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The Tagus estuarine plume induced by wind and river runoff: Winter 2007 case study

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ABSTRACT

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Plumes of buoyant water produced by inflow from rivers and estuaries are common on the continental shelf. Buoyancy associated with estuarine waters is a key mediating factor in the transport and transformation of dissolved and particulate materials in coastal margins. The dispersal of the Tagus Estuary plume, for January 2007, induced by wind and river flow forcing is studied using a set of three-dimensional nested models. The numerical model used is Mohid (www.mohid.com). The model domain includes the whole Portuguese coast, the Estremadura coast and the Tagus River estuary with a realistic coastline and bottom topography. River discharge and wind forcing of January 2007 are considered as landward and surface boundary conditions, respectively. Ambient shelf conditions include tidal motion and low frequency circulation downscaled from Mercator Ocean Global Solution. As a prior validation, model's outputs of salinity and water temperature were compared to available data (near the Costa do Estoril, January 30th) and were found minor differences between model outputs and data. On January 30th, outside the estuary, the model results reveal a stratified water column, presenting salinity stratification of the order of 3-4. On the shelf, near the Tagus mouth, the export of estuarine waters forms a plume which is highly influenced by the geography of the coastline, inducing a plume trajectory very close to the shore. Northern winds events cause a displacement of the coastally trapped plume, driving a new offshore plume. The relaxation of the northern wind regime pushes back the coastal jet toward the coast, propagating estuarine water to the north along the Estremadura coast.

ADITIONAL INDEX WORDS: *upwelling, vertical structure ,salinity, temperature, Extremadura coast*

INTRODUCTION

Freshwater discharges from rivers and estuaries forms an outflow that is advected onto the near shelf during the ebb tide. When this estuarine water spreads over more saline coastal water, vertical mixing occurs, inducing a stronger seaward transport. In compensation, the lower layer tends to flow landward, onto the estuary. This classic two-layer circulation has been observed in many estuarine regions. Observations and numerical simulations have shown that local winds and river runoff affects the dispersal of a river (or estuarine) plume as it enters the coastal ocean (WITHNEY AND GARVINE, 2006; CHOI AND WILKINS, 2007).

Idealized model simulations of river plumes are typically implemented with a straight coastline and a river represented by a point source (HETLAND, 2005). Other plume model studies have been implemented using realistic geometry and imposed observed river flow and wind forcing (PULLEN AND ALLEN, 2000) and tides (WITHNEY AND GARVINE, 2006) in order to examine the dispersal of a river plume in comparison with observations.

The offshore displacement of the plume is influenced greatly by the local alongshore wind, which will tend to advect the plume either offshore or onshore, consistently with the Ekman transport (FONG and GEYER, 2001). In the west coast of Portugal, for the case of upwelling favorable winds, the expected response is an offshore displacement of the plume at the surface and an onshore water movement over the continental shelf and toward the coast.

The model presented here includes the whole Portuguese coast, the Estremadura coast and the Tagus River estuary with a realistic coastline and bottom topography. The wind forcing (MM5 data) and river discharge of January 2007 are imposed as landward boundary conditions. Initial ocean stratification is from the MERCATOR solution (BAHUREL *et al.*, 2001).

In this paper, a three-dimensional ocean circulation model with realistic high and low frequency forcing is used to get insight on how the Tagus River plume responds to wind and freshwater discharge during winter. The model set-up and initializations are described in the next section.

NUMERICAL MODEL

The numerical model used is the MOHID – Water Modelling System (information online at www.mohid.com), a three-dimensional marine model that has been implemented in several studies of estuaries and shelf circulation (MARTINS *et al.*, 2001,

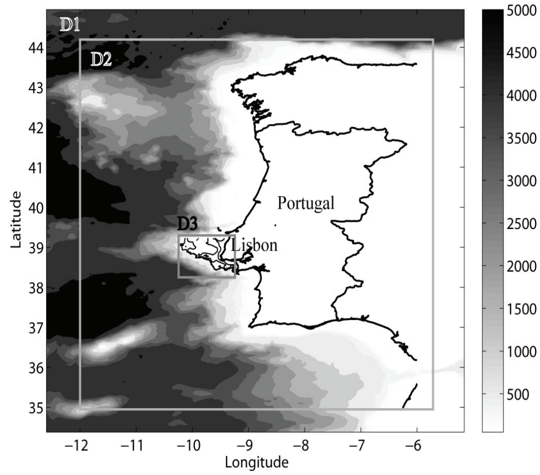

Figure 1. The MOHID nesting system, showing D1 and D2 and D3 (Estremadura Coast). Gray scale is bathymetry in meters

COELHO *et al.*, 2002, VILLARREAL *et al.*, 2002, VAZ *et al.*, 2007, VAZ *et al.*, 2009). Details of the MOHID numerical algorithms are summarized by MARTINS *et al.* (2001) and LEITÃO (2002). Vertical turbulence closure scheme is the κ-ε model (BURCHARD and BOLDING, 2001) with the parameterization proposed by CANUTO *et al*. (2001).

