DESCRIPTION AND APPLICATION OF THE OPERATIONAL OIL SPILL FORECAST SYSTEM TESEO

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ABSTRACT
In the framework of the ESEOO Project (Spanish Operational Oceanography System) a complete set of models has been developed to simulate oil spills transport and fate processes. These models have been integrated in a user friendly operational system called TESEO. The main objective of the TESEO system is to integrate the meteorological and oceanographic data as well as the oil properties data required by the oil spill model to provide the evolution of contaminating spills at a regional scale. The system is linked with the operational winds and currents forecast system and, consequently, is able to provide useful information to decision-makers in a crisis situation. The performance of TESEO system has been successfully tested during four operational oil spills exercises organized by the Spanish Maritime Safety and Rescue Agency (SASEMAR) with the collaboration of the ESEOO Group. In these exercises, the TESEO system was used to provide forecast spill trajectories and fate processes to decision-makers in real time. Detailed information regarding the operational requirements of the system and its utilization during the Finisterre-2006 exercise is presented in this paper. The Finisterre-2006 exercise, as well as the other operational exercises performed, shows the TESEO system’s capability as a useful tool in an oil spill response.

INTRODUCTION
In the last decades, the Spanish coast has been affected by many severe oil spills, Urquiola 1976, Andros Patria 1979, Mar Egeo 1992 and most recently the Prestige accident in 2002. The Prestige oil tanker accident caused one of the major catastrophes related to oil pollution on the Spanish coast. The Prestige, carrying about 77,000 tons of heavy oil, began to leak approximately 30 nautical miles off the Galician coast (Le Cedre, 2002) on November 13th, 2002. The ship split in half and sank on November 19th at a depth of about 3500 m. The latest estimate of the amount of oil spilled until August 2003 was of 63,000 tons (Castanedo et al., 2006) affecting more than 2000 Km of shoreline (Ministerio de Medio Ambiente, 2005).

From the first stages of the accident, different Spanish institutions and public agencies started to work on the monitoring and forecasting of the oil spill. At that time, a national oceanography system did not exist in Spain that would be able to forecast currents and oil spill trajectories. Therefore, several improvised operational forecast systems were built in different regions along the northern coast of Spain with their common objective being to help manage the crisis (Castanedo et al., 2006, Gonzalez et al., 2006). During the crisis, numerical simulation and prediction of oil spill transport was an important tool for the planning of the protection and spill response operations.

The Prestige crisis showed the need to improve operational oceanography capabilities in Spain. After the accident, the Spanish Ministry of Science approved a project to promote operational oceanography in Spain with a particular focus on the development and implementation of products, including the design of action protocols suitable for use in marine emergencies at sea (Alvarez-Fanjul et al, 2007). This project is known in Spanish as Establecimiento Español de Un Sistema de Oceanografía Operacional (ESEOO) which roughly translates into Operational Oceanography System. It can be accessed at www.eseoo.org. The main objective of the ESEOO project was to develop a complete set of models for simulating oil spill transport and fate processes. These models have been integrated into a user-friendly operational system known as Modelo de Transporte de ESEOO (TESEO). The main objective of the TESEO system is to integrate the meteorological and oceanographic data as well as the oil properties data required by the oil spill model to provide the evolution of contaminating spills at a regional scale.

Oil spilled into the sea is transported by a combination of winds, currents and waves and is affected by different processes that transform its physical and chemical properties. When an oil spill occurs, data for the oil spill model, such as spill location, oil volume, environmental data and oil type are required to predict the transport and fate of the oil spilled. All this information is easily integrated in the TESEO system to provide useful information for decision-makers. The results provided by the TESEO system, are
The drift process of the spilled oil is described by tracking models, as part of the operational forecasting system created to respond to the Prestige oil spill (Castanedo et al., 2006). In this model, the drift process of the spilled oil is described by tracking numerical particles equivalent to the oil slicks. At each 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. The numerical model solves the following vector equation:

$$\frac{d \mathbf{x}}{dt} = \mathbf{u}(\mathbf{x}, t) + \mathbf{\bar{u}}(\mathbf{x}, t)$$  \hspace{1cm} (1)

where $\mathbf{x}$ is the particle position, and $\mathbf{u}$ and $\mathbf{\bar{u}}$ are the advective and diffusive velocities respectively in $\mathbf{x}$. The advective velocity, $\mathbf{u}$, is calculated as the linear combination of currents and wind velocity and the wave induced Stokes drift.

