Efficient tools for marine operational forecast and oil spill tracking

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A R T I C L E   I N F O

A B S T R A C T

Ocean forecasting and oil spill modelling and tracking are complex activities requiring specialised institutions. In this work we present a lighter solution based on the Operational Ocean Forecast Python Engine (OOF$_\varepsilon$) and the oil spill model General NOAA Operational Modelling Environment (GNOME). These two are robust relocatable and simple to implement and maintain. Implementations of the operational engine in three different regions with distinct oceanic systems, using the ocean model Regional Ocean Modelling System (ROMS), are described, namely the Galician region, the southeastern Brazilian waters and the Texas–Louisiana shelf. GNOME was able to simulate the fate of the Prestige oil spill (Galicia) and compared well with observations of the Krimsk accident (Texas). Scenarios of hypothetical spills in Campos Basin (Brazil) are illustrated, evidencing the sensitiveness to the dynamical system.

OOF$_\varepsilon$ and GNOME are proved to be valuable, efficient and low cost tools and can be seen as an intermediate stage towards more complex operational implementations of ocean forecasting and oil spill modelling strategies.

1. Introduction

Coastal areas house large populations and important economic activities (industry, tourism, fishing and ports). They constitute vulnerable regions with environmental sensitive areas which may be affected by pollution accidents occurring inside harbours or near the coast. The accident may also take place away from coast, but the pollution transported onshore by the ocean currents and surface winds. The outcome may result in catastrophic impacts on populations and devastating effects on marine life. The effects caused by an accident are dependent on many factors, such as the type and quantity of the pollutant, the geometry of the region, the prevailing wind system (direction and magnitude), the ocean currents, the small and mesoscale dynamics, as well as sea temperature, salinity and atmospheric variables (e.g. surface temperature).

A sustainable management of coastal regions, thus, benefits from the implementation of ocean forecast systems and pollution transport models. The ability to predict the evolution of an oil spill and to have data to analyse extreme events and scenarios, constitutes an indispensable tool for risk assessment, safety and contingency planning as part of the decision support framework. The

monitoring and forecasting of marine pollution and impacts of offshore activities are two of the main uses of operational ocean numerical modelling (Hackett et al., 2006).

In order to deal with oil spill accidents, the marine security and safety agencies must have real time accurate ocean observations and forecast of oil trajectories for the next few days. Observations and monitoring of the spill are needed for model trajectories initialization, update and uncertainty assessment. Surface spills can be detected by airborne and satellite instruments (Brekke and Solberg, 2008; Ferraro et al., 2009; Cheng et al., 2011).

A key feature of operational forecasts is the data availability. End users should have easy web access to main model input/output figures as well as access to the full data sets in standard formats and service specifications. The freely distributed results are a useful tool for scientific applications and for the general community.

Ocean and atmospheric climatological data draw a picture of the seasonal variability of winds and currents scenarios, but it is inappropriate for oil spill forecast. Much of the mesoscale structures, meanders, eddies, are transitory so that averages fade out the amplitudes (e.g. the Loop Current in the Gulf of Mexico, Barth et al. (2008b), Marta-Almeida et al. (accepted for publication)) and may point for places too away from reality, putting the predicted impacts in question. It is nowadays known that pollution forecasts are much more reliable when based on realistic numerical forecast than based on climatological information. Moreover, the data

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frequency is also very important and depending on the location, frequency higher than one day may be required. The outputs of the current global and large scale models (such as HYCOM, http://www.hycom.org and MERCATOR, http://www.mercator-ocean.fr) are in general issued as daily snapshots or averages. In spite of including model assimilation and being capable of reproducing part of the mesoscale structures, short term events, tidal currents and coastal dynamics are not well resolved. The solution is the implementation of regional coastal models which may be nested in those larger scale assimilated models. Hence, high resolution model configurations and adequate observational facilities which provide data for model forcing (e.g. winds), calibration, validation and assimilation, are required to properly simulate the ocean circulation in coastal regions. A continuous effort must be done to improve model results and reduce forecast errors by accompanying developments of model physics and parametrisations, and by adopting suitable and advantageous assimilation techniques. The accuracy of atmospheric forcing and ocean currents forecast is considered the main factor to predict reliable pollution trajectories and final destination ([e.g.]González et al., 2008; Hackett et al., 2009; Broström et al., 2011). Pollution prediction quality is more related with the difficulty of the model to reproduce small scale eddies and meanders than with errors associated with the surface winds or even, sometimes, errors related to lack of complexity of the oil transport model. For this reason, the increase of accuracy of short term ocean projections constitutes a great advantage and may allow a faster response in case of accident. For instance, by reducing the search region or the area to be under surveillance.

Several oil tracking model are nowadays in use by various oceanographic centres (Hackett et al., 2006; Hackett et al., 2009; Davidson et al., 2009). Their complexity has a wide range. Some are more dependent on parametrisations based on real wind, others rely on climatological ocean currents and they may consider oil as a lagrangian particle or use advection/diffusion algorithms. The oil weathering may also be or not taken into account. The influence of oceanic and atmospheric physical variables and processes like spreading, evaporation, dispersion, dissolution, emulsification, photo-oxidation, sedimentation and biodegradation, may change significantly the oil spill track and extension. Examples of operational implementations of oil spill modelling include the Norwegian Meteorological Institute Oil Spill Forecast System, based on the Oil Drift 3 Dimensional model (OD3D, Wettre et al., 2011; Broström et al., 2011); the Météo France Oil Spill Forecast System using the Météo France Oil Spill Model (MOTHY, Daniel et al., 2004; Daniel et al., 2005); The Japan Meteorological Agency Oil Spill Prediction (JMA, 2007); the Emergency Response Division of the United States Office of Response and Restoration, operating the General NOAA Operational Modeling Environment (GNOME, Beegle-Krause, 2001; Beegle-Krause and O'Connor, 2005).

In the present work we describe the development of a fully automated operational ocean forecast system, and the utilisation of the results to analyse and predict pollution dispersion with the NOAA oil spill model GNOME. This is a straightforward model to use and can be applied to any region in the world with few inputs, in opposition to most of the available oil spill models, which are more dependent on the study region and local parametrisations. GNOME uses wind and currents from the ocean model, so that it is possible to set-up hydrodynamical model configurations with realistic forcing in forecast mode and predict oil spill in different situations making the system robust and fully rellocatable. Wind and currents data from the implemented operational ocean modelling system can be easily converted to GNOME inputs. The operational system was developed and implemented at the Instituto Español de Oceanografía (IEO) at the Centro Oceanográfico A Coruña. The Galician operational effort was a consequence of the Prestige oil spill accident in Galician waters (NW Spain). The development and some results for the Galician region will be presented. Similar implementations are currently operating around the globe. Here we describe two of them with special interest concerning oil spill forecasts: the Brazilian region and the Northern Gulf of Mexico.

The Brazilian oil industry has seen a very fast growth in recent years caused by the discovery of new offshore oil sites and because of technological advances which allow oil drilling and extraction at deeper and deeper waters, in deposits inaccessible until very recently. This new oil race is synonym of high revenues and industrial opportunities, but it also represents an important environmental threat. Associated with oil industry and economic growth is the creation of oil pipelines, increase of maritime transit and ports size and activity. All of this means higher economic dependence on the sea, higher environmental impact and higher probability of accidents, like oil spills from ships or oil extraction facilities, accidents with containers and human lives. In spite of the importance of the capacity to perform oil spill forecasts in the Brazilian region, very few studies have been made so far, namely Lemos et al. (2009), Amorim (2005) and oil industry supported private initiatives by Applied Science Associates (Hackett et al., 2009). These studies have been forced with climatological data and/or model data to study events but without a systematic modelling approach.

The Northern Gulf of Mexico has been a major source of hydrocarbons in the United States for decades. But it is also a region of continuous concern due to oil spills originated by accidents, abandoned infrastructure, and natural leaks from the ocean floor. Very sensitive regions, like the Mississippi delta, are often threatened by the oil industry, like the Deepwater Horizon oil spill in April 2010, considered the largest accidental marine oil spill in the history of the petroleum industry.

The ability to understand the ocean circulation in these regions, and the capacity to predict the ocean state in a temporal window of a few days, is a decisive factor for the success of all kind of marine activities, enabling the creation of rapid response plans in case of an oil industry related accident. Ocean analysis and forecast can also help the study of hypothetical scenarios, water quality assessment, evaluate the impact of extreme events, etc., being useful for offshore industry much beyond the study of its impacts on the environment.

The aim of this article is to present efficient tools to run and distribute automatic ocean modelling implementations and to facilitate oil spill tracking in marine forecast systems. The article is organised in order to have the operational engine described in Section 2. The ocean and oil spill models are described in Sections 3 and 4, respectively. The implementation of the operational system for the Galician region (NW Atlantic Iberian coast) and some of its applications are outlined in Section 5. Section 6 covers the operational modelling set-up at the Brazilian region and simulations of hypothetical oil spill accidents under different oceanic and atmospheric conditions. Section 7 describes the Northern Gulf of Mexico (Texas–Louisiana shelf) operational forecast system and compares the track of a real oil spill with observations. Finally, Section 8 summarizes the achievements of the operational implementations described and concludes the work.

2. The operational engine

The operational system is fully supported by a comprehensive set of tools written in the Python programming language. These tools create and operate the model input/output and control all the required tasks for the operationality of the ocean model. Python is an object oriented scripting language and includes a very

extensive sort of built-in modules, and consequently it can be used to run all kind of daily tasks which usually require more than one language. The support for multidimensional arrays has been increasing the availability of community modules for data analysis and manipulation. Common data formats in ocean and atmospheric sciences can be efficiently managed with Python extensions: GRIB, HDF and especially NetCDF, which is becoming a standard in oceanography for model output and for satellite products (e.g. Blower et al., 2009; Signell et al., 2008). As an interpreted language that can run in interactive mode, Python simplifies coding for scientific applications that require use of large data sets and complex computational programs (e.g. Oliphant, 2007).

The operational engine executes daily analysis and forecast with atmospheric and lateral boundary data from regional, large scale or global models. River and tidal forcing are supported as well. The analysis and forecasts cycles are repeated continuously in a robust and fully automated manner.

For a description of the Python system, also known as Operational Ocean Forecast Python Engine, OOF$_\varepsilon$, see Marta-Almeida et al. (2011b). The operational engine includes a visualisation module able to produce many types of slices and plots from the ocean model inputs/outputs (temperature, salinity and currents at several depths, sea surface height, surface lagrangian dispersion, wind forcing, etc). Examples of the graphical outputs can be seen at the homepages of the implementations for the Brazilian region, http://oceano.fis.ufba.br/oof, or for the Texas Louisiana shelf, http://pong.tamu.edu/oof, for instance.

