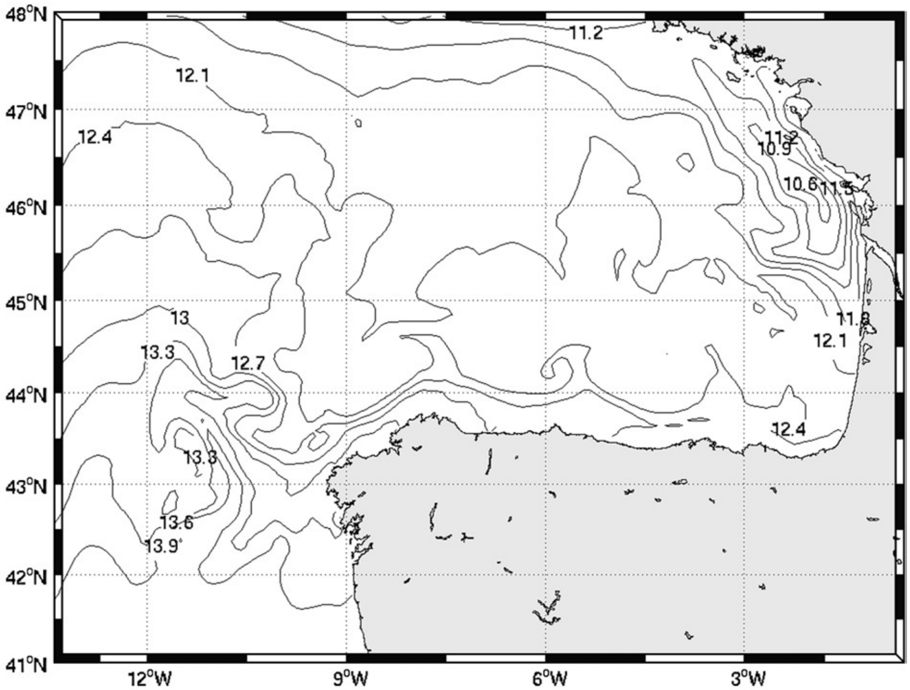

Fig. 5. Sea surface temperature map for the Bay of Biscay, derived by ROMS, for April 13th 2003.

towards the west in the ocean, and can be persistent in time, up to 1 year (Pingree and Le Cann, 1992b).

Further, a persistent poleward flow is detected; however, seasonal changes show different phases at different locations along the slope. Residual currents over the shelf are controlled principally by the wind, tides in the northern part, and water density (Koutsikopoulos and Le Cann, 1996). Several recent studies have shown that the currents in the upper layers of the water column of the Bay of Biscay are related directly with the prevailing wind fields (Fontán et al., 2006; González et al., 2006; Ferrer et al., 2007). Nearshore, the orientation of the coastline, together with the seasonal distribution of the prevailing winds, explains the drift of the water masses in the Bay of Biscay.

In autumn and winter, the Bay of Biscay is under the control of easterly moving low pressure systems and the winds blow predominantly from the southwest. Such winds generate marine currents which, on an average, cause drift towards the east and north. During spring, the wind regime changes towards the north-northwest, generating southerly and west-southwesterly currents along the French and Spanish coasts, respectively. The summer situation is similar to that of spring, although the weakness and high variability of the winds mean that the general drift direction of the currents remains uncertain (Borja and Collins, 2004).

Drifters released at the time of the *Prestige* oil spill, within the upper part of the water column (approx. 20 cm), have shown the complexity of surface water movements in the Bay of Biscay. The trajectory shown in Fig. 1 indicates the changing drift direction of the buoy located initially at 45°10′N and 6°36′W (close to the surface oil slicks originated by the *Prestige*) in response to changing wind directions. Based upon the buoy trajectories, the derived current velocities reached up to 95 cm/s, with most of them being below 75 cm/s; the average was around 25 cm/s (González et al., 2006).

For comparison, over this period of time, altimeter-derived geostrophic velocities for the winter slope current, or Navidad flow, originating from the west, were represented by values ranging from 5 cm/s (6th November 2002) to 35 cm/s (27th November 2002), with a mean of 17 cm/s (García-Soto, 2004). This comparison reveals that wind was the most important mechanism affecting the oil dispersion within the surface layers; it accounted for more than 95% of the drift speeds and directions (González et al., 2006).