$$\mathbf{\bar{u}} = \mathbf{u} + C_w \mathbf{u_s} + C_d \mathbf{u_n}$$  \hspace{1cm} (2)

where $\mathbf{u}$ is the surface current velocity, $\bar{u}$ is the wind velocity at a height of 10 meters over the sea surface, $\mathbf{u_s}$ is the wave-induced Stokes drift, $C_w$ is the wind drag coefficient and $C_d$ is the wave coefficient.

The wave-induced Stokes drift is calculated following Dean and Dalrymple (1991) as

$$u_s = \frac{gH}{8C}$$  \hspace{1cm} (3)

where $g$ is the gravitational acceleration, $H$ is the significant wave height and $C$ is the wave celerity associated to the mean period.

The turbulent diffusive velocity is obtained using a Monte Carlo sampling in the range of velocities $[-\bar{u}, \bar{u}]$ that are assumed proportional to the diffusion coefficients (Hunter et al., 1993). The velocity fluctuation for each time step is defined in the following way:

$$\mathbf{\tilde{u}} = \sqrt{\frac{6D}{\Delta t}}$$  \hspace{1cm} (4)

where $D$ is the diffusion coefficient.

**Weathering Model**

The oil spilled into the sea is transported by a combination of winds, currents and waves. Once oil is spilled on the sea surface, it is also affected by several physico-chemical processes that depend on the oil’s properties and environmental conditions. Fig. 3 shows the most important mechanisms affecting an oil slick in the marine environment. These processes are described in detail in several state-of-the art reviews (Spaulding, 1988; ASCE, 1996, Reed et al., 1999).

The mentioned oil spill fate processes have different time scales and different importance in terms of the oil mass balance. Therefore, the process’ relevance will depend on the time and spatial modelling scale. In order to simulate the fate of the oil in the regional scale, the weathering model includes evaporation and emulsification as the main processes affecting the spilled oil. The model also takes into account oil spilling: if the oil particle reaches the shoreline, it is identified as “beached” and it is removed from the computational process.

**Evaporation**

Evaporation is an important process that depends on the oil properties and its main effect is to decrease the amount of oil at sea. In a few days, light crudes can evaporate as much as 75% of the starting oil mass and medium crudes up to 40%. Heavy or residual oils may only evaporate up to 10% of their original mass in the first few days following a spill (ASCE, 1996).

In the present model, the oil evaporation is calculated based on an analytical model proposed by Stiver and MacKay (1984). In their formulation, the rate of evaporation is related to vapor pres-
Emulsification

Emulsification is the formation of a water-in-oil emulsion increasing the amount of product in the water. Here, the mouse formation is simulated by means of a first-order rate law proposed by Mackay et al. (1980). In this method, the rate of water incorporation is related to wind speed, maximum water-in-oil content, and a constant rate that depends on the type of oil.

The physical and chemical properties of the oil change due to the weathering processes. In the TESEO model, the evolution of the viscosity and the density of the oil are computed based on temperature, evaporative loss and water uptake.

The formulation used to calculate the density and viscosity transformation is described in Comerma (2004). Therefore, the increase of density is computed as follows:

\[ \frac{d\rho}{dt} = \frac{1}{\rho} \left( 1 - \frac{\rho}{\rho_w} \right) \left( 1 - C_1 (T - T_0) \right) \left( 1 + C_5 F \right) \]

Physicochemical properties

The increase in viscosity is calculated as a function of water content of the emulsion, the environmental temperature and the evaporation

\[ v_e = v_o \exp \left( \frac{C_4 Y}{1 - C_5 Y} \right) \exp \left[ C_3 (T - T_0) \right] \exp \left( C_6 F \right) \]

where \( v_e \) is the initial viscosity of oil at \( T_0 \) and \( C_1, C_2, C_3, C_4, \) and \( C_5 \) are adjusting parameters.