The numerical model was implemented using a three level nesting model (Figure 1). The first domain (D1) is a 2D barotropic tidal-driven model, which uses the FES2004 global solution (LYARD *et al.*, 2006) as forcing, and has variable horizontal resolution (0.02º-0.04º). This model domain covers most of the Atlantic coast of Iberia and Morocco. The second (D2) and third (D3) levels are 3D baroclinic models. The second domain (D2) has 0.06º horizontal resolution and is similar to D1. The third domain (D3) has 0.02º horizontal resolution and includes the Tagus Promontory area and it is directly coupled to D2 at the open boundaries.

The Tagus freshwater discharge is imposed offline. This discharge is computed with a 0.023º-0.0027º horizontal resolution model for the inner part of the estuary and directly imposed as a momentum, water and mass discharge to the coastal model. The open boundary conditions (OBC) for D2 are defined by adding to the solution of D1 (high frequency) the low frequency MERCATOR solution (BAHUREL *et al.*, 2001), which for this area has a resolution of ~0.05º. The surface boundary condition is imposed using high resolution results from the MM5 system (DUDHIA *et al.*, 2004) run by the Mechanical Engineering Department of the Instituto Superior Técnico of Lisbon. This system has a resolution of 9 km near the shore.

A z-level vertical discretization was adopted for the 3D models, with D2 and D3 having 43 and 35 vertical layers, respectively. The temporal discretization is done using an alternate direction semi-implicit (ADI) method (LEENDERTSE, 1967) for the 2D mass balance equation (used to compute the water level). For the 3D momentum (zonal and meridional velocities), heat and salt balance equations the vertical direction is computed implicitly while the horizontal directions are explicitly. The advection of momentum, heat and salt is computed using a total variation diminishing (TVD) scheme with a Superbee limiter. In this application MOHID runs with a time step of 180 s for D1 and D2, and 60 s for D3.

At the surface, the boundary conditions for vertical diffusion of momentum and turbulent kinetic energy were computed based on wind velocity fields from the MM5 model. Wind stress was computed using the formulation by LARGE AND POUND (1981). Heat fluxes were computed using atmospheric data (wind velocity, air temperature, solar radiation, relative humidity and cloud cover). At the bed, the bottom stress is imposed assuming for the bottom layer velocity a logarithmic profile. As landward boundary conditions, the model uses freshwater discharges and a null mass and momentum flux is imposed. At the open boundary, the 3D models uses data (water level, u and v velocity, water temperature and salinity) interpolated from the MERCATOR solution for the North Atlantic with the radiation scheme by FLATHER (1974).

SITE DESCRIPTION

The region which is under the influence of the Tagus River (D3, the Tagus ROFI, see Figure 1) is highly dynamic in terms of its physical and biogeochemical processes. The circulation in this area is mainly controlled by tide and wind forcing (LEITÃO, 2002). The wind effect over this area depends on the vertical stratification, which in turn is dependable on the heat exchanges with the atmosphere and the salinity advection. The Tagus River is the main source of stratification, having an average flow of 350 m^{3}s^{-1}. There are records of instantaneous maximum flows of about 15000 m^{3}s^{-1} (LEITÃO, 2002). The tides are semidiurnal, presenting tidal ranges from 2.0 to 2.7 m. In this area, the surface velocities present typical values of 1 ms^{-1} and the salinity above 20 meters depth is about 34 psu. On the bottom, this region present salinity values of about 36 psu (typical oceanic values), except during high river runoff events, when lower salinity (~34-35 psu) can be found.

ENVIRONMENTAL CONDITIONS

The simulation was performed for the period of January 2007, over which the river runoff and local wind were highly variable. Freshwater flow was measured at the stream gauge of Almourol (outside the influence of the tidal motion). The freshwater flow ranged from 800 m^{3}s^{-1} (at the early days of January) and 100 m^{3}s^{-1} (at the end of the month) (Figure 2a). The wind pattern was also highly variable, presenting southern winds until the middle of January and then rotating to northern winds after 20 of January (Figure 2b). The wind intensity presented a southern and northern maximum of about 7 ms^{-1} and 12 ms^{-1}, respectively.

STRATIFICATION AT THE TAGUS ROFI

At the region of freshwater influence of the Tagus River,

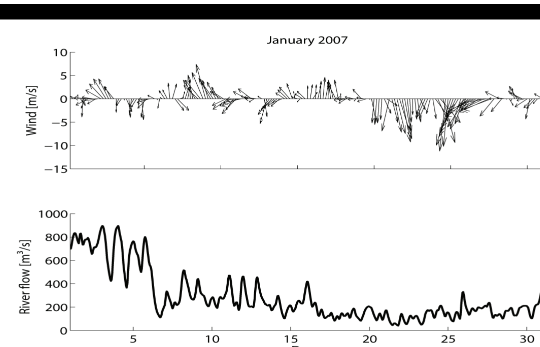

Figure 2. (a) Wind [ms^{-1}] at the Guia (MM5 data) and (b) River flow from the Almourol stream gauge [m^{3}s^{-1}].

