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HYDRODYNAMIC MODELLING AND THE PROBLEM OF OIL SPILLS ON THE COLOMBIAN CARIBBEAN SHORELINE

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The influence of hydrodynamic forces on oil spills on the Atlantic coast of Colombia is discussed in this article. A spill model, linked with a hydrometeorological forecasting system, is described that provides information about the fate of oil after a spill. The hydrometeorological module consists of a coupled mesoscale-meteorological model for the planetary boundary layer (PBL) and an oceanic model.

Introduction

In countries where the petroleum industry is located close to shorelines, there is a need to predict the fate and effects of oil spills in the marine environment. Such a prediction or forecast could be used to determine possible areas of oil pollution so that response strategies and cleanup methods can be planned if a spill occurs. Such preparedness is particularly important when oil spills occur close to shorelines as there is only a short time before the oil reaches land and the environmental damage is done.

Colombia has a large petroleum industry. Oil is shipped from ports in the Morrosquillo Gulf, Cartagena Bay, and the Santa-Marta area (see Figure 1). These are considered high risk areas for oil spills. Several spills have already taken place in these areas.

In response to this, a research group was set up at the Centre of Oceanographic and Hydrographic Investigations (CIOH), operated by the Colombian Navy. The aim of the group was to create a system for forecasting the movement of oil spills based on hydro-meteorological conditions. The spill model developed through this research is discussed in this article.

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Theory

In general, the behaviour of oil in seawater depends on meteorological or climatic conditions at the spill site. These include the following:

- wind and sea surface conditions;
- water currents;
- tidal fluctuations and other changes in sea level;
- ambient temperatures; and
- other hydrometeorological conditions, such as cloudiness and humidity, which indirectly affect hydrodynamic force fields.

Reliable information about winds, currents, and other parameters, both observed and forecast, is needed in order to forecast spill behaviour. From the hydrodynamic viewpoint, the main obstacle to obtaining a more accurate forecast of an oil spill's location is the poor forecasting of wind and currents and their changeability over time and space.

The system of weather stations in the tropical zone and Colombia, in particular, does not provide adequate coverage of the areas where oil spills are likely to occur. Furthermore, weather forecasting is more difficult in the tropical zone because of rapid climatic changes. It is easier to forecast temperatures accurately in tropical regions. As a rule, daily temperatures do not vary by more than a few degrees Celsius. It is therefore not difficult to identify the influence of temperature on such oil processes as evaporation. A more difficult problem is calculating turbulent surface flux (micro-scale wind eddies), which may affect the dynamics in the upper layer of the water. This problem, as well as the sensitivity of hydrodynamic fields to variations in air temperature, cloudiness, humidity, etc., was investigated as part of this research.

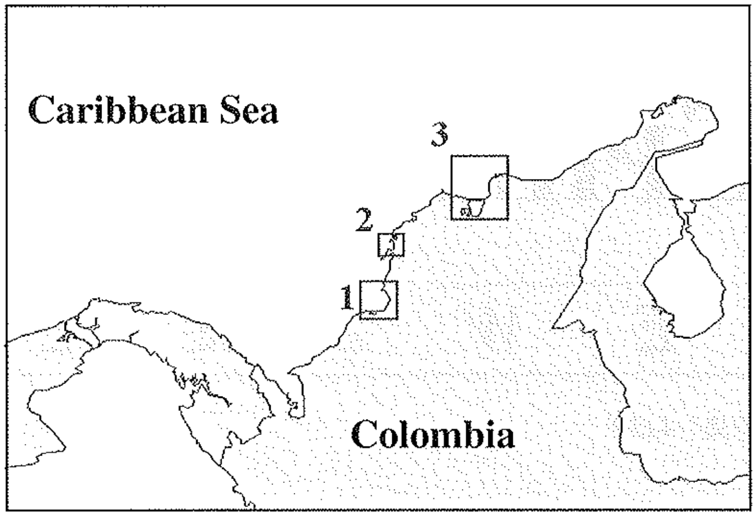

Figure 1. The principal Colombian ports used by the petroleum industry on the Atlantic coast: 1. Morrosquillo Gulf; 2. Cartagena Bay; 3. Santa Marta area.

