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A PRE-OPERATIONAL OCEANOGRAPHIC SYSTEM AS PART OF THE RESPONSE TO THE PRESTIGE OIL SPILL IN CANTABRIA (SPAIN)

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ABSTRACT

This paper presents a pre-operational oceanographic system which was developed to provide guidance for the actions taken in response to the Prestige oil spill in Cantabria.

The goal of this system was to forecast the wave climate, tidal and wind currents, and oil spill trajectories to provide the decision-makers with technical assistance in the response to the Prestige oil spill. The two main components of the system were data collection and processing, and its incorporation into numerical models in order to provide forecasts. Regarding the data used, the information from overflights received daily became essential in order to determine correctly the initial position of the oil slicks. Meteorological and oceanographic data were also received daily by means of an emergency protocol established between Puertos del Estado (Spain), the Naval Research Laboratory (USA) and the University of Cantabria.

These data were used to run the trajectory model, the wave propagation model and the shallow depth-integrated flow model. The information generated by the numerical simulations was presented to the decision makers every day in the form of maps of easy and quick interpretation as a tool to assist in response planning.

In addition, in order to develop a defensive or protection strategy for sensitive areas such as estuaries, a hydrodynamic study was carried out by the University of Cantabria in all the estuaries of the region. The results of this study consisted of a boom deployment plan for each of them.

Key words: Prestige, oil spill, operational oceanography

1. INTRODUCTION

On November 19, 2002 the single-hulled oil tanker *Prestige* broke in two about 130 nautical miles off the Spanish coast, west south-west of Cape Finisterre (42º15'N, 12º08'W). The stern of the Prestige sank into 3500 meters of water at 12:00 h and the bow followed at about 16:00 h. The tanker carried 77.000 tonnes of heavy fuel (fuel oil #6) and the initial amount of oil released was estimated at 30.000 tonnes. The oil spill reached Cantabria, which is located about 450 nautical miles east of the sinking point, 17 days later, on December 5, 2002 .

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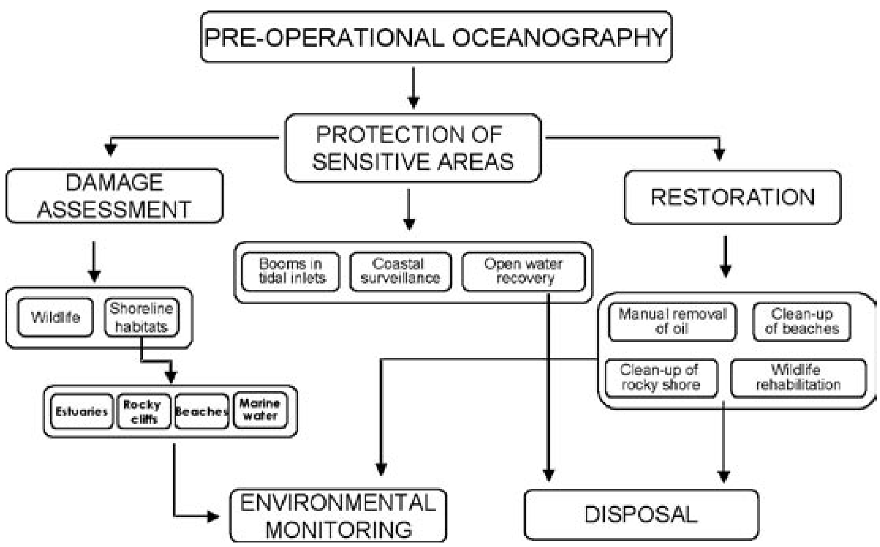
Cantabria is a region located on the Northern coast of Spain. Along more than 200 km of coastline there are a lot of rich marine/estuarine ecosystems, including more than 100 beaches, 14 estuaries and marshes, some of them with shellfish growing areas, European protected areas (Santoña Estuary, Oyambre Natural Park), areas of special protection for birds, etc. Also, economic activities related with the marine environment are very important in the region, such as fishing, commercial harvesting of algae and tourism which is becoming one of the most important factors in the region's development. The area initially affected by the Prestige oil spill covered almost 50 % of the coast, the west coast being the most affected.

In order to protect the Cantabrian coast from the damage induced by the accident of the oil tanker and due to the lack of a regional contingency plan for accidental marine pollution, an emergency spill response system was developed by both the local government of Cantabria and the University of Cantabria with the external collaboration of several national and international agencies and institutions. The organisation of this emergency plan started the day right after the Prestige sank in Finisterre. The main objectives of this plan were:

(1) To establish a pre-operational forecasting system for developing proper response strategies, for making detailed risk assessment and for protecting natural resources.
(2) To perform damage assessment and monitoring of coastal ecosystems
(3) To propose and apply restoration measures in oiled coastal areas

To carry out the aforementioned objectives, the system was organised according to the scheme presented in Fig. 1. Within this plan, developing a pre-operational forecasting system, the technical assessment of the protection of sensitive areas, the damage assessment and monitoring and the analysis of remedial techniques were the tasks that the University of Cantabria was directly involved in.

Figure 1. Structure of the response plan developed in Cantabria



Operational Oceanography can be defined as the activity of systematic and long-term routine measurements of the seas and oceans and atmosphere, and their rapid interpretation and dissemination. Important products derived from operational oceanography are: (1) nowcasts providing the most accurate description of the present state of the sea including living resources, (2) forecasts providing continuous forecasts of the future condition of the sea for as far ahead as possible and (3) hindcasts assembling long term data sets which will provide data for description of past states, and time series showing trends and changes (www.eurogoos.org).

There are some examples of Operational Oceanography Systems that are being developed or are already operating in the world: EuroGOOS (Woods et al., 1996), Nittis et al. (2001), Varlamov et al. (2001). However, in Spain, although a forecasting system for wind conditions and wave climate exists (www.puertos.es), at the time of the spill there was no operational response system ready to be used in an oil spill incident.