Additional Python routines are available for comparisons of model results and observations in order to validate model results and to control model performance. For example, the sites referenced above show images of satellite sea surface temperature from O&SI-SAF (Ocean & Sea Ice Satellite Application Facility, http://www.osi-saf.org: AVHRR data of the satellite MetOp-A from the EUMETSAT Meteorological Operational satellite programme processed by Meteo-France/CMS-Lannion). The Python scripts control the download of the SST data from the remote server and generate the plots in the domain of interest, shown in the operational homepage. Apart from illustrating OOF$_\varepsilon$ capabilities, comparison of the images demonstrates the skill of the implemented ocean model.

In addition to comparisons of 2D spatial fields, Python routines for visualisation of vertical profiles from model and observations aid in the operational skill assessment of the model. Temperature and salinity profiles measured by drifting ARGO floats (http://www.argo.net) in the global ocean are routinely assembled and distributed by different data centres (e.g. CORIOLIS data centre, http://www.coriolis.eu.org, USGODAE data centre, http://www.usgodae.org). The developed Python tools allow to pick ARGO data from the web server of these data centres and to plot comparisons to model profiles in the operational web interface.

The availability of the full model data sets is done through OPeNDAP. OPeNDAP is an efficient protocol for allowing the remote access of data sets (e.g. Cornillon et al., 2009; Signell et al., 2008). In OPeNDAP servers, the access to data usually available as a set of different individual large data files, is performed in an efficient and consistent way, as the client sees only a unique 4D data set from which parts can be extracted and downloaded. A standard OPeNDAP server is a rather complex system and preferentially requires a standalone machine. Nevertheless, a much simpler Python based easy to install and maintain exists (Pydap, http://pydap.org) and runs seamlessly integrated with the most used web server, Apache. A couple of Python OPeNDAP clients are available nowadays, enabling the access of OOF$_\varepsilon$ to OPeNDAP servers in order to acquire data needed for the creation of some input files, such as surface atmospheric data and boundary or 3D nudging data from a larger-scale model.

OOF$_\varepsilon$ was conceived intending to operate the ocean model ROMS (described below), but since many others ocean models use similar input/output schemes and sequences, OOF$_\varepsilon$ engine can be adapted to steer the execution and analysis of other ocean models with little effort.

OOF$_\varepsilon$ is presently implemented in four different countries: (i) Instituto Español de Oceanografía, Centro Oceanográfico A Coruña (IEO-A Coruña), Spain; (ii) Centro de Estudos do Ambiente, Universidade de Aveiro, Portugal (recently discontinued); (iii) Centro de Pesquisa em Geofísica e Geologia, Universidade Federal da Bahia (UFBA), Brazil and iv) Department of Oceanography, Texas A&M University, United States of America.

3. The ocean model

The numerical model in use is the Regional Ocean Modeling System, ROMS (Shchepetkin and McWilliams, 2005; Penven et al., 2006; Haidvogel et al., 2008). ROMS is a state-of-the-art free-surface terrain-following primitive equation hydrostatic model with Boussinesq and hydrostatic approximations. ROMS is configurable for realistic applications and has been used in a variety of time and space scales, from very small regions like harbours with horizontal resolution of few dozens on metres ([e.g.]Grifoll et al., 2009; Grifoll et al., 2011), to the coastal, large and global scale.

The model has been applied successfully in the Iberian region for several years to study the ocean dynamics (Marta-Almeida and Dubert, 2006; Peliz et al., 2007; Peliz et al., 2009), larvae dispersion and recruitment (Marta-Almeida et al., 2006; Marta-Almeida et al., 2008), river plumes (Silva et al., 2007; Otero et al., 2009) and pollution associated with contaminants transport (Sotillo et al., 2008). At the Brazilian region, the applications of ROMS are more recent and tend to be more focused on the ocean dynamics [e.g. Silva et al., 2009; Rezende et al., 2011; Amorim et al., submitted for publication]. ROMS modelling applications for the northern Gulf of Mexico have been used for some time and are mostly focused on coastal ocean dynamics (Barth et al., 2008a; Zhang et al., 2010; Zhang and Hetland, submitted for publication; Zhang et al., 2012b; Zhang et al., 2012a); hypoxia (Hetland and DiMarco, 2008; Hetland and DiMarco, 2012) and harmful algae plumes (Hetland and Campbell, 2007).

4. The oil spill model

The General NOAA Operational Modelling Environment, GNOME (http://response.restoration.noaa.gov) (Beegle-Krause, 2001; Beegle-Krause and O'Connor, 2005) is an oil spill trajectory model developed by the Emergency Response Division of NOAA's Office of Response and Restoration. GNOME requires, in general, fewer parameters than the majority of other oil spill models and can, thus, be set-up quickly for any region in the world by providing a realistic land-sea mask, ocean currents and surface wind. It can also run in the so called *Standard Mode*, using climatological data in the form of regionally specific location files, allowing the quick set-up of custom scenarios, or in *Diagnostic Mode* using realistic nowcasts and forecasts from oceanic and atmospheric numerical models. GNOME supports several types of pollutants and simple weathering algorithms. The oil spills are modelled as Lagrangian elements (splots) advected with the surface Eulerian current velocity field (The 3D velocity capability is still limited) and the diffusion is simulated as a random walk (Csanady, 1973). A wind drift parameter combines the several effects of the surface wind on the oil splots (surface and Strokes drift, wave stress and compression, over-washing and Langmuir circulation).

GNOME returns splots trajectories that collectively represent the most likely paths and extension of the spill (*Best Guess*

solution). Uncertainty on the input parameters and forcing fields can also be taken into account resulting in the *Minimum Regret* trajectories uncertainty bound.

GNOME interface is intuitive and the user can define a region or transect of splots released in a certain time or being released continuously between two dates, being the trajectories simulated through time. Wind and currents data are accepted in NetCDF format, thus can be effortlessly created from ocean models input/output data. The outputs can be saved in several formats, like GIS-compatible, movies and text files which may be easily parsed by analysis and visualisation programs.

GNOME has been applied in many places and in both hindcast and forecast mode, for example in the Gulf of Mexico (Klemas, 2010; Cheng et al., 2011), in the Persian Gulf (Farzingohar et al., 2011), in the Black Sea (Yurtsaba et al., 2011) and Bosphorus Strait (Başar et al., 2006). The general conclusions of the GNOME applications are similar to other models and reflect the effectiveness of the oil spill model given that adequate environmental data inputs are provided (coastline, atmospheric and oceanic forcing) and a good collaboration between modelling and observational facilities exists (land based facilities, satellite imagery and ship and aircraft sensors).

In the oil spill simulations presented in this work, the creation of the GNOME ready files was done with a Python script which extracts the surface currents from the ocean model outputs and the wind forcing from the model inputs. Since the ocean model land mask may differ substantially from the real coastline, due to resolution limitations, the ocean currents are extrapolated over the land mask. For this purpose, a high resolution vectorial coastline is used to constrain the GNOME simulations preventing land jumping. In applications reported in this article, the coastline was extracted from the Global Self-consistent, Hierarchical, High-resolution Shoreline Database (GSHHS, Wessel and Smith, 1996), available in several resolutions. The creation of the coastline was done with Python tools which can be applied to any world region.

The GNOME results presented in the next sections simulated spills as 1000 splots of non-weathering oil. The model was forced by surface currents and wind with the same spatial resolution of its associated ocean model grid. In terms of temporal resolution, the wind and current data were used as daily averages in the next two sections, which show GNOME results of the Galician and Brazilian implementations (Sections 5 and 6), and as snapshots with 4 h periodicity for the Northern Gulf of Mexico implementation (Section 7). The uncertainty associated with the currents was 10% in both east–west and north–south current components. The uncertainty associated with the wind direction was 23°, and with intensity, $1 \text{ m} \cdot \text{s}^{-1}$. Several experiments were done, changing the oil type and changing the wind and currents uncertainties. The results of these experiments are not shown, but are discussed when appropriate.

5. The IEO-A Coruña operational forecast system

The main focus of research and applications at IEO-A Coruña is the impact of circulation on ecosystem response in support of the intense IEO research in the area. The region of interest is the western and northern Iberian shelf and slope area, from the northern Portuguese shelf to the French Biscay shelf. The modelling configuration consists in two grids of resolution 1.3 km and 4 km, which run online nested. The implementation takes into account most of the relevant physical phenomena in the area: upwelling, river plumes and slope and shelf currents. As surface forcing the model uses realistic hourly limited-area atmospheric operational model results from WRF-MeteoGalicia (Meteogalicia implementation of the Weather Research and Forecasting Model, http://www.meteogalicia.es) and

HIRLAM-AEMet (Agencia Estatal de Meteorología – Spain – implementation of the High Resolution Limited Area Model, http://www.aemet.es).

The model configuration in use has been shown to simulate reasonably well the variability of shelf and slope circulation in response to wind events and to topographic differences in the area (Otero et al., 2008; Otero et al., 2009).

We have performed a hindcast simulation of the Prestige oil spill with our OOF$_\varepsilon$ and GNOME tools (Fig. 1). The main advantage of using this period in the testing is the abundant published related studies (Albaigés et al., 2006; Álvarez-Salgado et al., 2006; Ruiz-Villarreal et al., 2006a). The Prestige vessel broke in two and sank by 8 h of November 19th, 2002, releasing more than 60,000 tonnes of heavy oil, which travelled eastward and progressively dispersed due to the action of sea surface currents, waves and winds. This fuel stranded in several places along the Galician coast from the 29th November on. The GNOME trajectories proved the ocean model configuration ability to reasonably reproduce the arrival to the Galician NW coast at the end of November of the first oil patch.