The wind is one of the most important meteorological conditions affecting the movement of an oil slick due to its effect on the formation of waves and currents. In the area being studied, wind conditions change considerably with time and over space due to variations in surface contours and thermal conditions and to the unstable state of the lower atmosphere.

Information about water currents, particularly those formed by winds, depends on weather information. Information on other phenomena affecting current formation, such as the water temperature and changes in salinity, requires a knowledge of the hydrological structure of the water and its variability.

Complicated morphological features of the coastline and variations in water depth, as are found in Cartagena Bay, are a cause of detailed spatial variations or character of the wind, tidal, fluvial, and thermohaline currents. In this situation, it becomes crucial to forecast the current, which influences slick dynamics as much as the wind.

Sea levels in the Colombian region of the Caribbean Sea fluctuate less than 40 cm as a result of tides, which is not significant. The role of tides increases, however, in Cartagena Bay, where two straits and local tides cause uneven fluctuations in sea level that result in strong, fast currents.

The inertial forecast is also not reliable. The data available from the Tropical Prediction Center in Miami, Florida have a coarse spatial resolution (more than 4° of latitude) and a time interval of no less than 12 hours. In the tropical zone, observed wind variations are noted in the spatial scale at typically from 10 to 50 km and are reported on a time scale of only a few hours.

Unfortunately, all atmospheric and oceanic models for limited areas have a serious shortcoming: the accuracy of their predictions depends as a rule on imposing exact boundary conditions on arbitrary data. If the water-land boundary serves as this contour in the case of oceans, then there is no physical sense of the arbitrary open boundary in a meteorological model for a local area. For example, a land boundary is an exact boundary condition for an oceanic model, but there is no way of assigning an exact meteorological boundary.

Taking all these difficulties into account, some basic assumptions can be made. Let's suppose that it's necessary to give the forecast of wind fields and perhaps other meteorological parameters for the area shown in Figure 1, followed by the results of a regional forecast on air currents. Thus, the analyzed domain will extend to the upper limit of the atmospheric planetary boundary layer (PBL).

The difficulty created by the fact that the grid for the regional forecast is different than the grid for the local model is partially overcome by the fact that the regional forecast is already used in the local forecast. The regional forecast includes the influence of the free atmosphere and physics of the PBL, which in turn is a result of the earth's thermal and orographic features. Given this fact, the role of sea, land, and air interaction is very important in developing a coupled forecast of marine and atmospheric processes. On this basis, a coupled air-sea model has been developed for the Colombian shelf of the Caribbean Sea.

Coupled Hydrodynamic Model

The coupled model is a meso-meteorological model of the planetary boundary layer (PBL) (Kazakov *et al.*, 1996) and a variation on the well-known Princeton Oceanic Model (POM), (Blumberg and Mellor, 1987).

The atmospheric module has been presented on the polar coordinate system on the vertical axis to describe small contours in the land surface. The domain has been divided into two layers: the near-surface layer with the approximation of constant fluxes and the PBL, which encompasses the surface layer and 2 or 3 km above it. The near-surface layer was parameterized by the "bulk" formulas (Monin and Yaglom, 1971) with Businger and Dyer's universal functions.

The upper PBL has been described by the movement equations using the hydrostatic approach, as well as the continuity, temperature, and humidity equations.

The atmospheric and oceanic grid points are shown in Figure 2. The atmospheric spatial step is 20 km on the rectangular mesh, while the oceanic grid is in the polar coordinate system with steps of 2790 m on the radial axis and 7318 to 11,658 m on the angular axis.

Information exchange between the grids is carried out for each atmospheric time step (30 minutes). The oceanic module gives information about sea surface temperature to the atmospheric grid, while on the land surface, the soil temperature is calculated from the surface thermal balance.