This paper outlines the work developed by the University of Cantabria regarding the pre-operational oceanographic system. The goal of this system was to forecast the weather conditions, wave climate, tidal and wind currents and oil spill trajectories to provide the decision makers with technical assessment in the response to the Prestige oil spill. The main components of the system were the overflight information, meteorological and oceanographic data collection and numerical models.

In addition, in order to develop a defensive or protection strategy for sensitive areas such as estuaries, a hydrodynamic study was carried out by the University of Cantabria in all 14 estuaries of the region. The results of this study consisted of a boom deployment plan for each area.

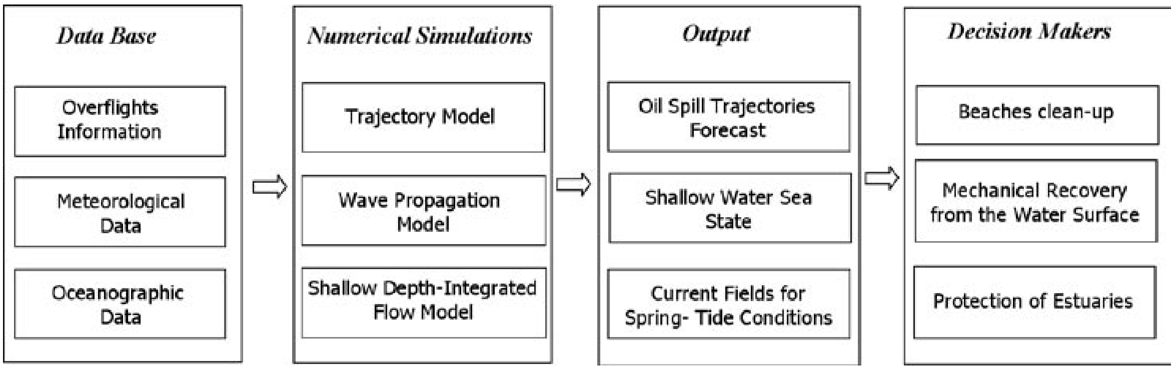
2. STRUCTURE OF THE FORECASTING SYSTEM

The pre-operational forecasting system was developed as a part of the emergency *Prestige* oil spill response plan established in Cantabria. Spilled oil moves horizontally in the marine environment under forcing from wind, waves and currents. To implement these effects the system had to include meteorological and oceanographic data along with overflight information from aircrafts. Next, numerical models were implemented in order to obtain a graphical output (see Fig. 2). The main objectives of this pre-operational system were the following:

• To provide in real time the location, size and predicted trajectory of the oil slicks, in order to evaluate the different strategies to minimise the damage induced by the oil spill in the coast.

• To provide in real time reliable information and forecast for weather conditions, wave climate and tidal and wind currents in order to plan cleaning-up of the shoreline, the recovery of oil from the sea and the protection of estuaries by means of booms. The different components of the system are described below.

Figure 2. Schematic structure of the pre-operational forecasting system



2.1 Description of the data

Overflight data

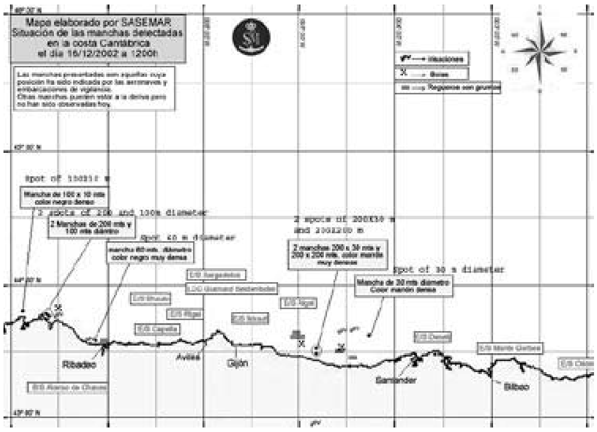
During the initial phases of an oil spill response, information about the release is often incomplete. Although various types of remote sensing techniques are available for detecting and mapping oil distribution, the most reliable technique is visual observations from aircraft (NOAA, 1996). One of the main components of the forecasting system developed by the authors was based on the information from overflights by aircraft belonging to several institutions.

Owing to the great distance that the oil travelled from the accident point to the Cantabria coast, its physical characteristics changed due to various processes usually referred to as *oil weathering*. The heavy crude from the *Prestige* reached Cantabria mainly in the form of water-in-oil emulsion or "mousse" which had approximately 80 percent of water and a brown/orange colouration and a cohesive appearance. This fact multiplied by five the size of the spill and the problems of cleanup and recovery were magnified. Moreover, the oil spill usually arrived in the form of tarballs increasingly fragmented and dispersed. This, combined with the lack of experienced observers, meant that the reports from aircraft were, in general, incomplete.

The overflight data were provided twice a day, at noon and at 17:00 h, by the Spanish Government and by the local government of Cantabria by means of fax and email. Theoretically, the information consisted of overflight hour, oil slick coordinates, coverage area and main characteristics of each oil slick, such as appearance, colour and thickness, but in fact, most of the time there was no information about the size and thickness of the oil slicks. Fig. 3 shows an example of the maps elaborated daily by SASEMAR (the Spanish organisation in charge of sea rescue and pollution control) based on aerial observations for the North of Spain.

All the information gathered from the different sources was processed and reviewed. A worksheet was filled in with these data and other interesting information about each oil slick such as whether there were ships recovering the oil spill at the moment that the overflight was taking place.