The data provided by the buoy trajectory shown in Fig. 1 have been used: (1) to analyse the accuracy of numerical models in their current and trajectory predictions; and (2) to establish the fundamental mechanism of oil dispersion, at the sea surface. This buoy transmitted data from the 29th December 2002 until

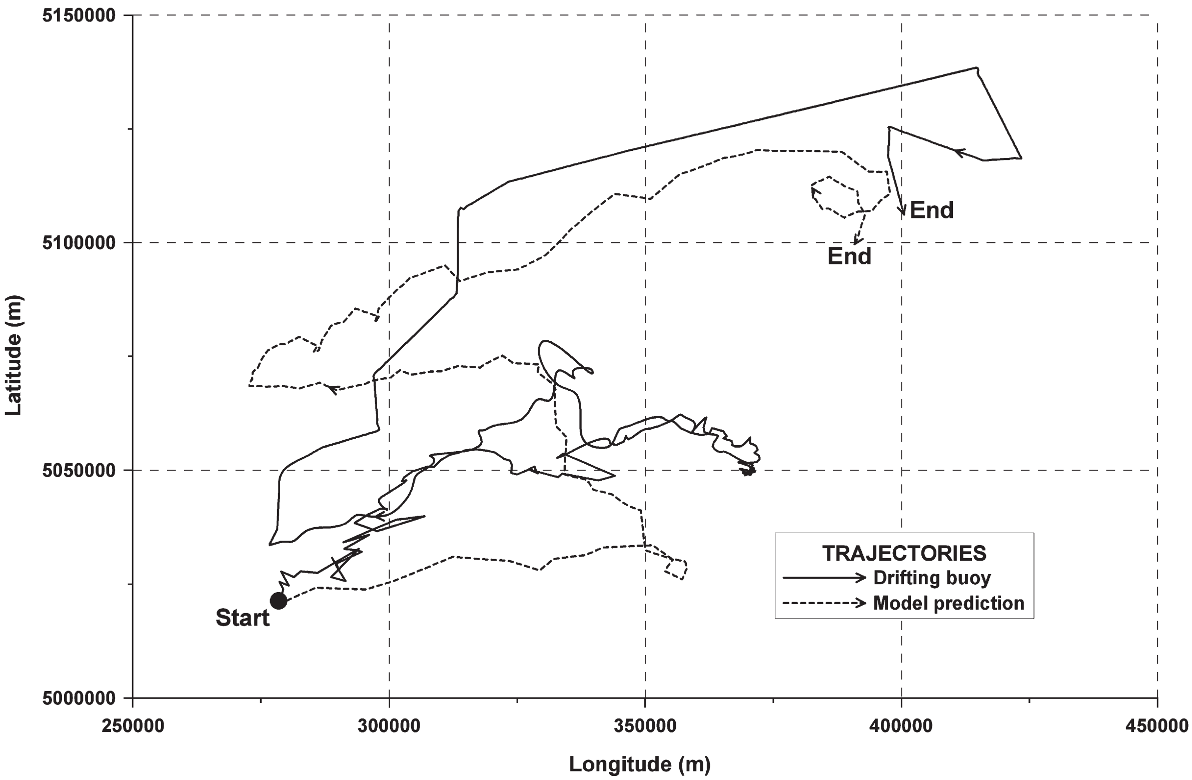

Fig. 6. Observed trajectory of the analysed surface drifting buoy, together with that predicted by the LPTM, during 26 days, from 1st January 2003.

the 26th May 2003; its position was relayed, via satellite, with a mean frequency of 3 to 4 times/day. Moreover, the information derived from the wind data of the Gascony buoy has been used to analyse the accuracy of the wind fields of the NCEP reanalysis data. These are the input data to estimate the current velocity fields for the Bay of Biscay.

The Gascony buoy is a fixed oceanic and atmospheric station located at 45°12′N and 5°00′W, owned and maintained by UK Met Office in cooperation with Meteo France Buoy. With respect to the NCEP reanalysis data, these are provided by the National Centers for Environmental Prediction, which is a National Weather Service of NOAA. These data are obtained using a state-of-the-art analysis/forecast system (historical observations and model simulations) to perform data assimilation, including past data from 1948 to the present. This reanalysis system provides a reconstruction of the climate. In this case, the six-hourly data for the years 2002 and 2003 have been used for the hydrodynamic modelling.