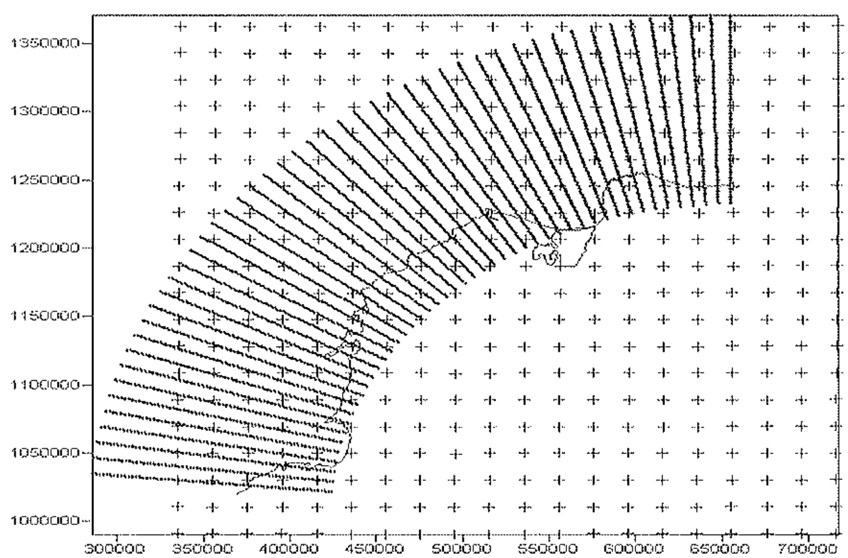

Figure 2. Atmospheric (+) and oceanic grid points for the coupled prognostic model.

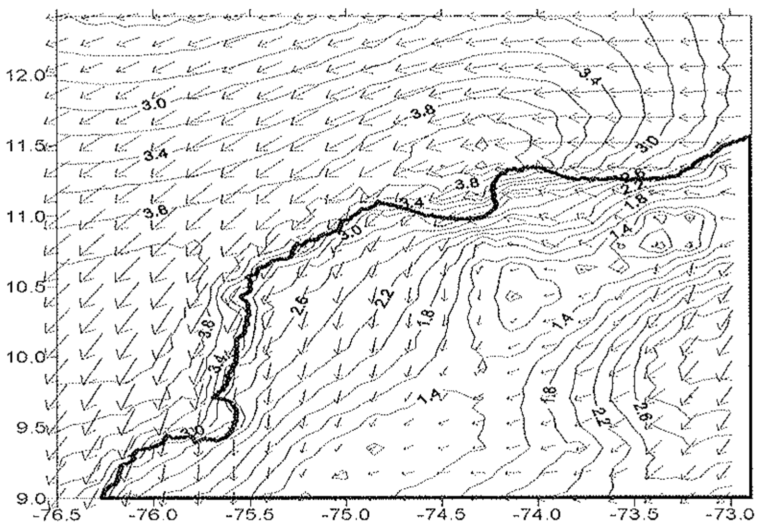

Figure 3. Near-surface wind field as a result of placement of the meteorological processes into the PBL.

From the atmosphere, the oceanic module obtains the fluxes of heat and impulse and the solar radiation on the surface.

The grids are not identical for the northwestern and eastern parts of the area and the grid nodes have different steps. For this reason, the interchanged information is interpolated from one grid to the other in each time step.

Results of the calculation include the following three-dimensional components: wind, air temperature and humidity, currents, sea temperature and salinity, etc. Results of such forecasts for the geostrophic winds of 3 m/s from the northeast in the top of the PBL are shown in Figures 3 to 5. The oceanic conditions correspond to the dry season in terms of the initial state of the sea currents.

After this placement, the data are transferred to a local subregion, either Morrosquillo Gulf, Cartagena Bay, or the Santa-Marta area.

Oil Spill Model

The oil spill model has both a hydrodynamic and an oil transport module. The hydrodynamic module is based on the MECCA model (Model of Estuarine and Coastal Circulation Assessment) (Hess, 1989) and calculates the sea level, currents, temperature, and salinity fields in the local domains using the prognostic information obtained from the coupled shelf model. The MECCA model was intended for use in shallow estuarine zones, such as in Cartagena Bay. Due to the limited availability of physical models for describing vertical turbulence and the fixed vertical grid step, the model cannot be used for areas in which the water is deeper than 50 to 100 m. For the Morrosquillo Gulf and the deepest areas of Santa-Marta, the model uses not only lateral boundary data from the large-scale model, but is also limited by the upper 70-m layer. Corresponding boundary conditions, obtained from the Princeton Oceanic Model (POM), are applied to the bottom of this layer.