The location of the spill was followed by planes and ships (Montero et al., 2003). Fig. 2 illustrates the spill trajectory between the day of the accident and the 30th of November, when the spill approached the coast. The simulations predict the transport of oil towards the coast and stranding of oil slicks from the 29th November. The comparison of modelled and observed oil spill locations, indicate our model predicts a faster advance towards the coast. However, we must note that oil spill locations were obtained in rough sea conditions and are an estimation of the actual position of the dispersed slicks. Additionally, there is uncertainty in the meteorological forcing that needs to be taken into account when evaluating oil spill predictions. Otero and Ruiz-Villarreal (2008), compared different wind products for autumn 2002, when the Prestige sank, and reported differences in wind patterns and in the results of ocean simulations forced by the different atmospheric products. The comparison included the HIRLAM-AEMET 0.2° 6-hourly model results used in the present simulations. The model predicts dispersion due to ocean mesoscale, especially on days 26th and 27th. Enhanced dispersion in the offshore area was put forth by Hackett (2004), who also noted that different ocean models predicted different mesoscale. As reviewed in Ruiz-Villarreal et al. (2006a,b), all reported model simulations of the Prestige oil spill (Hackett, 2004; Daniel et al., 2004; Carracedo et al., 2006) show strong differences in results and therefore on stranding positions. Furthermore, they are not focused on coastal circulation and none of them introduced river plumes. The configuration we have presented uses realistic forcing and includes river plumes. The variability of river plumes during the days of the simulation can be followed by the evolution of the surface salinity colour plot. Until 29th, downwelling conditions induced confinement of the river plume. On 29th and 30th, when the oil spill approached the coast, a relaxation of the wind induces an offshore displacement of the river plume. Our OOF$_\varepsilon$ – GNOME results indicate that the offshore displacement of the river plume can influence oil spill dispersion near the coast and avoid stranding in front of the Galician Rias as Montero et al. (2003) suggested. Fig. 2 also shows the ASAR (Advanced Synthetic Aperture Radar) image of the Galician west coastal region for the 2nd of December, released by the European Space Agency. Four major zones of oil spills are visible in the ASAR data (indicated with ellipses). They are very close to the shore and dispersed north of 42.3°N, indicating spill dispersion as it approached the coast, as predicted by our simulations. No good ASAR images are available in the period of oil spill transport towards the coast (see e.g. the European Space Agency web site about the satellite imagery related to the Prestige oil spill, ESA,
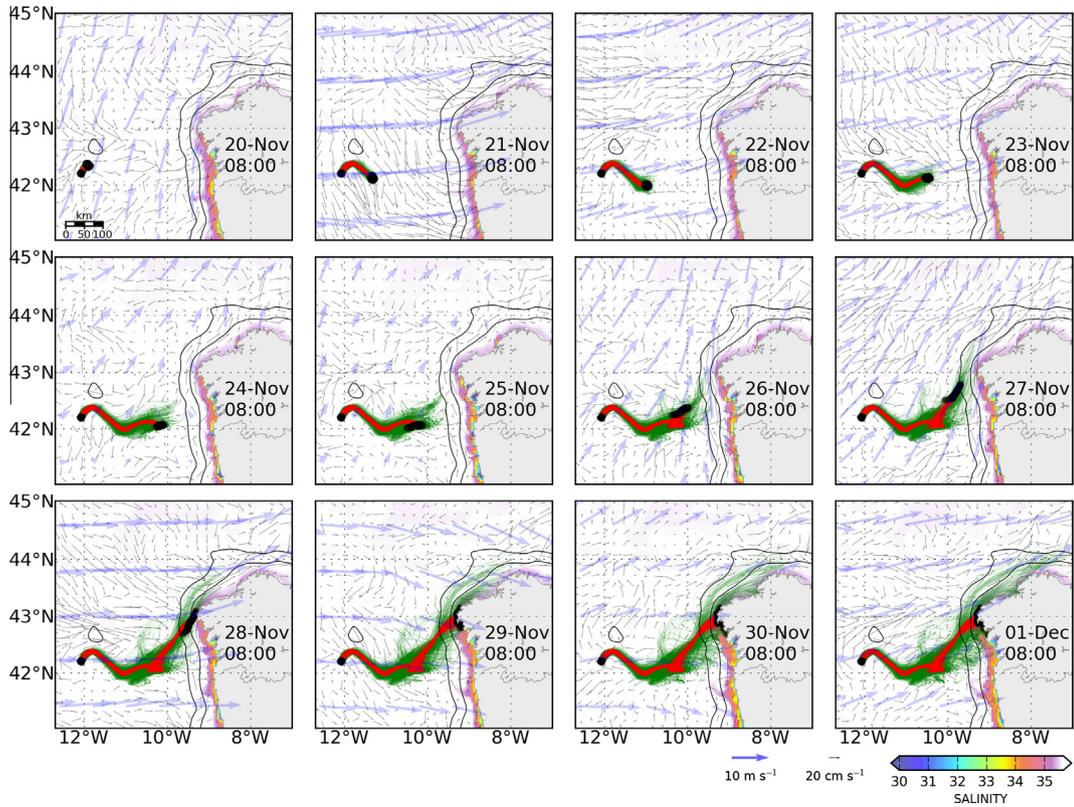
Fig. 1. GNOME oils trajectories from the Prestige main spill. The accident occurred by 8 h on November 19th 2002 at 42.20°N × 12.08°W. The oil path is shown in red (*Best Guess*) and its uncertainty in green (*Minimum Regret*). Black dots indicate the initial and final location of the *Best Guess* simulated splots. Wind and currents are instantaneous at 8 h of each day. Black solid lines represent the 200 and 1000 m isobaths. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)
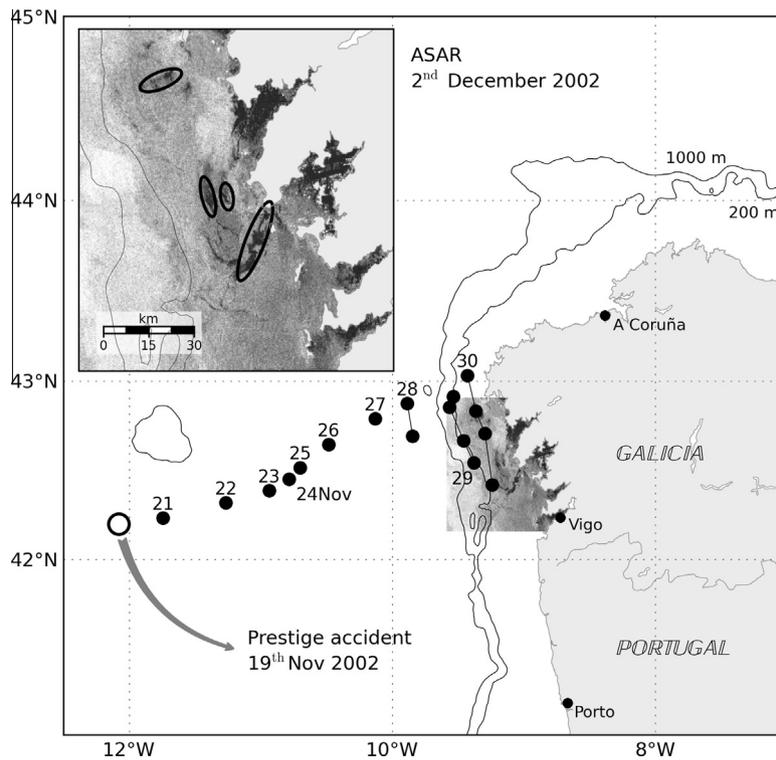
Fig. 2. Trajectory of the Prestige oil spill since the accident until the 30th of November 2002 and ASAR image of the Galician west region on the 2nd of December 2002.
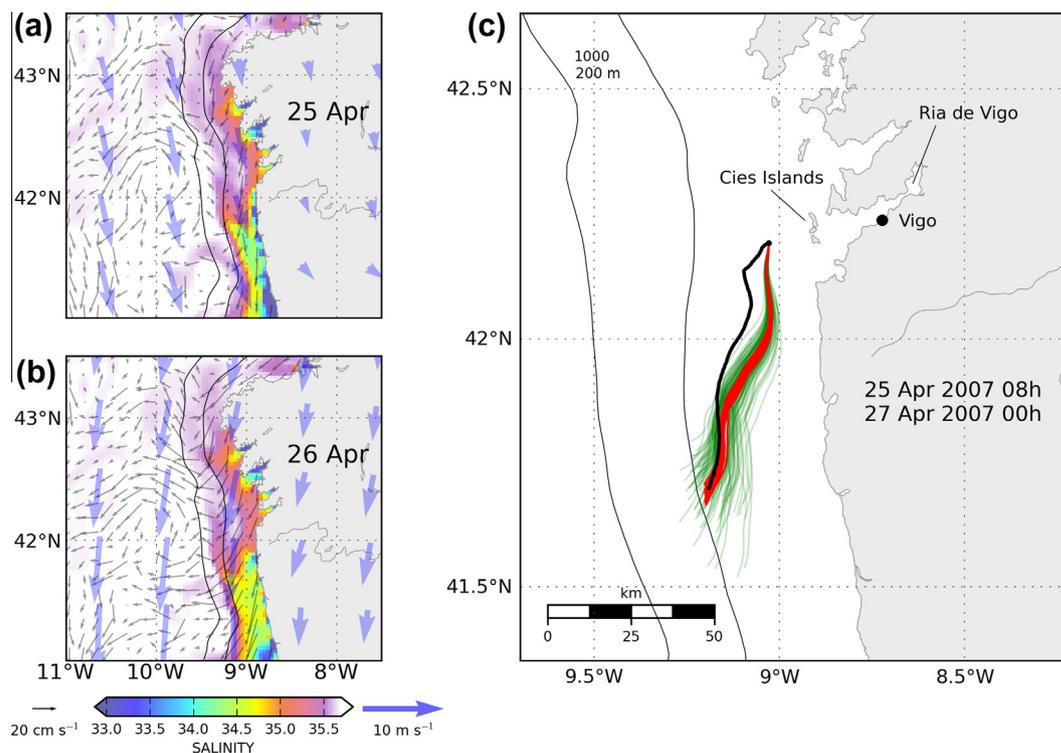
Fig. 3. Forecasts of surface salinity and velocities together with surface wind forcing (a and b) for 25–26th of April 2007, during the 2007 annual exercise of the Spanish National Marine Pollution Contingency Plan. Right panel (c) shows the trajectory of an ARGO buoy released at 8 h of the 25th of April 2007 until the end of day 26th (black line), and the GNOME simulated trajectories for the same period in red with associated uncertainty in green. Black solid lines represent the 200 and 1000 m isobaths.

2003). The only good image before this one is for November 17th, showing the route of the ship before sinking (e.g. Montero et al., 2003). For more information about this ASAR data processing see Palenzuela et al. (2006).