Figure 3. Map of the distribution of the oil slicks observed in the North of Spain on December, 16th, 2002 at 12:00h (SASEMAR)



Meteorological and oceanographic data

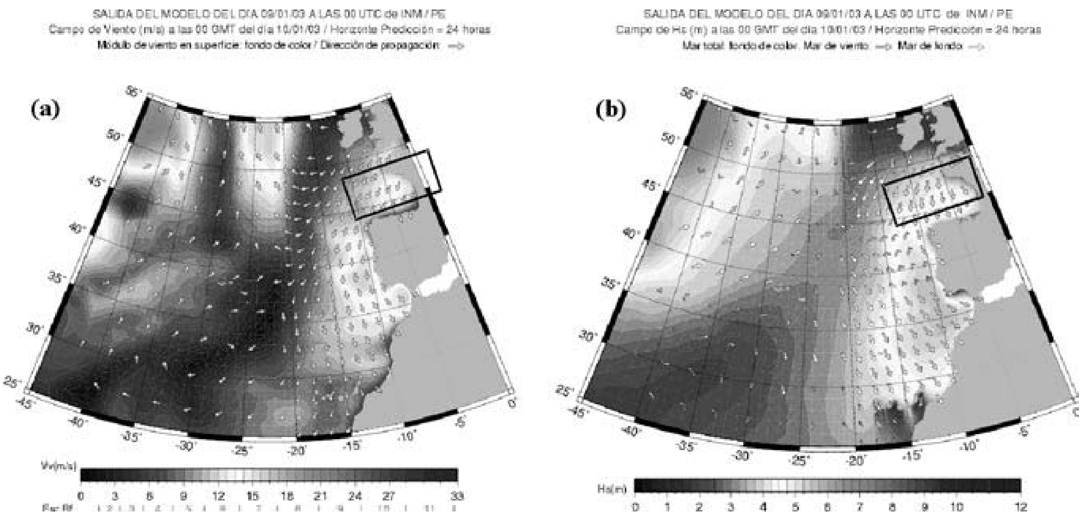
Meteorological and oceanographic conditions are crucial to the evolution of spilled oil in the marine environment. Given that most oils are initially buoyant and float on the sea surface, their transport is dominated by the surface current, winds and wave fields (ASCE, 1996). Although data from coastal stations and meteorological buoy stations would be more precise, direct observations and measurements in the place of incident are very rare. This is because in this work the output of numerical models was used as a source of regular data.

The forecast of wind data was provided by the INM (National Meteorological Institute) based on results from the numerical model HIRLAM (High Resolution Limited Area Modelling), a state-of-the-art analysis and forecast system for numerical weather forecasts (Cats and Wolters, 1996). The forecast model is a hydrostatic grid-point model, the resolution used in this work was 0.5° and the results were the 48 hours forecast of wind velocity and direction with a 6 h time interval.

Sea state conditions data were delivered by Puertos del Estado (State Ports of Spain) as an output from the numerical model WAM, a third generation model which computes spectra of random wind-generated waves (WAMDIG, 1988; Komen et al., 1994). The WAM model solves the energy transfer equation for the wave spectrum. The equation describes the variation of the wave spectrum in space and time due to the advection of energy and local interactions. The grid resolution used in this work was 0.25° and the results were the 48 hours forecast of significant wave height, direction and mean period with a 6 h time interval.

The numerical results of both models were provided by State Ports of Spain (www.puertos.es) daily, at 7:30 h, sending the data to the pre-operational system established at the University of Cantabria. An example of wind conditions and sea state calculated by HIRLAM and WAM respectively is shown in Fig. 4.

Figure 4. (a) Forecast wind field simulated by HIRLAM for January 10, 2003, 0 h.; (b) Forecast significant wave height calculated by WAM for January, 10th , 2003, 0 h. Source: puertos.es



Oceanic currents data were the output of a version of the Princeton Ocean Model (POM) (Blumberg and Mellor, 1987), implemented at the Naval Research Laboratory (NRL). This information consisted of 48 hours forecast of velocity and direction of surface currents in a grid of resolution equal to 0.05° and with a 3 h time interval. The data were sent daily at 17:30 h to State Ports of Spain and finally to the University of Cantabria over the Internet.

2.2 Oil Spill Model

There are a large number of oil spill models available today (Spaulding, 1988; ASCE, 1996; Reed et al., 1999; NOAA, 2002). The capability of the models depend on their final goals. Some were developed for providing rapid and accurate prediction to minimise environmental damage caused by oil, whereas other models were created to be used in oil spill contingency planning and/or training.

When oil is spilled into the sea it undergoes a number of physical and chemical changes that depend on oil properties, hydrodynamic conditions and environmental conditions. Spill models are usually composed of mathematical formulations to represent oil transport and fate processes (advection due to current and wind, spreading, emulsification, evaporation, dissolution, etc). The most sophisticated models currently available consist of a set of algorithms to simulate the transport and fate of oil in three dimensions: MOHID (Miranda et al., 2000), OILMAP (ASA, 1997), Chao et al. (2003), Tkalich et al., (2003).

However, when rapid response is required, models like GNOME, a widely used oil spill trajectory model that simulates oil movement due to winds, currents and tides (NOAA, 2002), is a good choice. Consequently, in this work, owing to the emergency response required in Cantabria during the *Prestige* incident, a two dimensional (2D) lagrangian model was used.

Model Description

The spilled oil at sea is usually transported by the movement of the surface seawater due to wind, wind-generated waves, wind-driven currents and tidal currents, and also it diffuses by turbulence. In order to consider all these factors, a two-dimensional lagrangian model was developed as a part of the pre-operational forecasting system. In this model, the drift process of the spilled oil was described by tracking the numerical particle equivalent to the oil slicks by means of the transport equation for non-weathering hydrocarbons.

Every time step, the new position of the particles is computed by the superposition of the transports induced by the mean flow, tides, wind/waves and turbulent dispersion

$$x_i^{t+1} = x_i^t + u\Delta t + TDT \quad \textbf{(1)}$$

where x_i^{t+1} and x_i^t are the location of the i^{th} particle at time $t+1$ and t respectively; Δt is the time step; u is a vector sum: $u = u_c + C_D W + u_w$; u_c is the surface current velocity; C_D is the wind drag coefficient which, according to the state-of-the-art, varies from 2.5% to 4.5% (ASCE, 1996); W is the wind velocity and u_w is the wave-induced Stokes drift, calculated as $u_w = (gH/8c)$, where g is the gravitational acceleration; H is the wave height and c is the wave celerity (Dean and Dalrymple, 1991).

