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Laboratory simulation of ocean surface circulation in the Canary Islands area: applications to pollutant transport prediction

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Abstract

The adverse effects of spilling pollutants in water have focused attention on the behaviour of contaminants at sea, especially at coastal and shelf seas due to their key role for a wide range of human activities and interest. In particular, when oil is spilled in the marine environment, a primary concern is where the oil will go. Oil spill models suitable for use in oil spill response and contingency planning, providing rapid predictions of the movement of spilled oil, require an adequate knowledge about the ocean surface circulation in the area around the oil spill launch site to estimate the probabilities of contacting portions of a coastline. Unfortunately, field measurement programs are so expensive and time consuming that usually the existing information is scant and sparse. Numerical and physical models represent an alternative to alleviate this drawback.

This paper presents preliminary results of ocean circulation in the Canary Islands area obtained through laboratory simulations. Experiments were carried out in the SINTEF Coriolis rotating basin, using a simplified topography that reflects the most relevant morphological aspects of the study area in the upper 400 m of the ocean. The tank was filled with water of homogeneous density, in such a way that the density stratification effects were removed. Therefore, the observed flow perturbations might be due to the gradients of fluid depths, or vorticity changes, the blocking effects of the islands on the incident flow and the topographic irregularities of the coastline. Ink and surface drifters were released to visualise relevant structures and to estimate the surface flow by tracking the drifter paths under different flow conditions.

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1 Introduction

Marine pollution has two main sources, the land and the sea. Land-based sources include pipelines and storm-water run-off, while marine sources include shipping accidental, deliberate and operational discharge and activities such as offshore oil-drilling operations.

Large oil tanker spills accidents (eg. the Urquiola, May 1976, in La Coruña, Spain; the Amoco Cadiz, March 1978, in France, and more recently the ERIKA, December 1999, in France) have demonstrated the particular susceptibility of the coastal environment to oil spills. These events evoke visions of despoiled coasts, oiled birds, and economic loss from ruined fisheries. Thus, for example, the ERIKA oil spill soaked in heavy crude more than 400 km of coast line and the costs related to the spill are estimated to exceed one billion French Francs (USD 160 million). In addition to pollute the coastal environment and damage marine life, the movement of oil slicks can cause the shutdown of power and desalination plants, cutting off supplies of fresh water and electrical power, with the consequent socioeconomic effects, particularly in small oceanic islands.

Due to their geographical location, the Canary Islands and the Saharan coasts are considerably vulnerable to oil spills because of the significant volume of oil transported through their surrounding waters from the Middle East to Europe around the South African shipping lane. This is one of the most important routes for crude transport in the world, and is known as "*Cabo de Buena Esperanza*" route. Thus, for example, on 19 December 1989 the Khark 5 tanker spilled some 20 million gallons of oil to the Atlantic Ocean, 185 km from Moroccan coast. So, it results evident that these regions should have a number of oil-spill contingency plans and personnel trained to forecast the movement of oil slicks, to ensure an efficient actuation in the event of a spill.

The development of adequate oil-spill contingency plans, to ensure that when oil spills do occur they can be dealt with effectively, requires information about oceanographic and meteorological regional conditions. Measurements of temperature and salinity distributions, wind and wave climatology, and bathymetry help to determine how spills will be transported and dispersed and the conditions that holding teams will encounter as they attempt to contain the oil. Knowledge of winds and ocean currents play a key role in the prediction of likely spill trajectories. However, field measurements of these parameters are seldom available.

Numerical models have been developed by several authors to simulate the time-space evolution of oil spills in the marine environment. These models can be classified into two main groups: At one hand, those considering the oil slick movement a primarily deterministic phenomenon governed, ultimately, by the transport equation derived from the general continuity and momentum conservation laws. On the other hand, those taking into account the random character of oil slicks movement at sea and, consequently, focussing the problem from a statistical point of view. Each group of models present advantages and disadvantages in relation to each other, but a common drawback is that most of

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the proposed models depend on some empirical relationship or simplification to circumvent theoretical and practical difficulties preventing to arrive at a successful resolution of the problem. Independently of the relative goodness of the different kind of mathematical models, it is clear that no agreement on a general theory to fully explain the oil spill movement exists.