The forecast capabilities of the OOF$_\varepsilon$ – GNOME system were shown in several pollution prevention exercises that were done during 2006 and 2007, as part of the National Marine Pollution Contingency Plan (Plan Nacional de Contingencias por Contaminación Marina Accidental). At this stage, the model configuration was executed in forecast mode, and results were provided to managers of the simulated crisis in order to evaluate the pollution response protocols (e.g. Sotillo et al., 2008). Fig. 3 shows an example of these exercises carried out during 25–26th of April 2007, when a virtual accident was simulated near the coast of Vigo (exercise Vigo 2007). Model execution controlled by OOF$_\varepsilon$ provided information on the foreseeable evolution of currents during the days of the exercise. As the exercise coincided with the commencement of an upwelling event, the model predicted southerly surface currents over the shelf and an offshore expansion of the river plume. This information implied that dispersion of the oil spill originally on the adjacent shelf to the Ría de Vigo was likely to be transported offshore and dispersed. As part of Vigo 2007, an ARGO buoy was released in front of Vigo, five miles west of Cíes Islands at 8 h of April 25th. Fig. 3c shows the trajectory of the buoy together with the GNOME simulated trajectories, using the ocean model data, which closely follow the observed path moving southwestward.

OOF$_\varepsilon$, apart from steering model execution and plotting, is a useful tool for the distribution of forecasts and analysis to different end users. As an illustration of this capability, during spring 2007 and 2008, the daily runs of the model were generated and distributed with the developing version of OOF$_\varepsilon$ for providing information on event variability of circulation during the PELACUS oceanographic cruises. These cruises consist of radial transects of observations (egg acoustic surveys, plankton and thermohaline properties)

performed every spring and distributed along the area from the western Iberian shelf to the southeastern Bay of Biscay. This intensive sampling of the pelagic ecosystem is made in support of the EU Common Fisheries Policy. The survey lasts for one month and variability of circulation in response to wind events has to be resolved in order to interpret the observations. Thanks to OOF$_\varepsilon$, the evolution of surface winds and the ocean circulation at various depths during the cruise was highlighted, illustrating the strong event variability and helping to interpret the observed data (Fig. 4).

6. The REMO operational forecast system

The ocean modelling operational implementation for the Brazilian region was done at Federal University of Bahia in the context of the research project Oceanographic Modelling and Observation Network (Portuguese acronym REMO), which aims to improve the understanding of circulation in the Brazilian waters, including mesoscale, shelf and tidal circulation. One of the main objectives of REMO is the development of assimilative numerical oceanic models for the Brazilian shelf/slope region in support of the activities of the oil industry. After a phase of pre-operational development in 2008, operational forecasts started on the 1st of July 2009. Analysis (nowcasts) and 5 day forecasts are produced ever since (the modelling results are available at the site http://oceano.fis.ufba.br/oof). This system is currently under development to improve the quality of the forecasts.

The model domain covers the southeast and part of the northeast Brazilian region. The grid is rotated to approximately follow the coast, extending offshore about 900 km between the latitudes 31°S and 13°S at coast (Fig. 5). The northern boundary is the northernmost latitude reached by the South Equatorial Current bifurcation at the surface. The southern boundary includes the SEC bifurcation in depth and is somehow above the Brazil–Malvinas Confluence. The north–south grid resolution is about 9 km and
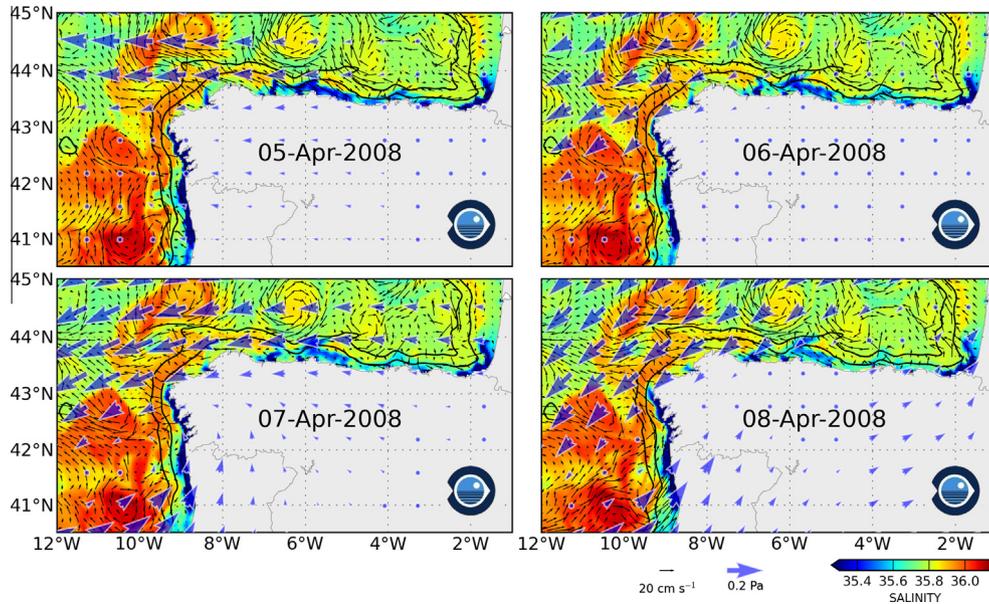
Fig. 4. Output of OOF$_\varepsilon$ at IEO-A Coruña during the PELACUS cruise in spring 2008. The panels show surface salinity, currents and wind forcing between 5th and 8th of April 2008, when PELACUS sections on the northwestern and northern Galician coast (north from 43°N between 9.5°W and 7°W) were occupied. Easterly winds on the north coast on April 5th were associated with upwelling and offshore surface currents in the northern coast. During the relaxation of easterly wind and veering to northeasterly wind, surface flow turned mainly westwards in the northern Galician coast. Black solid lines represent the 200 and 1000 m isobaths.
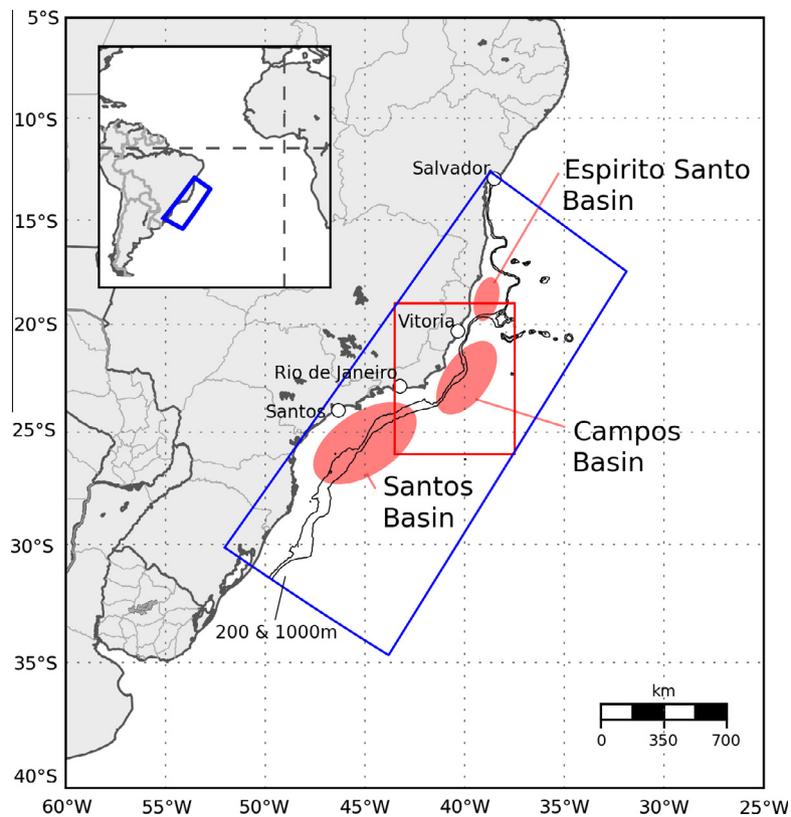
Fig. 5. Brazilian operational model domain. The model grid covers the Brazilian coast south of Salvador and has a variable resolution, increasing shoreward. The three largest offshore oil exploration basins are indicated. The enclosed red rectangle shows the GNOME oil spill model domain.

the cross-shore resolution is variable, from 2 km near the coast, where higher bathymetric gradients are found, to 12 km offshore. The model runs with lateral monthly climatologycal conditions from OCCAM (Ocean Circulation and Climate Advanced Modelling System, Coward and Cuevas, 2005) with a resolution of 1/12°, but

the system is transitioning to obtain them from a regional downscaling configuration of the ocean model HYCOM (HYbrid Coordinate Ocean Model, http://www.hycom.org). Atmospheric data for momentum, salt and heat air-sea fluxes is provided by GFS (Global Forecast System, Environmental Modeling Center, 2003), a global

spectral data assimilation forecast model. The horizontal resolution of GFS outputs is 0.5° and the output sampling rate is 3 h (the same rate is used to feed the ocean model with atmospheric data). In the near future the atmospheric data is expected to be provided by a higher resolution local atmospheric model. Tidal elevations and barotropic currents are also used to force the model boundaries, with the main primary and long period constituents obtained from the global dataset TPXO 7.1 (Egbert and Erofeeva, 2002).

For a full description of the operational system and preliminary results/validation, see Marta-Almeida et al. (2011a).

6.1. Oil spill simulations: forecast trajectories for the Campos Basin

The Campos Basin is the main offshore oil exploration site along the Brazilian coast. It extends from Vitoria-ES to Arraial do Cabo (Fig. 5) on the northern coast of the state of Rio de Janeiro, in an area of approximately $115 \times 10^3 \, km^2$ (da Costa Fraga et al., 2003). This basin currently has more than 40 units of oil production and processing, operating more than 500 wells, with a daily production of about 1.5 million barrels, being responsible for 85% of the Brazilian oil production. The oil production in the Campos Basin is similar to some OPEC (Organization of Petroleum Exporting Countries) countries. The production units are divided into three types of systems: fixed platforms, semi-submersible and FPSO vessels (Floating, Production, Storage and Offloading).

The location of six platforms of the Campos Basin was used as the origin of hypothetical oil spill accidents. GNOME forecasts of oil trajectories were done for different seasons, wind conditions, type of oil and uncertainty of wind and surface currents. The release of splots was done in three transects between the consecutive pairs of platforms indicated in Table 1. Each transect spilled the 1000 splots at 00 h (instantaneous oil spill, IOS), and their trajectories were calculated using the ocean model five days forcing winds and forecasted surface currents. In another set of experiments, the same amount of splots was released continuously during the five days of simulation (continuous oil spill, COS). In this case the release location chosen was the geographical centre of each of the three transects.