4. Numerical models

The hydrodynamic model used to estimate the current fields for the Bay of Biscay is the Regional Ocean Modeling System (ROMS). ROMS is an evolution of the S-coordinate Rutgers University Model (SCRUM), described by Song and Haidvogel (1994). It has been expanded to include a variety of new features including: high-order advection-schemes; accurate pressure gradient algorithms; several subgrid-scale parameterizations; atmospheric, oceanic, and benthic boundary layers; biological modules; radiation boundary conditions; and data assimilation. Presently, ROMS does not designate a single model, but a variety of versions; these have been developed, in the open literature, by different institutions.

The numerical aspects of ROMS have been described in detail by Shchepetkin and McWilliams (2005). ROMS has been used to model the circulation in a variety of different regions of the world ocean, ranging from local to basin scale (e.g. Haidvogel et al., 2000; Malanotte-Rizzoli et al., 2000; She and Klinck, 2000; Penven et al., 2001; MacCready and Geyer, 2001; Marchesiello et al., 2003; Di Lorenzo et al., 2004; Ferrer et al., 2007). Nowadays, the model has already a large user community.

The domain used for the model, in its configuration for the Bay of Biscay, extended in latitude from 41°00′

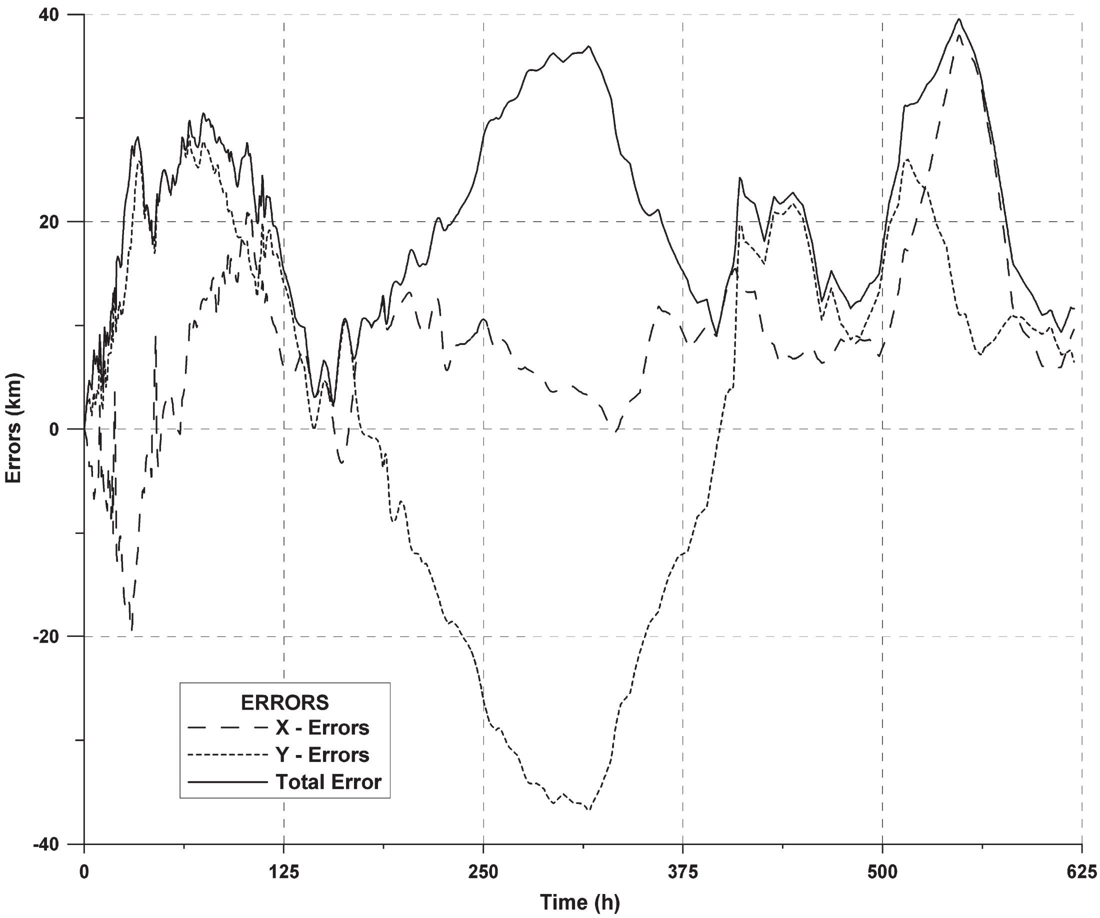

Fig. 7. Location errors in the trajectories (in the X and Y axes, and the total error), during 26 days, from 1st January 2003.