The oil transport module consists of the following main

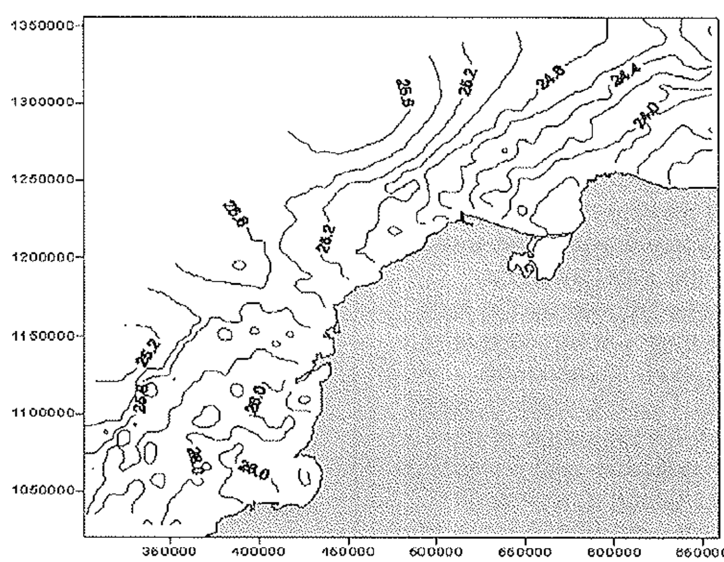

Figure 4. Sea surface temperature due to calculations by the coupled model.

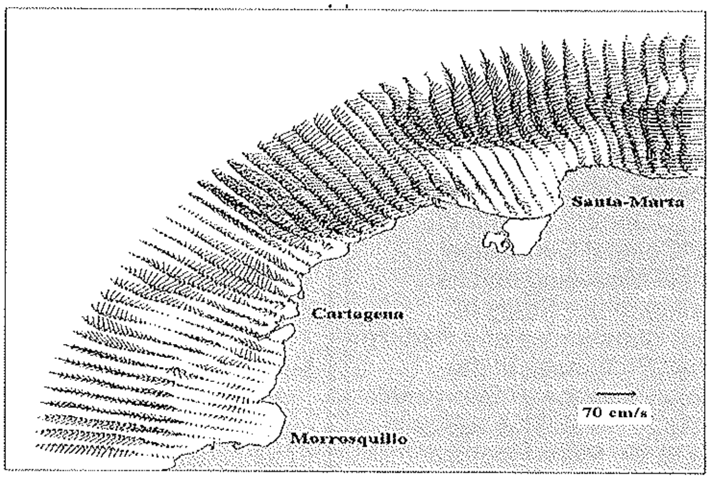

Figure 5. Sea surface currents, induced by near-surface wind (Figure 3) and the thermohaline processes.

parts: surface slick transport; changes in dispersion; oil-shore interaction; evaporation; water-in-oil emulsification; and changes in the oil properties from weathering.

Sea surface slick is presented in the form of the Lagrangian particles (tracers) with initial oil properties. The same tracer model simulates the first stages of oil spreading, using the "random walk" technique with the dispersion rate σ_u dependent on time, following Johansen (1985). The value, σ_u, related with the turbulent oil transport, is calculated from the Eulerian hydrodynamic model using Smagorinsky's formula.

Dispersion is defined by Delvigne and Sweeney (1988) and the droplet diffusion is formulated more precisely in the vertical than in the horizontal processes. The reasons for this are: a) the fast temporal variability of the vertical processes; b) the short lifetimes of the vertical turbulent eddies; and c) the vertical structure of currents may be important to vertical diffusion simulations. Thus, the Langevin equation is used to simulate droplet movement, having taken into consideration stochastic perturbations from Markov's chain in the field of decelerating forces and the buoyancy of the particles.