These experiments were done in several days along 2010 and 2011, covering different seasonal patterns of circulation and forcing winds. The surface currents in the region are predominantly southward (Brazil Current) and the winds have a prevailing northerly component, with seasonal variations controlled by the intensity and variability of the South Atlantic High Pressure System, resulting in strong northeasterly winds in the summer which become weaker during the austral winter (Grodsky and Carton, 2003). Of special interest are the events of wind caused by frontal activity which may result in wind reversal, i.e., directed to north or to the coast. Cold fronts occur during all the year with a period of one to two weeks (Garreuad, 2000) but are more common during the winter and spring (Lupo et al., 2001). The duration of these cold events is on average three days for the south Brazil coast (Rodrigues et al., 2004). The coastline of Campus Basin region has

a concave geometry. In theory, is thus unlikely that the coast may be affected by oil from an offshore accident. Some of our experiments, however, show the possibility of coastal regions of the states of Espírito Santo and Rio de Janeiro being affected by an oil spill at the Campos Basin.

Here we present the results of some of the simulations which exemplify, as case studies, some possible and interesting dispersion patterns. Fig. 6 shows the five days trajectories forecast for an episode during the summer 2011, starting on March 9th, 2011. The wind and currents arrows represent daily averaged values. In the upper panel are shown the results for the full instantaneous release at 00 h (IOS) and in the lower panel are shown the result for the continuous release (COS). In the beginning of the simulation, the region was under the influence of a strong cyclone, centred around 39.5°W × 22°S, so that the oil spill region was forced by easterly winds, with a small southerly component. In both IOS and COS scenarios, the coast at Cabo de São Tomé (cape at the north of the state of Rio de Janeiro, around 41°W × 22°S) was reached during the second day of the simulations, i.e., between 24 h and 48 h after the release (beginning of the release, for the COI case). These GNOME simulation results mean that very fast response mechanisms should be considered by marine safety and environmental agencies. During the third day of the IOS simulations, the cape south of Cabo de São Tomé was reached (Cabo Frio, around 42°W × 23°S). By day four and five (day five for the COS case) all the coastal region between these two capes was fully affected by the accident, in spite of the continuous southward transport of the splots by the Brazil Current.

Fig. 6 shows that an error of about 1° in latitude in the position of the cyclone during the first day would give totally different results. If the cyclone was slightly displaced south, the oil would be drifted by offshore cyclonic winds during the first days of simulation. Notice that the cyclone moves north in the first three days, so, the spill would be affected by shoreward winds anyway. But in the case of full release (IOS) the splots would be transported offshore during one or two days, so that the probability of reaching the coast during the next days, even being under shoreward wind conditions, would be strongly diminished, or at least, contingency timing would be much more favourable. Of course, in the case of the continuous emission the scenario would be different because there are always particles in the release region, even if some have been transported offshore.

Simulations with weathering spills (like crude, diesel, etc.) result in a very similar dispersion pattern and make sense only in case of quantitative analysis. In our simulations the splots correspond to an arbitrary concentration of pollutant, so that the analysis is qualitative. Quantitative studies would require real data of spilled type, times and quantities.

All the simulations have been repeated doubling the uncertainty associated with winds and currents. In general the dispersion area increased about 10–20%. This was not enough to affect greatly the transport of the pollutant, but increased the quantity of splots reaching the coast in simulations where the coast was not affected or very slightly affected.

Another set of simulations with interesting features is shown in Fig. 7. It corresponds to a late winter scenario, starting on the 18th of September 2010. The wind is highly variable during this five days simulation, being weak during the first day, from southwest in the next two days and then from northeast. Worth to notice in these IOS simulation results is the large separation of splots from the first transect (northernmost) and the other two. This separation is already visible in the first day and increased through the simulation. The original separation between transects is quite small (about 50 km) but the circulation regimes may be quite different. This feature was more or less clear in all the simulations and may indicate that the dynamic system is unstable in the region,

Table 1
Location and type of Campos Basin offshore platforms used as locations of hypothetical oil spill accidents.

Transect	Platform	Lon (°W)	Lat (°S)	Type	Depth (m)
T1	FPBR	39.817	21.934	Semi-submersible	1258
	P-31	39.966	22.129	Semi-submersible	302
T2	PPG-1	40.329	22.255	Fixed	101
	PCH-1	40.480	22.432	Fixed	117
T3	P-08	40.546	22.673	Semi-submersible	423
	PPM-1	40.762	22.798	Fixed	115
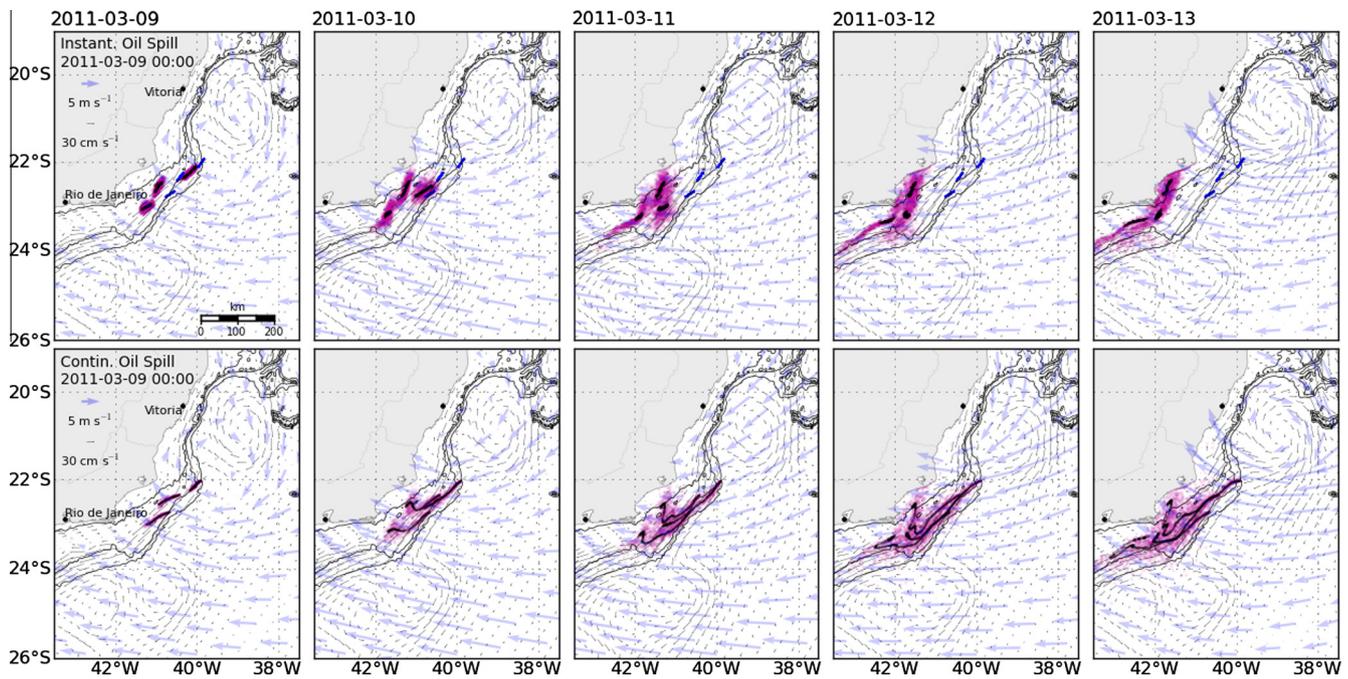
Fig. 6. Oil spill locations of a GNOME simulation, forced with five days forecast data, of a scenario starting on March 9th, 2011. The upper panels show results for the total release of the splots at the begining of the simulation. The lower panels show results for the continuous release during the five days. The wind and currents depicted are daily averages. The black and magenta dots correspond to the *Best Guess* and uncertainty results, respectively. The contours are the isobaths 50, 200 and 1000 m.
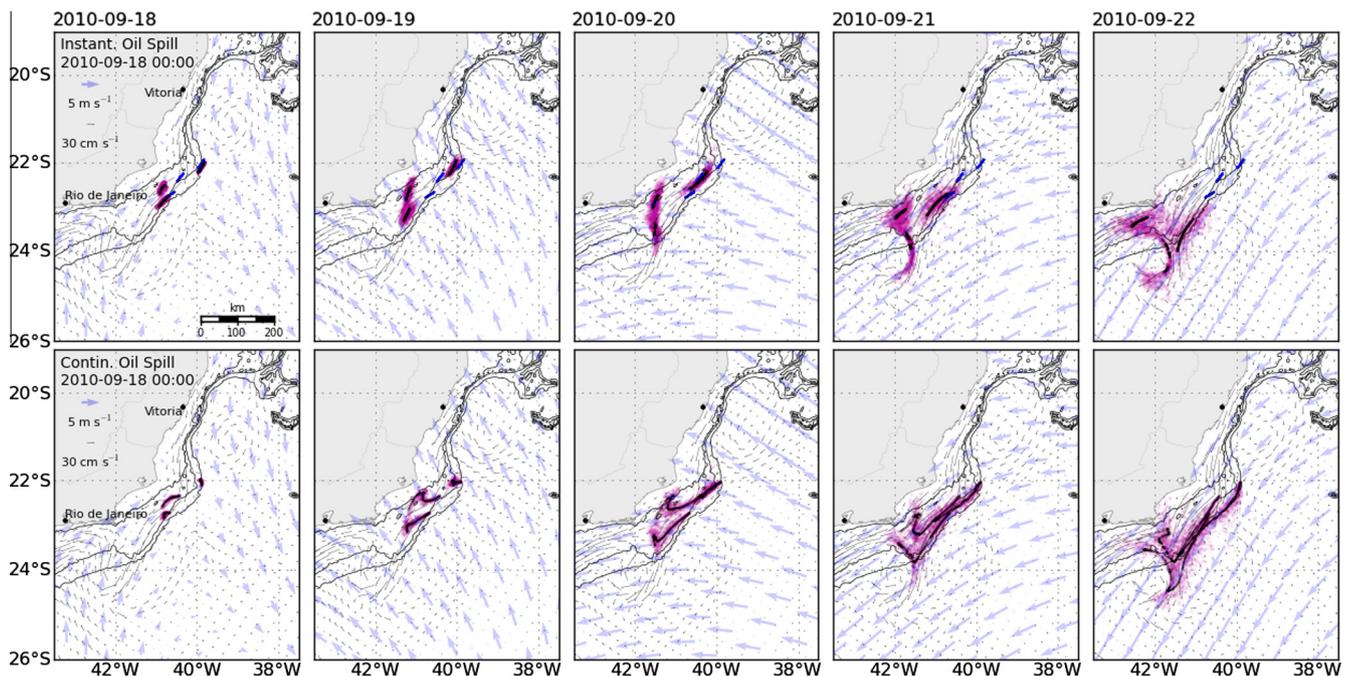
Fig. 7. Same as Fig. 6 but for an episode starting on the 18th of September 2010.

with the existence of a weak repellor between the first transect and the others. Apparently, this instability has relation with the tidal circulation, i.e., it looks to be dependent on the tidal phase. In the continuous release (Fig. 7, lower panel) the importance of the tidal phase vanishes since the emissiom crosses all the possible phases. Indeed no different behaviour distinguishes the splots from the three COS locations.