In equation (1) TDT stands for the turbulent diffusion transport. This term is calculated by a random walk procedure where diffusion is simulated by a random Brownian motion of the particles (Koutitas, 1988).

Model calibration

On December 20th, 2002 four Argos drift buoys were deployed by the Marine Research Institute (IIM-CSIC) and the University of Vigo (GOFUVI) on a large oil slick from the tanker *Prestige* in order to follow the oil slick trajectory. In Fig. 5 the paths followed by the buoys are shown. Buoys number 16751 and 16753 arrived at the coast on January 30th, 2003 and buoy 16754 grounded on February, 1st 2003. However, buoy 16752 was captured at sea on January, 19th, 2003. As can be seen, all three buoys that grounded were found on the Cantabrian coast (black rectangle) which was consistent with the fact that the largest amounts of beached oil were found in this part of the Spanish north coast.

In order to verify the oil spill model performance and to estimate the value of the wind drag and turbulent diffusion coefficients, a comparison between buoy trajectories and numerical predicted paths was performed. In Fig. 6 the comparison between model results and buoy paths on 23-24th of December, 2002 is presented. As can be seen, in this case, for C_D=0.02, the predicted trajectories show good agreement with the actual path of the two buoys nearest to the coast; however, the model overpredicted the transport for the other buoys. This kind of analysis was carried out periodically in order to correct the model parameters.

Figure 5. Trajectory of Argos buoys deployed on December, 20th, 2002. Source: http://eddy.uvigo.es/Argos/

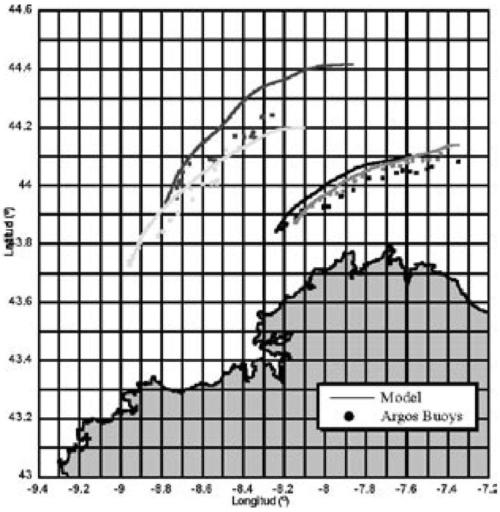
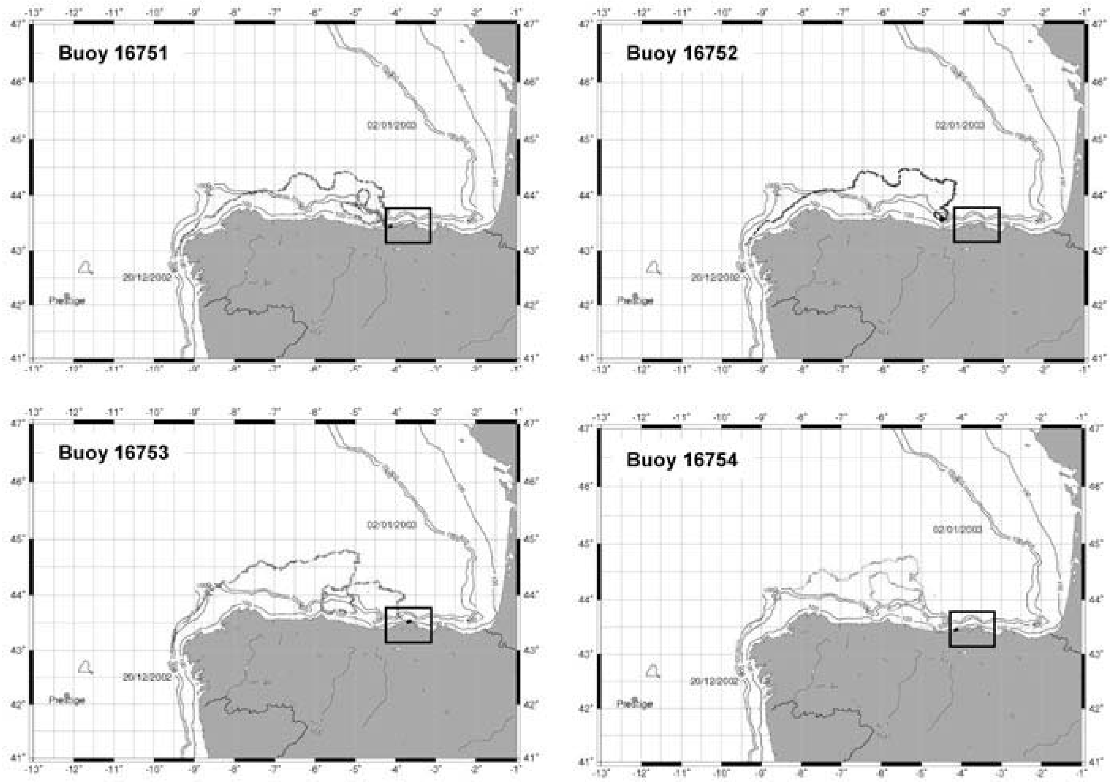