Operationally, the oil spill model is controlled by the 'Model' Dialog shown in Fig. 4. In this dialog, several oil spill model parameters can be selected as well as information related to the spill scenario, i.e. spill location, released volume or type of oil. Fig. 4 shows an example of this window. It is possible to simulate the trajectory of several oil slicks in the same model run. Once all information has been introduced, the simulation can be launched with the run button.

Graphical Output Module

Results of the oil spill predictions are provided in the graphical output module. As mentioned above, this information is presented in easy and quickly interpreted maps as tools to help in the response planning process.

The graphical output module is divided into five sections that present different model results. The first three sections provide oil spill transport information: (1) trajectory of the centre of mass; (2) particle distribution and (3) the probability of finding an oil slick at a specific location. These plots can be zoomed in on to show greater detail in any given location.

The last two sections present the evolution of properties of the pollutant and the mass balance. Temporal variation of density, viscosity and water content is provided. The mass balance includes the evolution of the amount of evaporated oil, beached oil and the oil remaining on water. The mass balance also provides the amount of emulsified product that reaches the coast and the amount of emulsified product that remains at sea. The amount of product on the water increases due to the emulsification process. This effect has to be taken into account for the cleaning operations planned at sea and along the coast.

Some examples of the graphical results provided by TESEO are shown in Fig. 5. For example, the user may wish to plot the displacement of several oil slicks observed in the affected area. Fig. 6 shows an example of the particle distribution and probability map of several oil slicks in the Balearic and Canary Islands respectively.

APPLICATION TO THE OPERATIONAL EXERCISE FINISTERRE-2006

The performance of TESEO system has been successfully tested during four operational oil spill exercises organized by the Spanish Maritime Safety and Rescue Agency (SAEMAR) with the collaboration of the ESEO group. During the exercises, a mock oil spill accident and an at sea rescue and marine pollution response were simulated.

Exercise description

Finisterre-2006, an operational exercise, was developed off the Galician coast on the 14th, 15th, and 16th of November, 2006. As part of the exercise, an oil-spill crisis scenario was simulated based on several oil slicks. The geographical domain and the oil spill scenario are shown in Fig. 6. On the first day of the exercise, three offshore oil slicks were reported 28 miles from the Galician coast (see Fig. 6). A day later, three more oil slicks were observed close to the coast.

To simulate the motion of the spilled oil, seven satellite-tracked Lagrangian buoys were deployed in the framework of the ESEO project. Four of them were launched over the offshore oil slicks and three of them over the near coast oil slicks (see Fig. 6). The purpose of these buoys was to simulate the motion of the oil during the exercise and to collect information to validate the oil spill model in a post-exercise study.

As part of the exercise, an operational procedure coordinated by the scientific ESEO group support project (USyP) was implemented. The USyP unit is the framework in which specialists from different technical fields and working for different institutions analyze the available information (i.e. observations, climatological and simulated data) and synthesizes it to provide the best answer to the crisis (Sotillo et al., 2007). The integration of the USyP unit in the oil spill response is a novelty in this kind of exercises and it is the result of the collaboration between the ESEO group and SAEMAR.

During the Finisterre-2006 exercise the USyP unit involved specialists from different national and local institutions. It was the first time that representatives of local institutions were incorporated to the USyP to provide high resolution environmental data for the affected area, mainly in the coastal region. Using the TESEO system, the USyP satisfactorily provided the forecast spill trajectories and fate processes in real time.
Data
Meteorological and oceanographic models were running operatively to provide the numerical data required by the oil spill model. Wind, waves and currents data were available in real time via FTP. The data transfer worked successfully and the first oil transport and fate processes’ forecast were provided in less than 30 minutes.

The national forecast systems were in charge of the ocean and weather forecast during the first day of the exercise. Numerical data provided by regional models were used to simulate the motion of the offshore oil slicks. Meteorological and oceanographic models were running in an operational way in the Spanish Meteorological Institute (INM) and Ports of Spain (PE) respectively.