The last results, shown in Fig. 8, illustrate a scenario where the wind is from south during the 5 days of simulation (with variable zonal component). Because the underlaying currents are

southward and wind drifts to north, the result is a very elongated pollution region, threatening an extensive coastal region of the states of Espírito Santo and Rio de Janeiro, more than 300 km by the fifth day of simulation.

7. The TXLA operational forecast system

The Texas–Louisiana (TXLA) operational model covers the entire Texas and Louisiana shelf and slope area (Fig. 9), with a resolution of ∼500 m near the coast, and ranging from 1 to 2 km on
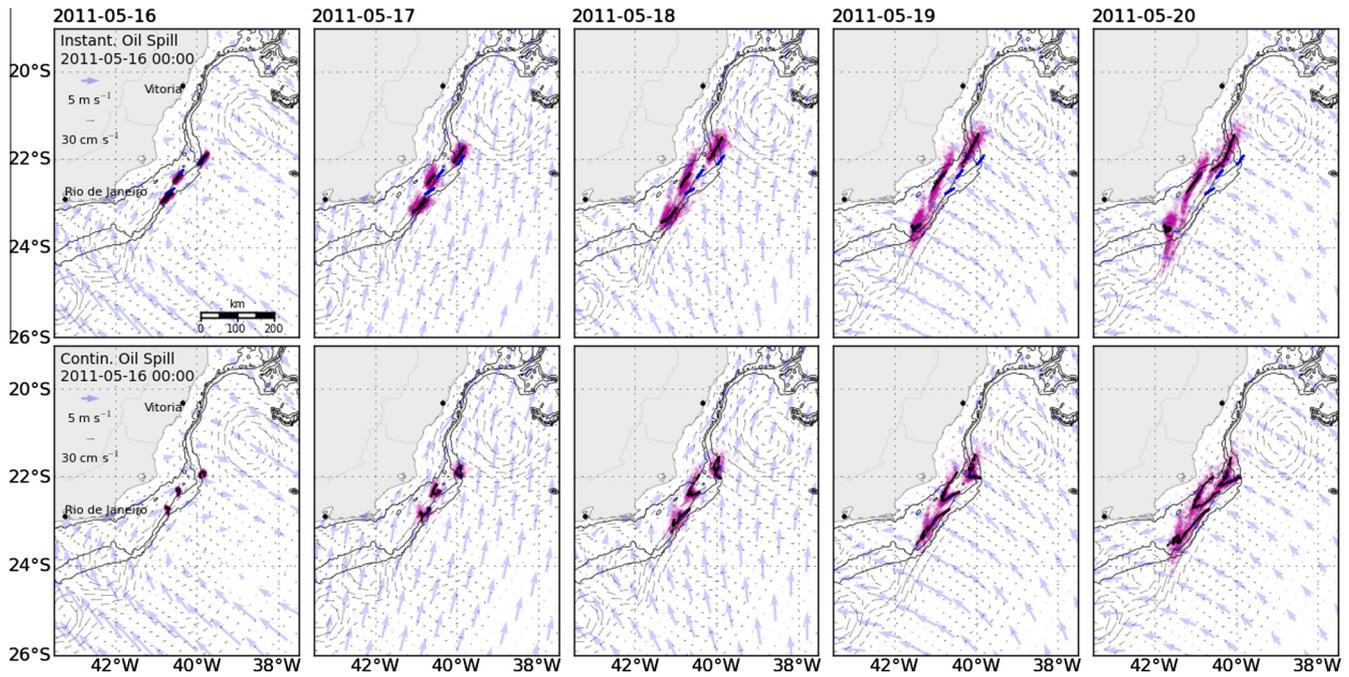
Fig. 8. Same as Fig. 6 but for an episode starting on May 16th 2011.
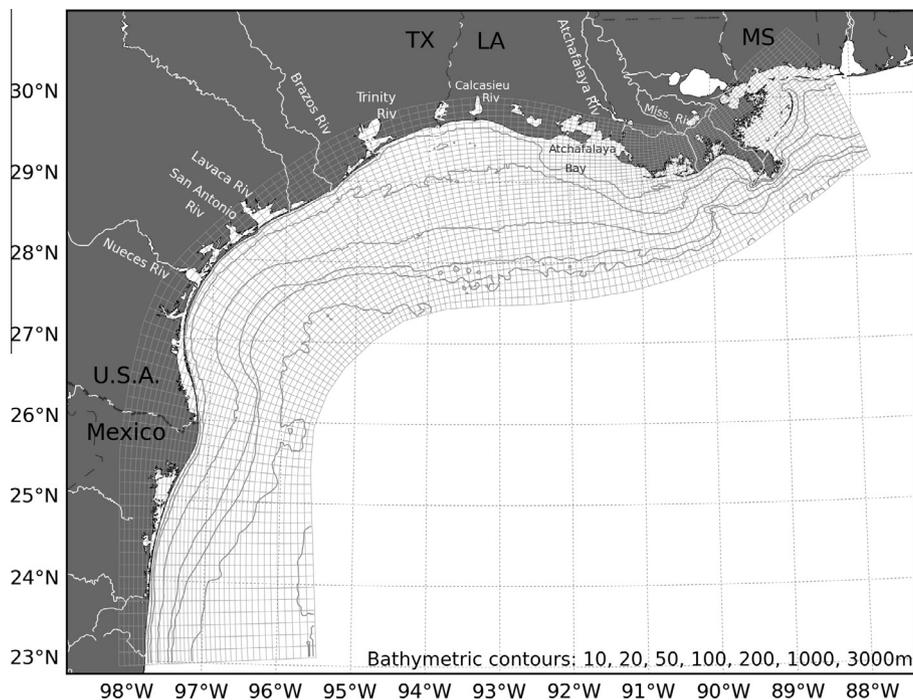
Fig. 9. Texas–Louisiana numerical grid shown in relation to bathymetry (black contours) and the location of geographic features and landmarks. For clarity only one in five grid points is plotted in the along and cross shore direction.

the outer slope area (higher near the Mississippi Delta). The model was initialized on the 1st of February 2003, with the initial and open boundary conditions provided by the Gulf of Mexico Hybrid Coordinate Ocean Model (GOM-HYCOM) (http://www.hycom.org), a hybrid isopycnal-sigma-pressure coordinate ocean model with horizontal resolution of 1/25°. HYCOM assimilates data from several sources, including along-track satellite altimetry observations, satellite-measured and in situ surface temperature, and vertical temperature profiles from XBTs, ARGO and moored buoys.

Assimilations are done with the Navy Coupled Ocean Data Assimilation system (NCODA).

The hindcast model is forced with 2-d wind, and sea surface heat (short wave) and salt fluxes from the North American Regional Reanalysis (NARR) dataset. The forcing has 3 h temporal resolution and 32 km spatial resolution so that it is able to resolve the strong land/sea breeze on the shelf. Long wave radiation, latent, and sensible heat fluxes are calculated in ROMS internally. Fresh water fluxes from the Mississippi and Atchafalaya Rivers are

specified using daily measurements of Mississippi River Transport at Tarbert Landing by the US Army Corps of Engineers. Fresh water fluxes from the other seven rivers (the Nueces, San Antonio, Lavaca, Brazos, Trinity, Sabine, Calcasieu Rivers) are prepared based on the USGS (US Geological Survey) Real-Time Water Data for the Nation. Tides are not included, but are known to be small in the region (DiMarco and Reid, 1998; Gouillon et al., 2010). The hindcast simulation is run for about eight years from 2003 to 2011. For the forecast model, the atmospheric forcings are changed to GFS (Global Forecast System) since NARR has neither nowcast or forecast. The horizontal resolution of GFS outputs is 0.5° and the output sampling rate is 3 h.

This model parametrisation was implemented pre-operational using OOF$_\varepsilon$ (Marta-Almeida et al., 2011b) since the 1st of July 2011 and since then is providing daily analysis and five days forecast. For a more detailed description of this forecast system and model validations see Zhang et al. (2012b). The pre-operational results are made available through the site http://pong.tamu.edu/oof where end users can visualise several ocean state variables and currents at several depths. The forecast model output is also available in the local OPeNDAP server http://pong.tamu.edu/opendap) to facilitate data extraction and visualisation. Model five days forecast wind input and model output currents with sampling rate of 3 h are converted every day to a GNOME ready format.

Only huge oil spills attract the public attention, but oils leaks are frequent in the Northern Gulf of Mexico. As one of the energy centres in the world, there are more than 1.2 billion barrels of oil passing near Texas and Louisiana wetlands, bays and beaches each year. Oil spill accidents happen more than 900 times per year on average on the Texas and Louisiana shelf and slope. To locate and track the oil may not be easy and to spot it in different times and places is uncommon. As a practical example of applicability of model forecasts and GNOME, the simulated trajectory of a real spill is compared with observations (the oil was spotted five times). The oil spill accident took place at the Galveston Lightering Zone by 2 h (GMT) on October 21st 2009 due to a collision between a supply vessel and the Liberian heavy fuel oil carrier Krymsk. The tanker vessel lost about 60 to 80 m^3 of heavy fuel oil into the Gulf

Fig. 10. Simulation of the Krymsk oil spill (blue lines) and locations where oil was sighted by spotter aircrafts (green dots). The spill accident occured by 2 h GMT on the 21st of October 2009 when the heavy fuel tanker vessel Krimsk leaked 60–80 m^3 of oil at the Galveston Lightering Zone. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

of Mexico. The green dots shown in Fig. 10 are the locations where the oil have been spotted by planes from October 22nd to 25th, 2009. The blue lines shows the trajectory simulated with GNOME using one week TXLA surface currents and wind hindcasts. The trajectory predicted by TXLA is consistent with oil spotted on the shelf and shows the effect of a series of cold fronts passing through while the oil is transiting the coast.