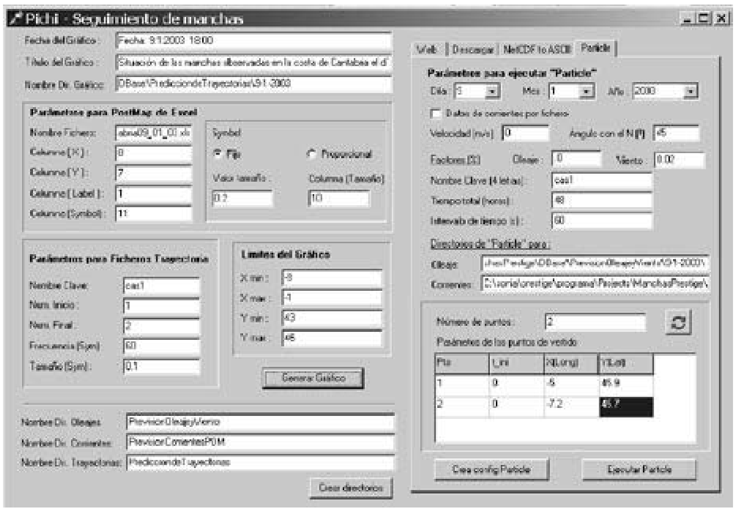
Figure 6. Simulated trajectories by Oil spill model (solid line) for 23-24 December 2002 compared with actual drift buoys paths (doted line).



Simulation results

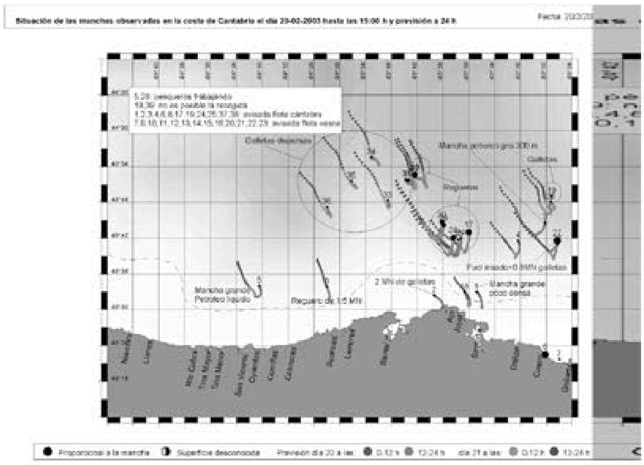
The oil spill model described above was operated with data from aerial observations and the aforementioned meteorological and oceanographic data. In order to make the process user-friendly and operational, the input and output operations were implemented through a graphical user interface (GUI) (see Fig. 7).

Figure 7. GUI developed to operate the oil spill model and data base.



The output of the oil spill model consisted of oil spill trajectories forecast for a 12-, 24- and 48-hour horizon period. This result was presented in the form of maps such as that shown in Fig. 8. In this figure the initial location of each oil slick is represented by means of a black circle with a diameter proportional to the size of the oil slick. The path followed by each oil slick is shown by means of coloured dots and each colour stands for a 12-hour forecast period. Moreover, some additional information relevant for each oil slick was usually included in the map.

Figure 8. Predicted oil spill trajectories for the Cantabrian coast on February, 20th, 2003

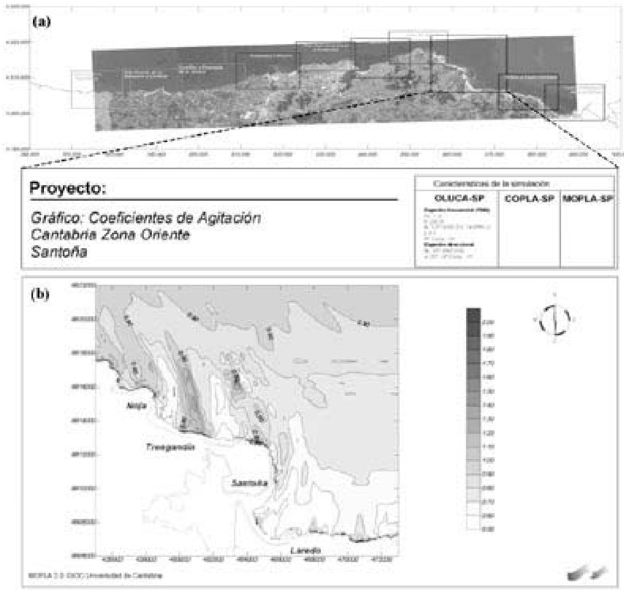


2.3 Wave propagation model

The model used to simulate the shallow water sea state was the OLUCA-SP. This wave propagation model, developed by the University of Cantabria, simulates the behaviour of a random sea over irregular bathymetry, incorporating the effects of shoaling, refraction, diffraction and energy dissipation. OLUCA-SP includes most features present in the model REF/DIF developed by Kirby and Dalrymple (1992). The model is constructed in parabolic form and finite difference techniques are used to solve the equations.

In order to apply the wave propagation model, the Cantabrian coast was modelled using several grids to achieve the necessary resolution for wave height and direction (see Fig. 9).

Figure 9. (a) Numerical grids used in Cantabrian coast; (b) Shallow water propagation coefficients for Santoña coast



The boundary conditions at the open boundaries were provided by the numerical model WAM described before. The model was run every day to obtain the shallow water wave height and direction forecast for a 48-hour period. These results were sent to the decision- makers in the form of shallow water propagation coefficient maps. Fig. 9 shows one of these maps for the Santoña coast.

2.4 Shallow depth-averaged flow model

In order to develop protection strategies for sensitive areas, one of the tasks of the pre-operational system was to carry out a hydrodynamic study of each estuary of Cantabria. The purpose of this work was to provide the decision-makers with technical assessment about boom deployment. In order to do this, a shallow depth-averaged flow model developed by the University of Cantabria was used. This model has been widely applied in previous studies in the Northern estuaries where it was calibrated in order to achieve reliable simulations of the specific circulation in these shallow areas.

The numerical model, H2D, used in this study was based on the solution of the depth-integrated shallow water wave equations. For the numerical solution of these equations an alternating direction implicit (ADI) finite difference scheme was used (Leendertse, 1970). The forcing included in the model are astronomic tide, river discharge, wind and horizontal gradients of density. The results provide by H2D consist of surface elevation, and depth-averaged currents and density for the numerical grid considered. Section 3 of this paper shows the results of this model and its application.