Wind fields provided by the INM were the output of the third generation HIRLAM model (Cats and Wolters, 1996). The resolution of the model was 0.15° and the results were the 72-hour forecast of wind velocity and direction with a 1-hour time interval.

Sea state conditions data were the output of the numerical model WAM, a third generation model which computes spectra of random wind-generated waves (Komen et al., 1994). The model’s grid resolution was 0.05° and the results were the 72-hour forecast of significant wave height, mean direction and mean period for sea and swell components with a 3-hour time interval.

Surface currents data were the output of the ESEOAT forecast system developed in the framework of the ESEO project to provide oceanographic forecast of the northwestern Atlantic area, closest to the Iberian Peninsula (Sotillo et al., 2007). The ESEOAT forecast is performed by means of an application based on the POLCOMS shelf-area model. The model’s grid resolution was 0.05° and the results were the 72-hour forecast of surface currents with a 1-hour time interval.

During the second day of the exercise the ocean and weather forecast was provided by the regional meteorological agency in Galicia (MeteoGalicia). Meteorological and oceanographic models for the Galicia coastal areas were running operationally at MeteoGalicia. These data were used to simulate the motion of the coastal oil slicks.

The wind fields were the output of the MM5 model (Mesoscale Model of the 5th Generation). The resolution of the model was 0.1° and the results were the 72-hour forecast of wind velocity and direction with a 1-hour time interval.

In order to properly simulate the conditions in the near coastal area, surface currents were provided by the high resolution application developed by MeteoGalicia for the Galicia coastal areas inside the local scale approach of the ESEO project (Torres et al., 2007). This system is based on MOHID hydrodynamic model forced with the operational meteorological model MMS supported daily at MeteoGalicia. The initial 3-D temperature and salinity fields used to start MOHID run from a resting period were obtained from ESEOAT reanalysis performed by Puertos del Estado using POLCOMS model. The model’s grid resolution was 0.02° and the results were the 48-hour forecast of surface currents with a 1-hour time interval.

Operational results
As mentioned above, one of the functions of the USyP was to forecast marine environments. An example of the forecast wind fields during the exercise is displayed in Fig. 7. Fig. 7a shows the wind field data provided by HIRLAM model for November 14th, 2006 at 15:00 UTC, the day which the offshore oil slicks were reported. Fig. 7b shows the wind field data provided by MM5 for November 15th, 2006 at 15:00 UTC, the day which the oil slicks were observed near the coast. The module and direction of the wind field displayed in Fig. 7b shows the dominant S and SW wind direction along and towards the coast in the study area.

Meteorological and oceanographic data as well as oil data were used by the oil spill model to forecast the transport and fate of the spilled oil. Model simulation was performed using 1000 particles that constituted the oil slick. The wind and wave coefficients required by the model (see Eq. 2) were based on the values reported in the bibliography. The wind drag coefficient was considered as 3% of the wind speed (ASCE, 1996). The wave coefficient value was $C_w = 0.022$ based on the results obtained by Abascal et al. 2007 (accepted) in the Galician coast and the Bay of Biscay.

The centre of mass of the offshore buoys’ trajectory predictions for a 72 h forecast is displayed in Fig. 8. The simulated trajectories present a displacement to the North, according to the existing wind conditions (see Fig. 7a) during the first day of the exercise. Fig. 9 shows the probability of finding the oil slick on November 16th, 2006 at 23:00 UTC.

The transmission of satellite data was in real time and the buoys’ data positions were available from the beginning of the exercise. Once the buoy positions were received, the TESEO model predictions were qualitatively compared to the actual buoys’ trajectories. Fig. 10 shows the high level of agreement found between the actual and predicted trajectories performed with the TESEO model. The offshore buoy trajectory prediction was computed using ESEOAT surface currents, HIRLAM meteorological data and SWAM sea state conditions. The trajectory prediction of the near coast buoy was computed using MOHID surface currents, MMS meteorological data and SWAM sea state conditions.