to 48°00′N and in longitude from 13°30′ to 0°30′W, with a mean horizontal resolution of 6.6 km. Vertically, the water column was divided into 20 sigma coordinate levels; these were concentrated at the surface, where most of the variability occurs and in order to retain a good resolution of sea surface processes. The topography of the model was obtained by interpolation, following optimisation analysis, of the ETOPO2 (2 minute digital Elevation Topographic model), GEBCO (General Bathymetric Chart of the Oceans) and IBCM (International Bathymetric Chart of the Mediterranean). This approach was adopted in order to get a realistic bathymetry, which was smoothed to ensure stable and accurate simulations (Haidvogel et al., 2000).

The surface forcing inputs used in the model were the six-hourly NCEP reanalysis data, for the years 2002 and 2003. The variables used from this meteorological database were: winds and air temperature at 10 m and 2 m height above sea level, respectively; precipitation rate; relative humidity; and long and short wave radiation fluxes. The conditions used on the western, northern, and southern open boundaries were a combination of outward advection and radiation, together with flow-adaptive nudging towards prescribed external conditions (Marchesiello et al., 2001). These external conditions were estimated using climatological data (Levitus and Boyer, 1994; Levitus et al., 1994), used also for initialisation.

For the tidal forcing, data from the OSU TOPEX/Poseidon Global Inverse Solution version 5.0 (TPXO.5) have been used. This is a global model of ocean tides, which best-fits (in a least-squares sense) the Laplace Tidal Equations and along-track averaged data from TOPEX/Poseidon orbit cycles (Egbert et al., 1994). The tides are provided as complex amplitudes of earth-relative sea surface elevation and tidal currents, for 8 primary harmonic constituents (M2, S2, N2, K2, K1, O1, P1, and Q1). These harmonics are introduced in ROMS through the open boundaries, using the Flather condition (see Marchesiello et al., 2001). The volume is automatically conserved in the domain, and variations due to physical forcing such as tides (also the other sub-tidal components) are introduced through the external data.

To compute the buoy trajectory (which simulates the oil movement) at a moderate computational cost, a Lagrangian Particle-Tracking Model (LPTM) has been developed in a modular way (Ferrer et al., 2004). In this case, the velocity fields computed on the ROMS grid were averaged and stored periodically (every 6 h); these were used to estimate the velocities of the tracked buoy. In addition, a random turbulent horizontal velocity term is computed to parameterize unresolved subgrid-scale phenomena along the horizontal axis (in the vertical directions, the effect of the subgrid-scales is less significant and is, therefore, neglected). The method used for the particle movement is based on the 4th order Runge–Kutta scheme (Benson, 1990).

5. Results and discussion

Between the 29th December 2002 and the 22nd January 2003, under predominant southwesterly winds, the trajectory of the drifting buoy (Fig. 1) was to the northwest, close to the Brittany coast. From this date, until 5th February 2003, a change in its movement was observed; this was in response to a changing wind direction towards the south-southeast, which drifted the buoy to the centre of the Bay of Biscay. During the last days of January and first week of February 2003, the oil impacted heavily on the coasts of Cantabria and the Basque Country (González et al., 2006). After the impacts in February, the wind direction in the area changed again, causing the buoy to drift towards the west-northwest; at the same time, the oil impacts on the coasts decreased significantly.

The progressive wind vector for the above dates, obtained from the Gascony station data, is shown in Fig. 2. There is a similarity between the buoy drift (Fig. 1) and the progressive wind vector, even when the buoy position was located significantly far away from the Gascony station. This drifting pattern is characteristic of winters, in the Bay of Biscay, where the depressions with southwesterly winds occur frequently near the coast of Galicia. These are combined with northwesterly storms, caused by low pressure systems located to the west of the British Isles. The influence of the former extends up to the eastern part of the Bay of Biscay, whilst the latter reaches the Cantabrian coast. Following this comparison, wind appears to be a basic mechanism affecting oil dispersion processes.