2.5 Decision makers

Every day at approximately 18.00 h, the decision-makers received the information, via fax and email, from the pre-operational forecasting system. This information included the graphical output of the numerical models described above: the oil spill trajectories forecast map, the shallow water propagation coefficient maps and the depth-averaged estuarine currents maps, and the weather forecast based on the HIRLAM output.

Based on this information along with the information from other sources such as the 25 surveillants provided by the Environmental Agency of Cantabria covering all the coast and the fishing boats positioned at tidal inlets, the decision-makers had to decide the following day's response strategies for protecting the natural resources. These strategies consisted of deploying booms at tidal inlets, recovering oil spill at sea and cleaning-up the shoreline.

Based on the oil spill forecast map and on the aerial information, the decision makers had to decide how many fishing boats would be operating the next day and which would be the nearest port to optimise operations. Also, the shallow water propagation coefficient maps became a useful tool in order to know the sea state near the coast where the fishermen had to go to recover the oil. Regarding the cleaning-up of the shoreline, based on the information received, the number of persons required and the areas affected had to be determined.

The next section describes how the depth-averaged estuarine current maps were used.

3. PROTECTION OF ESTUARIES AND MARSHES

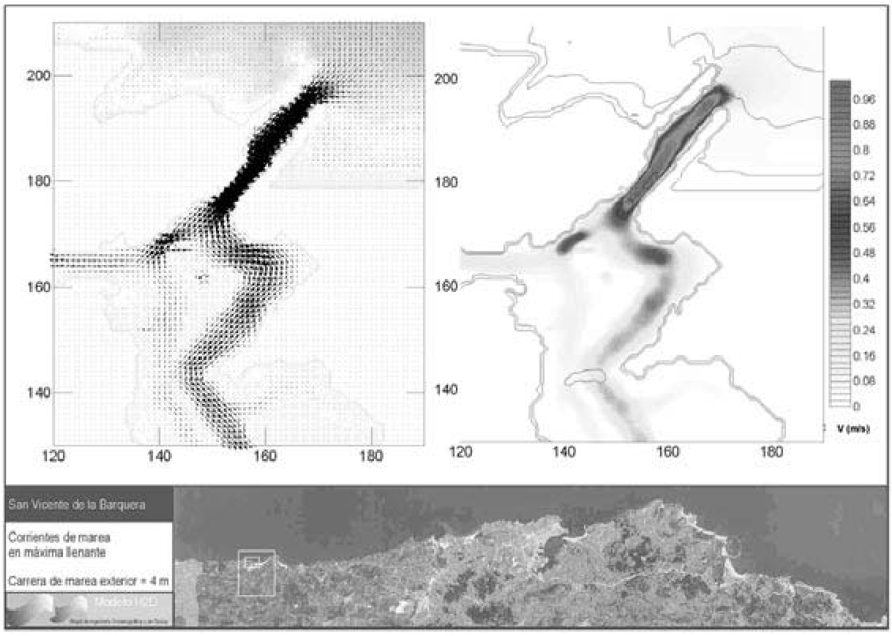
Apart from oil recovery at sea and surveillance of tidal inlets, the primary tools used in Cantabria for protection of sensitive areas were the containment booms. Oil boom types vary considerably in size, shape, design and intended use. There is no single type of boom well suited to meet all on-water conditions including current, tides, winds or deployment area factors. The most ideal situation is where pre-selected booming strategies have been adopted. If, however, a site has not been tested, as was the case for the Cantabrian coast, it will be necessary to check anchor points, shoreline moorings, water depth, currents, tidal effect and whether or not the site is exposed to high energy weather conditions. Therefore, before a booming strategy was implemented, a protection plan was carried out. The plan consisted of the following tasks:

I. Boom location, mooring and anchoring plan.
II. Design of boom anchoring.
III. Boom deployment and maintenance.
IV. Boom monitoring and cleaning.

In this plan, the University of Cantabria was involved in developing the studies needed to carry out Task I. The main objectives of these studies were to obtain the necessary data (wind waves, currents, tide, wind) to adequately set up the containment booms and to analyse the effects that the partial closure of estuaries, bays and marshes would have on the flow and transport of substances.

In order to undertake these studies, the first step was to gather information about boom types, mooring and anchoring systems, aerial photographs and existing bathymetry of the estuaries. The next task was to study the hydrodynamics of all the estuaries of the region. To do this, the aforementioned shallow depth-averaged flow model was applied in all sensitive areas in order to calculate the maximum ebb/flood velocities for spring tide conditions. Depth-averaged estuarine current maps were obtained for each estuary as a result of this study. Fig. 10 shows one of these maps for the San Vicente Estuary.

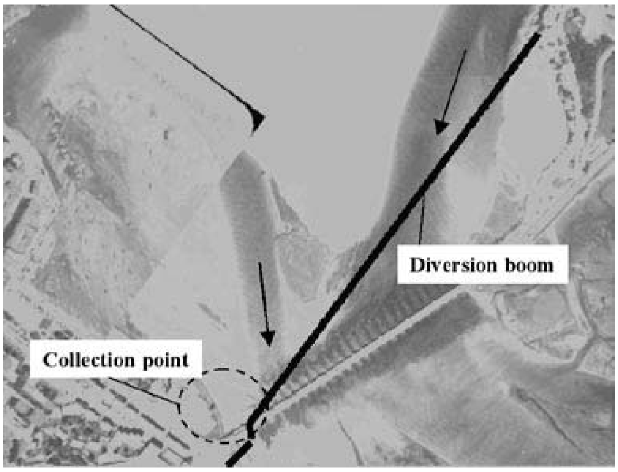
Figure 10. Current field calculated by H2D for spring tide conditions at San Vicente Estuary (Cantabria)



After verifying the hydrodynamics of all areas as well as the characteristics of different types of oil booms, the location of the containment systems was decided depending on several criteria such as boom design maximum velocity, maximum angle between boom and currents, shoreline mooring points, port operating and dredged channels.