The differences between the actual and predicted trajectories were calculated for all buoys deployed by means of the Root Mean Square Error (RMSE). The mean RMSE for the coastal and offshore buoys was approximately 2 and 8 Km respectively.

The time evolution of the oil mass balance for offshore oil slicks is shown in Fig. 11. At the end of the simulation about 1,000 tonnes of oil had evaporated and approximately 5000 tonnes of oil remained on the sea surface. In this case, no oil reached the coast after three days of simulation.

All this information, as well as the time evolution of the density, viscosity and content in water, was required by the decision-makers to plan the oil spill response.

CONCLUSIONS
A user friendly operational system called TESEO has been developed in the framework of the ESEO project for the simulation of oil spill transports and fate processes. TESEO is linked with the Spanish operational winds, waves and currents forecast systems, and able to provide useful information for the decision-makers in a crisis situation.

The TESEO system has been developed to be applied in Spanish waters and along the Spanish coastline. Currently, bathymetry and operational forcing data for three different regional areas are integrated in the system. Therefore, TESEO is ready to provide oil spill forecasts over the Northeastern Atlantic, the western Mediterranean basin and the area surrounding the Canary Islands. Additionally, the system is can be easily extended to any location provided data is available.

The performance of TESEO has been successfully tested during four operational oil spill exercises organized by the Spanish Maritime Safety and Rescue Agency (SASEMAR) in the Atlantic and Mediterranean Sea. These experiments were the first attempt in Spain to include an operational system in an oil spill response. During the exercises, oil spill accidents, search and rescue operations and marine pollution response were assumed. The exercise Finisterre-2006, briefly described in this paper, showed the ability of the developed system to provide useful information in real time to the decision-makers. The forecast model was operated by the USyP, a scientific group established by the ESEO partners. Comparisons between the model predictions and buoys’ trajectory-
ries showed a high level of agreement, which demonstrated the promising behaviour of the model.

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REFERENCES


FIGURE 3. PROCESSES AFFECTING THE OIL SLICK (HTTP://WWW.SINTEF.NO/STATIC/CH/ENVIRONMENT/OIL_WEATHERING_MODEL.HTM).

FIGURE 4. DIALOG OF TESEO SYSTEM TO CONTROL THE OIL SPILL MODEL PARAMETERS, OIL SPILL LOCATION AND TYPE OF OIL.

FIGURE 5. GRAPHICAL RESULTS PROVIDED BY TESEO SYSTEM. PANEL A) SHOWS THE TRAJECTORY OF THE CENTRE OF MASS OF THREE OIL SLICKS IN THE CANTABRIC SEA, PANEL B) THE PARTICLE DISTRIBUTION OF SEVERAL OIL SLICKS IN THE BALEARIC-ISLANDS AND PANEL C) THE PROBABILITY OF FINDING THREE OIL SLICKS LOCATED IN THE CANARY ISLANDS.

FIGURE 6. GEOGRAPHICAL DOMAIN AND OIL SPILL SCENARIO OF THE FINISTERRE-2006 EXERCISE. THE POSITION OF HYPOTHETICAL OIL SLICKS AND THE BUOYS DEPLOYMENT ARE INDICATED BY RED CIRCLES.

FIGURE 7. FORECAST WIND FIELD SIMULATED BY HIRLAM FOR NOVEMBER 14TH, 2006 AT 15:00 UTC (PANEL A) AND FORECAST WIND FIELD SIMULATED BY MM5 FOR NOVEMBER 15TH, 2006 AT 15:00 UTC (PANEL B).

FIGURE 8. THREE DAYS FORECAST TRAJECTORY FOR OFFSHORE BUOYS SIMULATED USING ESEOAT SURFACE CURRENTS AND HIRLAM METEOROLOGICAL DATA.
FIGURE 9. PROBABILITY OF FINDING THE OIL SLICK ON NOVEMBER 16TH, 2006 AT 23:00 UTC.


FIGURE 11. OIL MASS BALANCE FOR OFFSHORE OIL SLICKS.