A recent approach that could alleviate some of the existing problems and contribute to significant improvements in predicting oil spill movements is the use of laboratory circulation models, such as suggested by McClimans [7]. According to McClimans [5] a laboratory model is an advanced experiment where the boundary and forcing conditions are as close to natural conditions as the governing conditions allow. Several laboratory models have been used for dispersion studies [3].

In regions where the topography steers the flow, there is often a good validation to field measurements. In these regions, the requirement for geographical resolution of a numerical model is also very stringent. In spite of their good topographic resolution capabilities, differences up to 50% between laboratory and field dispersion measurements have been reported [6]. The lower dispersion values observed in laboratory have been attributed to the wind effects that are seldom included in this kind of model, due to technical difficulties.

Nevertheless, large-scale motions can be simulated accurately in a rotating basin. This is because of such flows, where the force balance is nearly geostrophic, are governed by the gravitational Froude and rotational Rossby similitudes, which are compatible [5]. The viscous Ekman layer near the bottom is only a few millimetres thick in most of these laboratory models. The most important effect of friction is therefore the wind forcing of surface currents, technically difficult to simulate in the laboratory, as mentioned above, and is therefore relegated to numerical models, which play an important role in this context.

Laboratory model approach is used in this study to simulate circulation in the upper layer of the ocean in the Canary Islands region. Results from the present study should improve our understanding of the surface dynamics in the study area and, consequently, our ability to predict the movement of potential oil or other pollutant discharges at sea, even though the stratification effects and the wind shear stress are not considered.

2 Background

The Canary Archipelago is placed at about 28 degrees North in latitude in the North Atlantic Ocean, very close (approx. 200 Km) to the north-west coast of Africa. Along this eastern boundary of the Atlantic Ocean flows the Canary Current, which is associated with the Northwest African upwelling. Furthermore, the Canary Archipelago acts as a barrier of about 500 km for the Canary Current. As a consequence of the African coast proximity and the obstruction of the ocean current flow by the islands, this region is characterised by a large mesoscale activity on the backside of the islands [8].

Surface manifestations of various mesoscale features, such as island wakes, large cyclonic and anticyclonic eddies downstream of the islands, and cool water filaments extending offshore from the upwelling region, sometimes reaching the islands, have been revealed by means of satellite observations [10, 9]. While clearly observed in satellite images and inferred from some in situ measurements (temperature and salinity fields), the physical origin and the necessary conditions for the generation of these mesoscale features is not well understood.

The physical processes underlying the dynamics of the formation and the stability of these features have been partially examined by using numerical models, in situ measurements and remote sensing data. However, the present knowledge of these physical processes does not result enough to give an appropriate explanation of the observed patterns, giving place to discrepancies among different hypothesis.

3 Laboratory model

The laboratory model was developed in the Coriolis rotating basin at SINTEF NHL. It has a size of 5 m diameter and 0.5 m height and was equipped with a video camera rotating firmly with the tank, viewing from above. Experiments were performed with a simple topography representing the most relevant morphological aspects of the study area in the upper 400 m of the ocean.

The tank was filled with water of homogeneous density, removing in this way the effects of density stratification and baroclinic motions. Therefore, observed flow perturbations might be due to the gradients of fluid depths, or vorticity changes, the blocking effects of the islands on the incident flow and the topographic irregularities of the coastline.

The model was run for three different flow conditions (1.5 Sv, 3 Sv and 6 Sv). Sets of 20-30 surface drifters were released, regularly spaced and aligned to the source orientation, at various instants and distances upstream Canary Islands, to track the flow along the African coast and across the islands, under different flow conditions. Ink of different colours was spilled at different places, inside the source, close to the African coast, around the islands, etc., to visualise relevant structures, also under different flow conditions. Tracking individual particles allows the identification of surface oceanographic features too. However, structures such as, eddies and filaments are easier observed by following the dye evolution or the ink plume envelope. Particles used to follow surface currents were black colour while used dyes had different colours (red, blue, green and black) to facilitate visual recognition from different dye spills.

It is worth of mention that particles and ink spills can be considered as imaginary oil spills. So they can be tracked and obtain information about the likely oil slick paths in terms of the point where it was spilled and the flow conditions.