8. Conclusion

We describe the development and implementation of a tool for the operationalization of ocean forecast models (OOF$_\varepsilon$) and the applicability of the ocean model outputs to the NOAA oil spill model GNOME. The possibility to set-up realistic ocean modelling forecast configurations and predict oil spill in different situations, makes both tools highly versatile and fully relocatable. OOF$_\varepsilon$ and GNOME constitute an efficient set of instruments able to be easily implemented in order to provide oceanic and oil spill forecasts.

The development of OOF$_\varepsilon$ at IEO-A Coruña proved to be important for marine pollution exercises done in the Galician coast. GNOME simulations forced with data from the ocean forecasts compared well with the trajectories of a lagrangian float released during one of the annual exercises (Vigo 2007) of the Spanish National Marine Pollution Contingency Plan. GNOME forced with ocean model hindcast data for the period of the Prestige oil spill accident, reproduced the trajectory and arrival of the oil at the Galician northwest coast by the end of November 2002.

The ocean model forecasts of the OOF$_\varepsilon$ implementation for the Brazilian southwest region were used to feed the oil spill model in several scenarios during 2010/2011, simulating the fate of oil from hypotetical accidents in offshore extraction platforms of the Campos Basin, the major Brazilian extraction site. The results for these GNOME simulations appear to be very sensitive to the dynamical system. Small differences in the location of the spill or the position of atmospheric mesoscale features may have a determinant importance on the consequences of the oil spill. Another important issue is the model resolution. In the outer shelf and slope, the grid smoothing required when dealing with terrain-following vertical coordinates, may displace the isobaths by dozens of km. It means the location of some spill over the slope may actually be considered at a much lower depth by the ocean model, and consequently, with a different dynamic regime (tidal currents may change drastically when the tidal wave crosses the continental slope, for instance).

The Northern Gulf of Mexico OOF$_\varepsilon$ based pre-operational forecast system has been used to understand the dynamics and oceanic processes in the Texas–Louisiana shelf and slope region. The model forecasts are routinely converted to a GNOME-ready format and may be used to predict the fate of an eventual oil spill, in a sensitive and economically important region where small leaks are quite frequent. The fair comparison of the GNOME trajectories with aircraft spotted oil of a leak from the Krimsk vessel, occurred in October 2009, gives confidence in the ocean modelling implementation and in the applicability of the oil spill model.

The improvement of oil spill prediction capability is dependent on increasing the accuracy of the oceanic and atmospheric model. Higher spatial resolution, tuning parametrisations in use, with systematic observations, and development of data assimilation procedures, are the right steps for higher quality in the results. Oil spill models may be more dependent on the ocean physics than in the complexity of the oil advection, diffusion and weathering algorithms. In this way, GNOME may replace the implementation of highly complex oil spill models in many regions and situations. At least while the ocean model does not achieve an acceptable level of confidence, it may not make sense to waste resources trying to develop and implement a sophisticated oil model.

Acknowledgements

References

Albaigés, J., Morales-Nin, B., Vilas, F., 2006. The prestige oil spill: a scientific response. Mar. Pollut. Bull. 53, 205–207.

Álvarez-Salgado, X.A., Herrera, J.L., Gago, J., Otero, P., Soriano, J.A., Pola, C.G., García-Soto, C., 2006. Influence of the oceanographic conditions during spring 2003 on the transport of the Prestige tanker fuel oil to the Galician coast. Mar. Pollut. Bull. 53, 239–249.

Amorim, F.N., 2005. Caracterizaç ao Oceanográfica da Baía de Camamu e Adjacências e Mapeamento das Áreas de Risco a Derrames de Óleo. Master's thesis, Universidade Federal da Bahia.

Amorim, F.N., Cirano, M., Marta-Almeida, M., Middleton, J.F., Campos, E.J.D., accepted for publication. Circulation of the Eastern Brazilian Shelf between 10°S and 16° S: a modeling approach. Cont. Shelf Res..

Başar, E., Köse, E., Güneroglu, A., 2006. Finding risky areas for oil spillage after tanker accidents at Istanbul strait. Int. J. Environ. Pollut. 27, 388–400.

Barth, A., Alvera-Azcárate, A., Weisberg, R.H., 2008a. A nested model study of the Loop Current generated variability and its impact on the West Florida Shelf. J. Geophys. Res. 113, C05009.

Barth, A., Alvera-Azcárate, A., Weisberg, R.H., 2008b. Benefit of nesting a regional model into a large-scale ocean model instead of climatology: application to the West Florida Shelf. Cont. Shelf Res. 28, 561–573.

Beegle-Krause, C.J., 2001. General NOAA oil modeling environment (GNOME): a new spill trajectory model. In: IOSC Proceedings. Mira Digital Publishing Inc., Tampa FL, pp. 865–871.

Beegle-Krause, C.J., O'Connor, C., 2005. GNOME Data Formats and Associated Example Data Files. Tech. Rep., NOAA Office of Response and Restoration, Emergency Response Division, Seattle, 49p.

Blower, J., Blanc, F., Clancy, M., Cornillon, P., Donlon, C., Hacker, P., Haines, K., Hankin, S., Loubrieu, T., Pouliquen, S., Price, M., Pugh, T., Srinivasan, A., 2009. Serving GODAE products to the ocean community. Oceanography 22, 70–79.

Brekke, C., Solberg, A.H.S., 2008. Classifiers and confidence estimation for oil spill detection in ENVISAT ASAR images. IEEE Geoscience and Remote Sensing Letters 5 (1).

Broström, G., Carrasco, A., Hole, L.R., Dick, S., Janssen, F., Mattsson, J., Berger, S., 2011. Usefulness of high resolution coastal models for operational oil spill forecast: the "Full City" accident. Ocean Sci. 7, 805–820.

Carracedo, P., Torres-López, S., Barreiro, M., Penabad, E., Leitáo, P.C., Pérez-Muñuzuri, V., 2006. Improvement of pollutant drift forecast system applied to the Prestige oil spills in Galicia Coast (NW of Spain): development of an operational system. Mar. Pollut. Bull. 53, 350–360.

Cheng, Y., Li, X., Xu, Q., Garcia-Pineda, O., Andersen, O.B., Pichel, W.G., 2011. SAR observation and model tracking of an oil spill event in coastal waters. Mar. Pollut. Bull. 62, 350–363.

Cornillon, P., Adams, J., Blumenthal, M.B., Chassignet, E., Davis, E., Hankin, S., Kinter, J., Mendelssohn, R., Potemra, J.T., Srinivasan, A., Sirott, J., 2009. NVODS and the development of OPeNDAP. Oceanography 22, 116–127.

Coward, A.C., Cuevas, B.A., 2005. The OCCAM 66 Level Model: Physics, Initial Conditions and External Forcing. Southampton Oceanography Centre Internal Document 99, Southampton Oceanography Centre, Southampton, UK.

Csanady, G.T., 1973. Turbulent Diffusion in the Environment. Geophysics and Astrophysics Monographs, vol. 3. Springer, p. 248.

da Costa Fraga, C.T., Borges, F.A., Bellot, C., ao, R.B., Assayag, M.I., Petróleo Brasileiro S.A., 2003. Campos Basin – 25 Years of production and its contribution to the oil industry. In: Offshore Technology Conference, Houston, Texas, pp. 865–871.

Daniel, P., Dandin, P., Lefevre, J.-M., Lery, G., Cabioch, F., Gouriou, V., 2004. Forecasting the prestige oil spills. In: Proceedings of the Interspill 2004 Conference. Trondheim, Norway.

Daniel, P., Josse, P., Dandin, P., 2005. Further improvement of drift forecast at sea based on operational oceanography systems. In: Coastal Engineering VII: Modelling, Measurements, Engineering and Management of Seas and Coastal Regions. WIT Press, pp. 13–22.

Davidson, F.J.M., Allen, A., Brassington, B., Breivik, Ø., Daniel, P., Kamachi, M., Sato, S., King, B., Lefevre, F., Sutton, M., Kaneko, H., 2009. Applications of GODAE Ocean Current Forecasts to Search and Rescue and Ship Routing. Oceanography 22, 176–181.

DiMarco, S.F., Reid, R.O., 1998. Characterization of the principal tidal current constituints on the Texas–Louisiana Shelf. J. Geophys. Res. 203, 3093–3110.

Egbert, G., Erofeeva, S.Y., 2002. Efficient inverse modeling of barotropic ocean tides. J. Atmos. Oceanic Technol. 19, 183–204.

Environmental Modeling Center, 2003. Global Climate & Weather Modeling Branch: The GFS Atmospheric Model. Tech. Rep., NCEP Office Note 442, Camp Springs, Maryland, USA.

ESA, 2003. European Space Agency: Earthnet Online – Prestige oil spill, Galicia, Spain. <https://earth.esa. int/web/guest/ content?p_r_p_564233524_assetIdentifier =prestige-oil-spill-galicia-spain-1623> last accessed 02.13.

Farzingohar, M., Ibrahim, Z.Z., Yasemi, M., 2011. Oil spill modeling of diesel and gasoline with GNOME around Rajaee Port of Bandar Abbas, Iran. Iran J. Fish Sci. 10.

Ferraro, G., Meyer-Roux, S., Muellenhoff, O., Pavliha, M., Svetak, J., Tarchi, D., Topouzelis, K., 2009. Long term monitoring of oil spills in European seas. Int. J. Remote Sens. 30, 627–645.

Garreaud, R.D., 2000. Cold air incursions over subtropical south america: mean structure and dynamics. Mon. Weather Rev. 128, 2544–2559.

González, M., Ferrer, L., Uriarte, A., Portualdea, A., Caballero, A., 2008. Operational oceanography system applied to the prestige oil-spillage event. J. Mar. Syst. 72, 178–188.

Gouillon, F., Morey, S.L., Dukhovskoy, D.S., O'Brien, J.J., 2010. Forced tidal response in the Gulf of Mexico. J. Geophys. Res. 115, C10050.

Grifoll, M., Fontán, A., Ferrer, L., Mader, J., González, M., Espino, M., 2009. 3D hydrodynamic characterisation of a meso-tidal harbour: the case of Bilbao (northern Spain). Coast. Eng. 56, 907–918.

Grifoll, M., Jordà, G., Espino, M., Romo, J., García-Sotillo, M., 2011. A management system for accidental water pollution risk in a harbour: the Barcelona case study. J. Mar. Syst. 88, 60–73.

Grodsky, S.A., Carton, J.A., 2003. The intertropical convergence zone in the South Atlantic and the equatorial cold tongue. J. Climate 16, 723–733.