Owing to the strong currents in most Cantabrian estuaries, in most cases, the boom protection technique consisted of diversion booming, with the boom-to-flood currents angle being less than 45°. This strategy was used primarily to divert oil flow away from a sensitive area or to a collection point. As can be seen in Fig. 11, this was the type of boom installed in the San Vicente Estuary.

Figure 11. Diversion boom installed in San Vicente Estuary (Cantabria)



On the other hand, in some estuaries with small tidal prism the protection technique used was a kind of mixed solution between exclusion booming and a rubble dam which closed part of the tidal inlet. Before choosing this technique, the hydrodynamic study described before was used to analyse the effect that this partial closure would have in the estuary.

In those inlets that had to allow the maritime traffic, diversion booms were used attempting to have a free navigation channel at the same time that they guarantied most of the oil would be trapped.

4. CONCLUSIONS

In this paper a pre-operational system to respond to the Prestige oil spill crisis has been presented. The pre-operational system, which started from scratch the day right after the Prestige sank in the Galician coast, is based on an innovative way of integrating previous knowledge and numerical tools together with the help of external institutions providing fundamental data. The key-bone of the system is the development of a robust, efficient and reliable protocol, able to satisfy the requirements imposed by the decision- makers who where demanding a quick response.

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APENDICE: SISTEMA DE OCEANOGRAFÍA PRE-OPERACIONAL COMO PARTE DE LA RESPUESTA FRENTE AL VERTIDO DEL PETROLERO PRESTIGE EN LAS COSTAS DE CANTABRIA

INTRODUCCIÓN

El accidente del petrolero Prestige frente a las costas gallegas en Noviembre de 2003 y la posterior afección del derrame a las costas de Cantabria a partir del 5 de Diciembre del mismo año hicieron necesario la puesta en marcha de un complejo operativo que permitiera: (1) Predecir la llegada de nuevas manchas de fuel y (2) proteger la costa, y fundamentalmente los estuarios, ante dichas manchas.

METODOLOGÍA

Sistema de predicción

Los objetivos del sistema de predicción elaborado eran los siguientes:

1. Proporcionar de forma operacional las posiciones, tamaño y evolución de las manchas de fuel a diferentes escalas espaciales con el fin de poder evaluar en tiempo real las estrategias correctas de actuación para minimizar los efectos sobre el litoral.
2. Proporcionar de forma operacional las condiciones meteorológicas y de clima marítimo necesarias para planificar las actividades de las embarcaciones que operan en mar abierto.
3. Proporcionar de forma operacional las condiciones de oleaje, corrientes y marea y viento en la costa para planificar las actividades de limpieza en playas y acantilados.

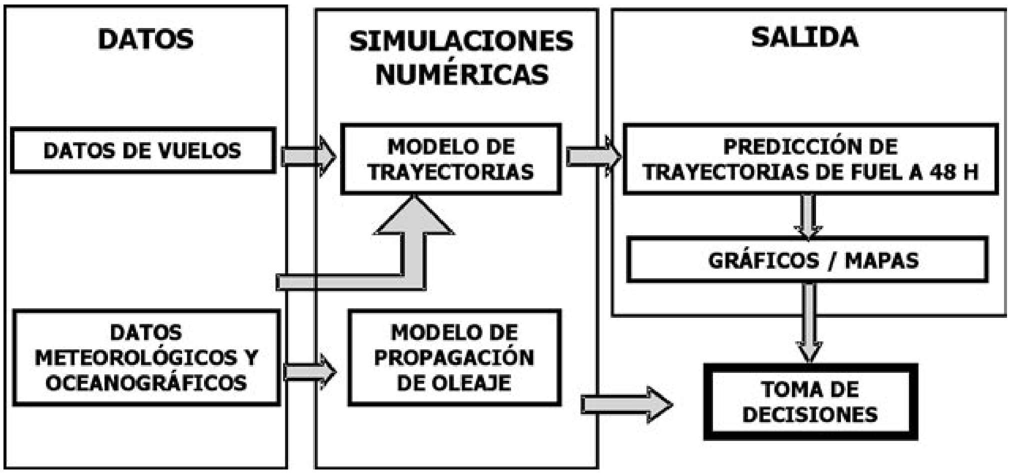
Para ello, y con base en los modelos desarrollados en la Universidad de Cantabria y la información facilitada por otros organismos (Puertos de Estado, INM, NRL, SASEMAR, Delegación de Gobierno de Cantabria, Consejería de Medio Ambiente) en la Universidad se elaboraba todos los días dos predicciones de la previsible evolución de las manchas de hidrocarburos, una de detalle referida al ámbito de la Comunidad Autónoma de Cantabria y otra general de la cornisa Cantábrica.

El protocolo de trabajo era el siguiente (Figura 1):

1. A las 12,00 horas se recibe información relativa a predicción a dos días de oleaje, viento, corrientes en la plataforma Cantábrica. Esta información es facilitada por Puertos del Estado, el INM y el NRL americano.
2. Con base a esta información se ejecutan los modelos de detalle de predicción local (referidos a la comunidad de Cantabria) de la Universidad de Cantabria.
3. A las 15,00 horas se reciben los partes de avistamientos de manchas reportados por las diferentes administraciones y servicios públicos (marina mercante, salvamento, Policía Nacional, Guardia Civil...). Esta información es facilitada por la Delegación de Gobierno.