The model scaling was determined by practical considerations of laboratory conditions. The horizontal length scale (ratio) was given as L_r = 1500 km/5 m = 300000 and a convenient vertical length scale (ratio) was H_r = 500 m/50 cm = 1000, leading to a vertical model distortion of 300. Time scale is $T_r = L_r\,(H_r\,\varepsilon_r)^{-1/2}$

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≈ 9500, where ε_r is the ratio of natural to model density gradients, in this case $\varepsilon_r = 1$, and a day is simulated in 9.1 s.

The model bathymetry, the solid boundaries, and the source and sink are sketched in figure 1., where the circle represents the Coriolis basin wall. The shaded rectangle is the camera field of view, and the two zigzag lines stand for the coastline and the 200m isobath, which are overlapped with the true coastline and isobath (wrinkled lines).

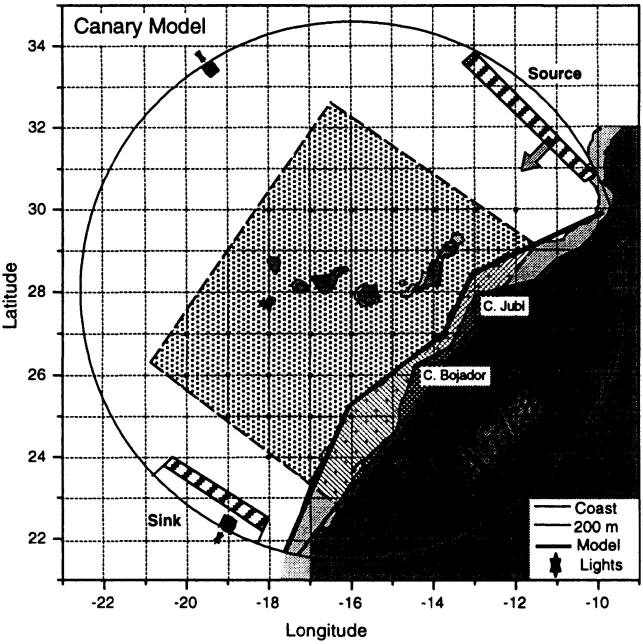

Figure 1: Canary Islands model region.

Note that between these two topographic levels the bathymetry displays, in a simplified but realistic way, two broadening zones, northward of Cape Jubi and southward of Cape Bojador. Below the 200m isobath the shelf falls vertically to the model bottom (400m), which is also a realistic simplification.

4 Results

About 100 particles, from the several hundreds released during the experiment, were chosen to be examined in the image sequences obtained by digitising the video camera film. Each sequence of video frames was manually analysed to establish the paths of individual particles and therefrom determine the velocities.

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Velocities are estimated measuring the displacement of particles during the prescribed time between two consecutive video frames.

The selection of particles was conditioned by the interest of examining the possible paths followed by the oil patch spilt from a hypothetical accident of a tanker navigating along the "*Cabo de Buena Esperanza*" route, and occurred northward Canary Islands. This idealised oil spill could be one similar to that, mentioned in section 1, of the Khark 5 tanker, which in 1989 spilled 80,000 tonnes of oil, 185 km from Moroccan coast, just in the zone where is placed the source in the model, marked with an arrow in Fig.1.

Each particle has been considered as an idealised oil patch. Particle paths have been classified in two groups, those travelling close to the African coast and those passing close or through the islands. Furthermore, these two groups of particle paths also allow the detection of two classes of mesoscale structures. At one hand, the structures associated to the Coastal Transition Zone (CTZ) of the Canary Current, produced by the interaction of this current with the Northwest African coastal and shelf topography. On the other hand, those observed backside of the Canary Archipelago, and generated by the islands obstruction of the Canary current (cyclonic and anticyclonic eddies).

4.1 Circulation in Northwest African Coastal Transition Zone

Flow patterns in the CTZ show similar characteristics under different simulated flow intensity. Particles released next to the African coast were transported to the south by the currents showing a strong meandering in their trajectories, such as can be observed in the particle paths depicted in Figs. 2a and 2b, indicating the presence of energetic mesoscale features in this area. Note that, for clarity, only a small number of particle paths have been represented in these figures. Another generally observed remarkable feature is the increase of the velocity of the particles when they move downstream of Cape Yubi.