Hackett, B., 2004. The Impact of Global Ocean Model Forcing Data on Oil Spill Fate Prediction: A Comparative Study of the Prestige Accident. Tech. Rep. 13, Norwegian Meteorological Institute, Oslo, Norway.

Hackett, B., Comerma, E., Daniel, P., Ichikawa, H., 2009. Marine oil pollution prediction. Oceanography 22, 168–175.

Hackett, N., Breivik, Ø., Wettre, C., 2006. Forecasting the drift of objects and substances in the ocean. In: Chassignet, E.P., Verron, J. (Eds.), Ocean Weather Forecasting, An Integrated View of Oceanography. Springer, pp. 507–524.

Haidvogel, D.B., Arango, H., Budgell, W.P., Cornuelle, B.D., Curchitser, E., Lorenzo, E.D., Fennel, K., Geyer, W.R., Hermann, A.J., Lanerolle, L., Levin, J., McWilliams, J.C., Miller, A.J., Moore, A.M., Powell, T.M., Shchepetkin, A.F., Sherwood, C.R., Signell, R.P., Warner, J.C., Wilkin, J., 2008. Ocean forecasting in terrain-following coordinates: formulation and skill assessment of the regional ocean modeling system. J. Comput. Phys. 227, 3595–3624.

Hetland, R.D., Campbell, L., 2007. Convergent blooms of Karenia brevis along the Texas coast. Geophys. Res. Lett. 34, L19604.

Hetland, R.D., DiMarco, S.F., 2008. How does the character of oxygen demand control the structure of hypoxia on the Texas–Louisiana continental shelf? J. Mar. Syst. 70, 49–62.

Hetland, R.D., DiMarco, S.F., 2012. Skill assessment of a hydrodynamic model of circulation over the Texas–Louisiana continental shelf. Ocean. Model., 64–76.

JMA, 2007. Outline of the Operational Numerical Weather Prediction at the Japan Meteorological Agency. Appendix to the WMO Technical Progress Report on the Global Data-Processing and Forecasting System and Numerical Weather Prediction, Japan Meteorological Agency, Tokyo, Japan.

Klemas, V., 2010. Tracking oil slicks and predicting their trajectories using remote sensors and models: case studies of the Sea Princess and Deepwater Horizon oil spills. J. Coast. Res. 26, 789–797.

Lemos, A.T., Soares, I.D., Ghisolfi, R.D., Cirano, M., 2009. Oil spill modeling off the brazilian coast: the effect of tidal currents on oil fate. Rev. Bras. Geofis. 27, 625–639.

Lupo, A.R., Nocera, J.J., Bosart, L.F., Hoffman, E.G., Knight, D.J., 2001. South American cold surges: types, composites, and case studies. Mon. Weather Rev. 129, 1021–1041.

Marta-Almeida, M., Dubert, J., 2006. The structure of tides in the western iberian region. Cont. Shelf Res. 26, 385–400.

Marta-Almeida, M., Dubert, J., Peliz, A., dos Santos, A., Queiroga, H., 2008. A modelling study of the Norway Lobster (Nephrops norvegicus) larval dispersal in southern Portugal: predictions of larval wastage and self-recruitment in the Algarve stock. Can. J. Fish Aquat. Sci. 65, 2253–2268.

Marta-Almeida, M., Dubert, J., Peliz, A., Queiroga, H., 2006. Influence of vertical migration pattern on retention of crab larvae in a seasonal upwelling system. Mar. Ecol. Prog. Ser. 307, 1–19.

Marta-Almeida, M., Hetland, R.D., Zhang, X., accepted for publication. Evaluation of model nesting performance on the Texas–Louisiana continental shelf. J. Geophys. Res. http://dx.doi.org/http://dx.doi.org/10.1002/jgrc.20163.

Marta-Almeida, M., Pereira, J., Cirano, M., 2011a. Development of a pilot Brazilian operational ocean forecast system, REMO-OOF. J. Oper. Ocean 4, 3–15.

Marta-Almeida, M., Ruiz-Villarreal, M., Otero, P., Cobas, M., Peliz, A., Nolasco, R., Cirano, M., Pereira, J., 2011b. OOF $_\epsilon$: a Python engine for automating regional and coastal ocean forecasts. Environ. Modell. Softw. 26, 680–682.

Montero, P., Blanco, J., Cabanas, J.M., Maneiro, J., Pazos, Y., Moroño, A., Balseiro, C.F., Carracedo, P., Gómez, B., Penabad, E., Pérez-Mu nuzuri, V., Braunschweig, F., Fernades, R., Leitão, P.C., Neves, R., 2003. Oil spill monitoring and forecasting on the *Prestige-Nassau* accident. In: Proceedings 26th Artic and Marine Oilspill Program (AMOP) Thecnical Seminar. Environment Canada, Ottawa, Canada, pp. 1013–1029.

Oliphant, T.E., 2007. Python for scientific computing. Comput. Sci. Eng. 9, 10–20.

Otero, P., Ruiz-Villarreal, M., 2008. Wind forcing of the coastal circulation off north and northwest Iberia: comparison of atmospheric models. J. Geophys. Res. 113, C10019.

Otero, P., Ruiz-Villarreal, M., Peliz, A., 2008. Variability of river plumes off Northwest Iberia in response to wind events. J. Mar. Syst. 72, 238–255.

Otero, P., Ruiz-Villarreal, M., Peliz, A., 2009. River plume fronts off NW Iberia from satellite observations and model data. ICES J. Mar. Sci. 66, 1853–1864.

Palenzuela, J.M.T., Vilas, L.G., Cuadrado, M.S., 2006. Use of ASAR images to study the evolution of the Prestige oil spill off the Galician coast. Int. J. Remote Sens. 27, 1931–1950.

Peliz, A., Dubert, J., Marchesiello, P., Teles-Machado, A., 2007. Surface circulation in the Gulf of Cadiz: model and mean flow structure. J. Geophys. Res., 107.

Peliz, A., Marchesiello, P., Santos, A.M.P., Dubert, J., Teles-Machado, A., Marta-Almeida, M., Le Cann, B., 2009. Surface circulation in the Gulf of Cadiz: 2. Inflow-outflow coupling and the Gulf of Cadiz slope current. J. Geophys. Res. 114, C03011.

Penven, P., Debreu, L., Marchesiello, P., McWilliams, J.C., 2006. Evaluation and application of the ROMS 1-way embedding procedure to the central california upwelling system. Ocean. Model. 12, 157–187.

Rezende, L.F., Silva, P.A., Cirano, M., Peliz, A., Dubert, J., 2011. Mean circulation, seasonal cycle, and eddy interactions in the Eastern Brazilian Margin, a nested ROMS model. J. Coast. Res. 7, 329–347.

Rodrigues, M.L.G., Franco, D., Sugahara, S., 2004. Climatologia de frentes frias no litoral de Santa Catarina. Rev. Bras. Geofis. 22, 135–151.

Ruiz-Villarreal, M., González-Pola, C., del Rio, G.D., Lavin, A., Otero, P., Piedracoba, S., Cabanas, J.M., 2006a. Oceanographic conditions in North and Northwest Iberia and their influence on the Prestige oil spill. Mar. Pollut. Bull. 53, 220–238.

Ruiz-Villarreal, M., González-Pola, C., Otero, P., Días del Río, G., Lavín, A., Cabanas, J.M., 2006b. Circulation in the Galicia–Southern Bay of Biscay: Reanalysis of the circulation influencing the Prestige oil spill. In: European Operational Oceanography: Present and Future. EuroGOOS, pp. 342–348.

Shchepetkin, A.F., McWilliams, J.C., 2005. The regional ocean modeling system (ROMS): a split-explicit, free-surface, topography-following coordinates ocean model. Ocean. Model. 9, 347–404.

Signell, R.P., Carniel, S., Chiggiato, J., Janekovic, I., Pullen, J., Sherwood, C.R., 2008. Collaboration tools and techniques for large model datasets. J. Mar. Syst. 69, 154–161.

Silva, M., Araujo, M., Servain, J., Penven, P., Lentini, C.A.D., 2009. High-resolution regional ocean dynamics simulation in the southwestern tropical Atlantic. Ocean. Model. 30, 256–269.

Silva, P.A., Ramos, M., Marta-Almeida, M., Dubert, J., 2007. Water exchange mechanisms between Ria de Aveiro and the Atlantic Ocean. J. Coast. Res. 29, 1622–1626.

Sotillo, M.G., Fanjul, E.A., Castanedo, S., Abascal, A.J., Menendez, J., Emelianov, M., Olivella, R., García-Ladona, E., Ruiz-Villarreal, M., Conde, J., Gómez, M., Conde, P., Gutierrez, A.D., Medina, R., 2008. Towards an operational system for oil-spill forecast over Spanish waters: initial developments and implementation test. Mar. Pollut. Bull. 56, 686–703.

Wessel, P., Smith, W.H.F., 1996. A global self-consistent, hierarchical, high-resolution shoreline database. J. Geophys. Res. 101, 8741–8743.

Wettre, C., Johansen, O., Skognes, K., 2011. Development of a 3-Dimensional Oil Drift Model at DNMI. Tech. Rep. 50, Norwegian Meteorological Institute, Oslo, Norway.

Yurtsaba, Y., Lisovskiy, R., Gavrilova, T., Semenov, V., Vasenko, O., Kresin, V., 2011. Black Sea Monitoring System for Oil Pollution (BSMS): Ukraine's experience in using different tools for forecasting and preparedness. In: 19th OSCE Economic and Environmental Forum. Prague, Czech Republic.

Zhang, X., Hetland, R.D., Marta-Almeida, M., DiMarco, S.F., 2012a. A numerical investigation of the Mississippi and Atchafalaya freshwater transport, filling and flushing times on the Texas–Louisiana Shelf. J. Geophys. Res. 117, C11009, http://dx.doi.org/10.1029/2012JC008145.

Zhang, X., Marta-Almeida, M., Hetland, R.D., 2012b. A high-resolution pre-operational forecast model of circulation on the Texas–Louisiana continental shelf and slope, continental shelf. J. Oper. Ocean 5, 19–34.

Zhang, X., Smith IV, D.C., DiMarco, S.F., Hetland, R.D., 2010. A numerical study of sea-breeze-driven ocean Poincare wave propagation and mixing near the critical latitude. J. Phys. Oceanogr. 40, 48–66.

Zhang, Z., Hetland, R.D., submitted for publication. A numerical study on convergence of along-shore flows over the Texas–Louisiana shelf. J. Geophys. Res. http://dx.doi.org/10.1002/jgrc.20163.