Further, the Gascony wind data have been used to investigate the accuracy of the six-hourly NCEP wind reanalysis data for this time period; these were used as surface forcing input, by the ROMS model, to predict the circulation patterns. The spatial coverage of these data is 88.542°N–88.542°S, 0°E–358.125°E, on a T62 Gaussian grid with 192x94 points. The air–sea heat and momentum fluxes in the model were calculated using the bulk formulae of Fairall et al. (1996, 2003), utilising the model sea surface temperature and the sea level air temperature, pressure, relative humidity, and 10 m winds of the NCEP atmospheric forcing.

Significant correlation exists between the NCEP wind data, at the location where the drifting buoy was (interpolated spatially, by an inverse distance to a power), and the wind information provided by the Gascony station (Fig. 3). For the U wind component, the coefficient of determination, r^2, was equal to 0.73, whilst for the V wind component was 0.64. The Gascony wind data were 1.20 to 1.25 times higher than the NCEP data. On this basis, taking into account the fixed location of the Gascony buoy, NCEP wind reanalysis data can be used to estimate current fields for the Bay of Biscay. Regarding this point, it is worth mentioning that the resolution of the NCEP data is too coarse to study coastal processes; but in this case, the work is centred on the deep water circulation.

The current fields, for the period over which the drifting buoy provided data, were estimated for the Bay of Biscay. This output information was used in the LPTM, to calculate the dispersion of a particle which simulates the movement of the drifting buoy. The sea surface current and temperature predictions derived by ROMS model for April 13th 2003 are shown in Figs. 4 and 5. Although current field structure is influenced highly by the wind characteristics on that particular day, some typical features of the general water circulation, for the Bay of Biscay system, can be observed.

On this day, the Atlantic southwesterly component of the wind stress forces the stable poleward current, established during previous days, towards the northeast along the continental slopes of Galicia and the Cantabrian Sea, and towards the north-northwest along the French coast (Fig. 4). Wind stress maxima and changes in coastline orientation and topography, force the flow offshore at some locations along the Cantabrian Sea; this generates, finally, cyclonic eddies (with average velocities around 20–30 cm/s). These structures transport both warmer waters and coastal waste products, inducing coastal upwelling; these warmer waters, which come from the southwest, are advected towards the Bay of Biscay by the poleward current established (Fig. 5).

The six-hourly averaged current fields, derived by ROMS and used in the LPTM to simulate the movement of the drifting buoy, have demonstrated to be underestimated. This is the result of the aforementioned underestimation of the NCEP wind data, compared to those registered by the Gascony station (1.20–1.25 times higher). Calibration of these NCEP wind data using this information, to estimate new current fields by ROMS, has resulted in high correlation between the LPTM output and the locations of the tracked buoy (Figs. 6 and 7).

The figures show the trajectory followed by the drifting buoy and that predicted by the LPTM (Fig. 6), together with location errors in the trajectories (in the X and Y axes, and the total error) during 26 days from January 1st 2003 (Fig. 7). The errors were within the ±40 km, with some variations likely to be related to wave effects on the buoy movements. From the results obtained, the wind influence on oil dispersion at the sea surface is high. Therefore, a more accurate representation of wind input to the hydrodynamic model will result in an improved forecast of surface current patterns and oil dispersion trajectories.

6. Conclusions

The pollution problem caused by the sinking of the *Prestige*, on the 19th November 2002, was managed by the establishment of an Operational Oceanography System for the Bay of Biscay, with data analysis of *in-situ* tracked buoys, satellite and visual observations of the oil, combined with numerical model forecasts. This contribution describes such a system and the behaviour of the present prediction tools (hydrodynamic and dispersion models) applied to it. The hydrodynamic model used to estimate the current fields for the Bay of Biscay has been the Regional Ocean Modeling System (ROMS), fed by the available six-hourly NCEP atmospheric information. The dispersion model to provide the oil spill trajectories was a Lagrangian Particle-Tracking Model (LPTM). The accuracy of these tools has been estimated by a reanalysis of field data transmitted by a sea surface drifting buoy, released at the time of the oil spill. The results demonstrate that the accuracy of the numerical models depends upon the quality of the meteorological input data. In this case, the current fields at the sea surface, derived by ROMS, have been underestimated by the wind fields of the NCEP reanalysis data. Calibration of these wind fields was made with the data provided by the Gascony buoy (fixed oceanic and atmospheric station). The current fields obtained with the ROMS, following this wind calibration, achieves more realistic looking results, as shown the comparison between the buoy trajectory predicted numerically, by the LPTM, and the tracked movements of the drifting buoy.

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