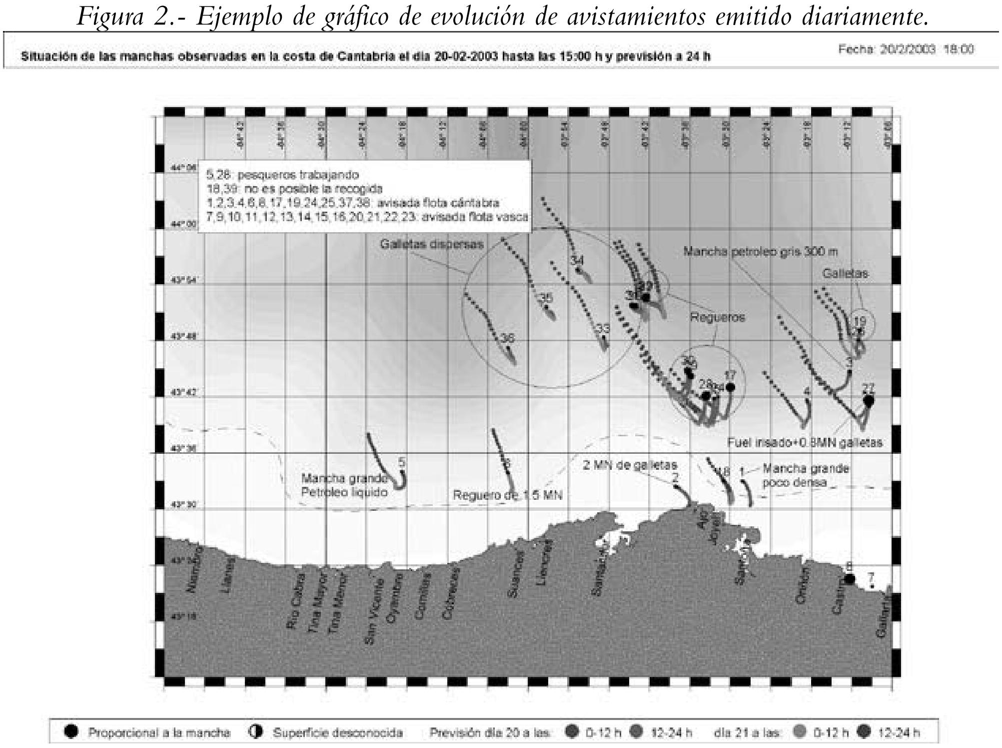
4. A las 17,30, una vez procesada la información oceanográfica y verificadas todas las observaciones, se emite un informe de posición de manchas y evolución a 24 y 48 horas. Este informe es enviado por la Universidad de Cantabria a la Delegación de Gobierno, CECOPI Cantabria, Sasemar y a la Consejería de Medio Ambiente para su posterior distribución a los operativos de limpieza y protección.

Figura 1.- Diagrama de flujo del sistema de predicción de evolución de los avistamientos de hidrocarburos.



Como parte de este informe se enviaba diariamente figuras como la presentada en la figura 2.

Figura 2.- Ejemplo de gráfico de evolución de avistamientos emitido diariamente.



SISTEMA DE PROTECCIÓN

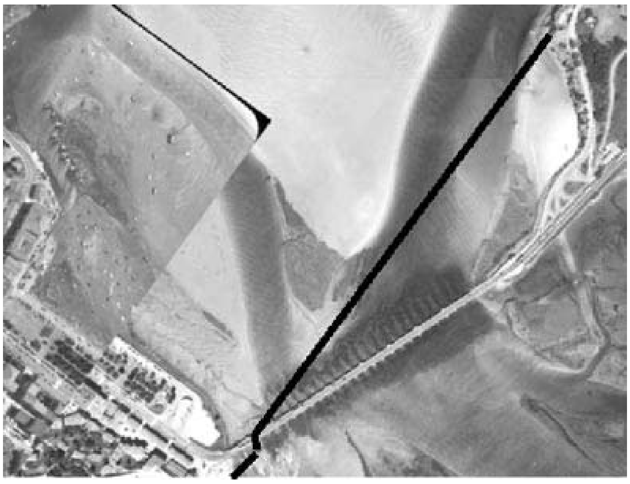
Los objetivos del programa de protección eran los siguientes:

1. Proporcionar la información de oleaje, corrientes, marea y viento necesaria para la correcta ubicación de medidas mecánicas de protección, tales como barreras, especialmente en la entrada de rías, estuarios y marismas en las zonas afectadas.
2. Generar la información hidrodinámica y de transporte de sustancias necesaria para valorar el efecto del cierre parcial de zonas estuarinas y de marisma sobre el ecosistema.

A tal fin se realizaron estudios hidrodinámicos de todos los estuarios de Cantabria. Estos estudios permitieron evaluar el campo de velocidades de máxima llenante en las bocanas y, con esta información, se realizó un análisis de la ubicación, disposición y sistema de protección mas adecuado (barreras flotantes, cierre parcial, cierre total ...) para cada una de las bocanas de los estuarios de Cantabria.

En la mayor parte de los casos, la solución propuesta se materializó en barreras oceánicas dispuestas con un ángulo igual a inferior a 45º con respecto a la dirección de la corriente en máxima llenante, en algún lugar de la desembocadura en la que se dispusiera de una zona de "sacrificio" en tierra donde poder recoger el fuel atrapado por la barrera, véase, por ejemplo la disposición de las barreras en la marisma de San Vicente de la Barquera a la altura del puente de la Maza (Figura 3).

Figura 3.- Ubicación de la barrera de contención en la marisma de San Vicente.



En algunas bocanas, como en el caso de la marisma de Joyel, la alternativa de cierre propuesta incluía el cierre físico de parte de la desembocadura por medio de un dique de escollera que permitiera limitar la longitud de la barrera de contención al tiempo que garantizara la correcta renovación de la masa del agua del estuario. A tal efecto se realizaron las correspondientes simulaciones numéricas por medio de un modelo no-lineal de propagación de ondas que resuelve las ecuaciones de Navier-Stokes integradas en vertical.

En aquellas desembocaduras en las que se ubican puertos comerciales o pesqueros (Santander, Santoña) las barreras fueron ubicadas de modo que se respetara un canal mínimo de navegación al tiempo que se garantizara que las líneas de corriente del flujo principal quedaban "atrapadas" por las barreras.