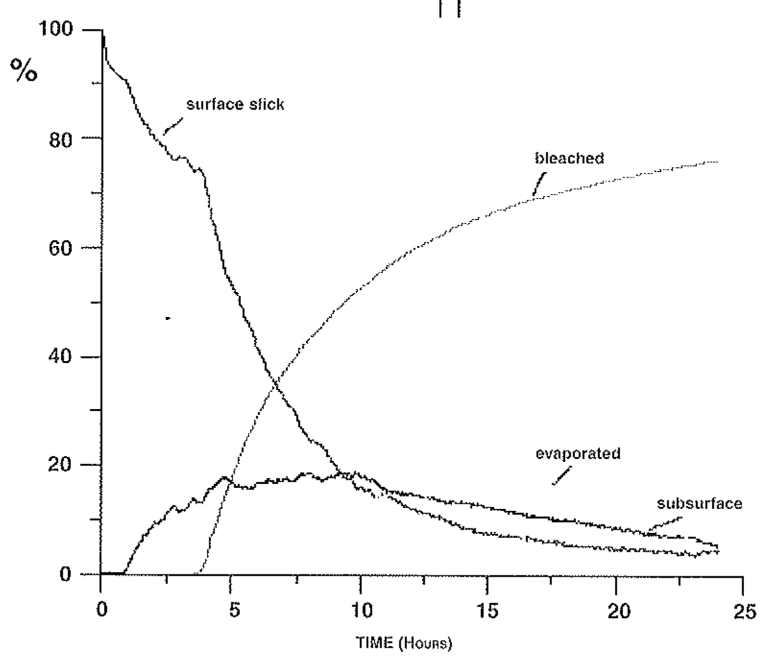

Figure 6. Time history of oil components in the model.

Evaporation from the surface slick is determined using a method developed by Fingas (1997). Moreover, the oil particles put into the water column by entrainment do not evaporate until they reappear on the sea surface. This phenomenon slows down the evaporation of the oil, but numerical experiments showed that less than 5% of this delay in evaporation occurred during 24 hours of calculations for the mean environment conditions at wind speeds of between 7 and 8 m/s.

Oil-coast interaction (beaching) has been predicted using a stochastic process. No specific physical solution has yet been applied.

The other factors use the traditional models used in many other oil fate models. Water-in-oil emulsification is calculated by Mackay *et al.* (1980), the increasing viscosity of the mousse or emulsion is

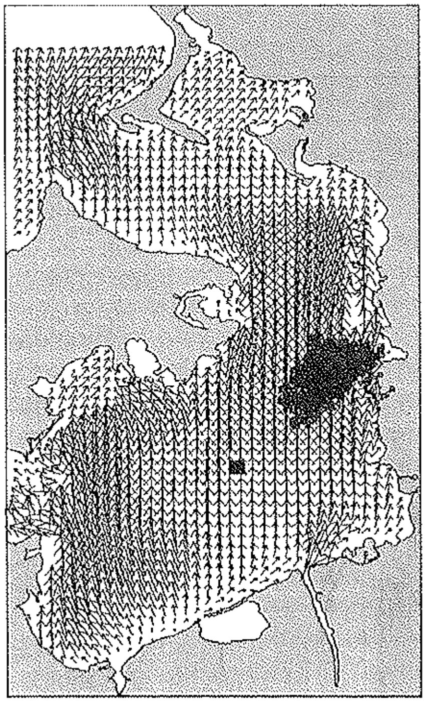

Figure 7. Slick, dispersed oil positions, and surface currents six hours after the spill. The square indicates the oil spill point.

computed by the Mooney equation, and density changes are determined by Buchanan and Hurford (1988).

The results of a hypothetical oil spill modelling are shown in Figures 6 and 7. It was assumed that 1000 m^3 of crude oil spilled instantaneously into Cartagena Bay. This example corresponds to the wind conditions of 7 to 8 m/s to demonstrate the dispersion of the oil.

Acknowledgements

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