The trajectories of some particles display one or more loops when trapped by cyclonic and anticyclonic eddies. Dye injected next to Cape Yubi, jointly with cyclonic loops described by particles, shows that cyclonic eddies are found next to the coastal shelf between Cape Yubi and Cape Bojador, and occasionally they are advected offshore principally when they go south of Cape Bojador. Moreover, dye and anticyclonic particle loops reveal that normally anticyclonic eddies are placed rather offshore than cyclonic ones at south of Cape Yubi and they are frequently viewed south of Cape Bojador.

Finally, in several occasions injected dye and particle paths deflect offshore, more frequently when they arrive south of Cape Bojador where continental shelf gets wider, as observed in Fig. 3.

In relation to our idealised oil patch, it is interesting to note that particles of this group flow generally along the African coast, but sometimes they are pulled to the African coast, while in some occasions are transported towards the island coasts, mainly toward those more oriental.

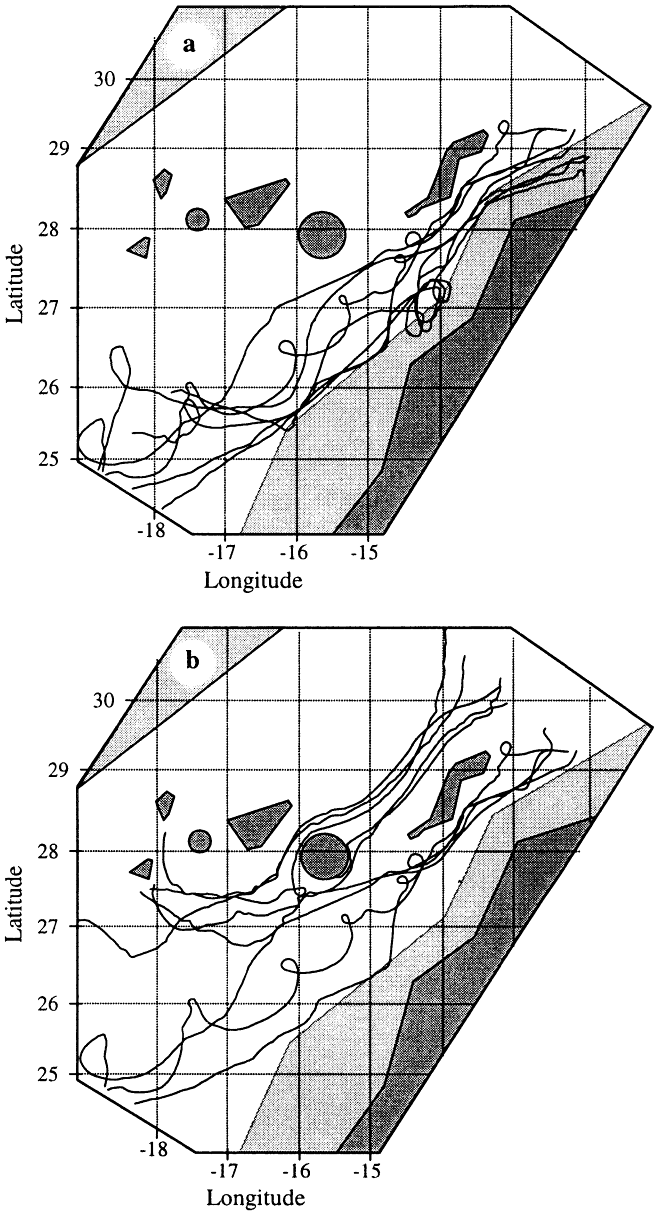

Figure 2: Laboratory model drifter paths; (a) particles moving close to the Northwest African CTZ; (b) particles through the Canary Islands.

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4.2 Circulation around Canary Islands archipelago

Particles released off the CTZ also progress southward, reaching the Canary Archipelago. In this case, particles move more rapidly when flow intensity increase, and under these conditions some of them seems to be accelerated through island channels. Generally, particles trajectories continue in a south-westward direction when they go south of the islands, but when they pass through the Gran Canaria – Fuerteventura channel, they can be deflected also to the African coast. Also, it is noticed that particles advancing close to the islands show a higher meandering when crossing the island channels displaying occasionally one loop, indicating a higher mesoscale activity just behind the islands.

This mesoscale activity is also evidenced by injecting dye quite closed to them. Dye injection at both sides of Gran Canaria shows clearly the generation and shedding of cyclonic and anticyclonic eddies sequentially leeward the island. Cyclonic eddies are formed in the western part of Gran Canaria while anticyclonic eddies surge in the eastern one, both of them propagating to the south as vortex streets. Additionally, it is frequently observed that these mesoscale features generated by islands flow perturbation interact strongly with those coming from the CTZ, giving place to a quite complex flow field in the rear side of the islands, such as observed in Fig. 2b and Fig.3.

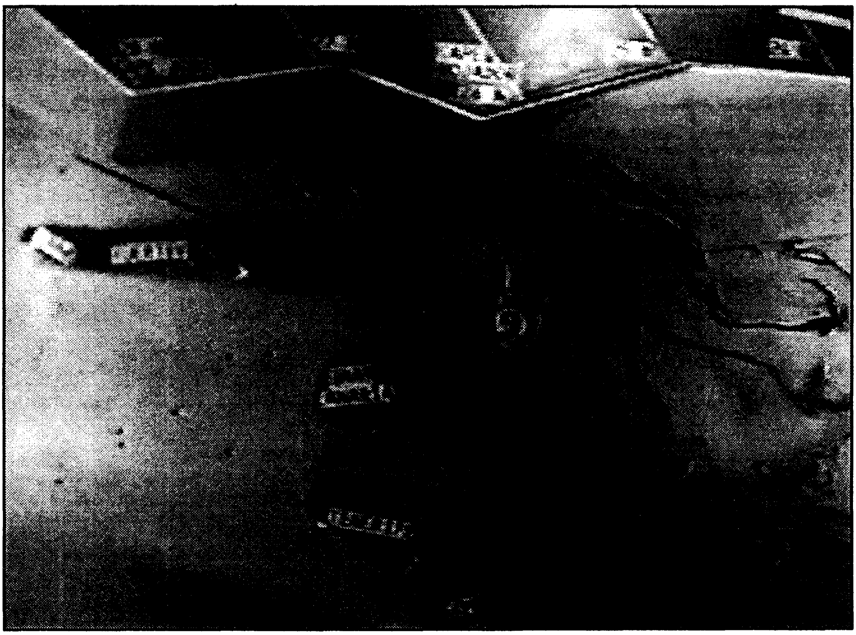

Figure 3: Mesoscale structures, generated by coastal irregularities and by islands blocking effect, marked by dye.

It is worth to note that in this case, a large number of particles (oil patchs) reach the island coasts and often impact coastlines, particularly those of the Gran Canaria, the most populated of the islands.

5 Conclusions

Laboratory model simulations reveal that great part of the observed mesoscale variability in the Canary islands area could be explained by the effect of coastal and bottom topography over the Canary Current flow. Respect to the observed features in the CTZ, laboratory simulations shows that flow around Cape Yubi could generate oceanic eddies downstream by separation of the current from the coast. Gyre formation at a curved coast in a rotating system has been observed in a number of simplified laboratory and computer studies [2, 4]. This supposes an alternative mechanism to that proposed by Barton *et al.* [1]. They suggest the origin of cyclonic eddies is probably vortex stretching of the flow exiting the shallower channel between Fuerteventura and Africa (this effect is not incorporated in the laboratory model).

It has been observed that Canary current is able to transport hypothetical oil patches spit north to the islands over considerable distance and impact their coasts, or deflect it toward African coasts. In addition, the variability of the currents due to mesoscale activity in the Canary Islands area could lead to a large shear dispersion of potential effluents of pollutants in the region. Both, mesoscale eddies and filaments, often seen in satellite images, enhance spreading of pollutants. Furthermore, filaments can transport pollutants from the African coasts to the islands. Then even if wind is attributed an important role in the spreading of surface discharges as oil spills, the variability of the background currents must be modelled correctly to obtain the true spreading [7]. Consequently, laboratory model simulations seems to be a useful tool for the prediction of pollutants transport that should be used jointly with numerical models and adequate databases to improve our ability to predict the movement of potential oil or other pollutant discharges at sea.

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