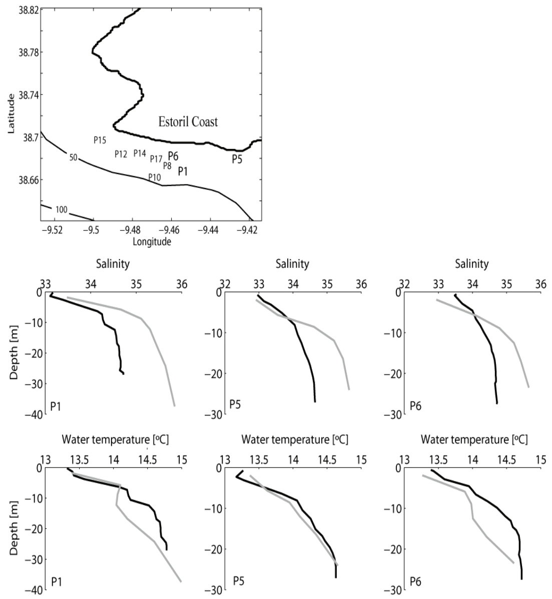

Figure 3. Top panel: The Estoril Coast with the location of the stations; middle panel: salinity profiles and lower panel: water temperature profiles [ºC]. gray and black lines are model results and observations, respectively.

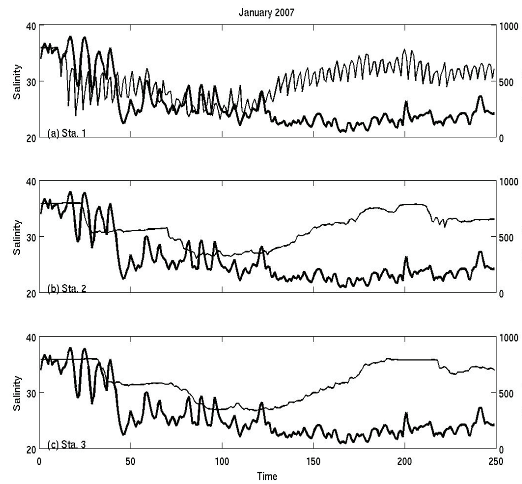

Figure 4. Surface salinity versus river flow at Almourol stream gauge at three stations over the influence of the Tagus esturine outflow. Thick solid line is river flow.

salinity and water temperature model results were compared to measurements taken at several points along the Estremadura Coast (see Figure 3, top panel) on the January 30th, 2007 during flood tide. These measurements were taken using an YSI probe and the survey was performed under the monitoring program of the Guia outfall.

Figure 3 depicts the results for three stations (P1, P5 and P6).

The salinity profiles (Figure 3, middle panel) reveal a stratified water column and a model's results over-prediction of the salinity near the bottom. Therefore an overestimation of the salinity stratification is observed. Nonetheless, the pycnocline is always well reproduced by the model, occurring at the same vertical level as observed. Differences in the salinity stratification are of the order of 3 psu (between model results and measurements). Apparently, the model does not reproduce vertical mixing below 15-20 meters depth. The water temperature profiles reveal small differences between model results and observations. These differences, between measurements and model results, are of the order of 0.75 ºC.

These results reveal that, in general, the model can reproduce thermohaline patterns at the near shelf close to the Tagus mouth. On the bottom, the overestimation of the salinity could be due to an improper prescription of the landward boundary condition – the Tagus Estuary outflow. This outflow was computed using the results of the Tagus River operational model (run at MARETEC, see details on www.mohid.com/tejo%2Dop/) and it should be improved using a more refined grid for the Tagus Estuary model.

CONTROLS OF THE RIVER PLUME BY FRESHWATER DISCHARGE

On time scales higher than the tidal cycle, the plume water may be related to the freshwater discharge from the Tagus river. In order to study how freshwater entering the estuary influences the plume water, surface salinity at the Tagus Region of Freshwater Influence (ROFI) is plotted against river flow from Almourol stream gauge. For that, three stations were chosen: Station 1 located near the Tagus Estuary mouth (near P5, see Figure 3); Station 2 located a few kilometers to the west at Guia, near P15, and Station 3 located on the west coast of D3. This last station is chosen in order to address some differences between stations that are located inside the Tagus ROFI and one that are outside this region.

At Station 1, near the Tagus mouth, surface salinity is influenced by the freshwater inflow as it can be observed in Figure 4a. When river flow is high, surface salinity remains relatively low (~30 psu). Moreover, at this location, surface salinity has a strong high frequency signal (~12 hours) corresponding to the ebb/flood cycle of the estuary. This means that on ebb, surface salinity values are lower, due to the effect of the tide enhanced by stream from the river. During the flood period, surface salinity suffers an increase due to the transport of oceanic waters toward the estuary.

At Stations 2 and 3, surface salinity has a smoother signal which is in phase opposition to the freshwater discharge signal (e.g. when freshwater discharge increase surface salinity decreases and vice-versa). That is, in these stations, salinity is less variable than near the Tagus mouth. At these locations, the surface salinity signal is similar. However, near P15 (at Guia), plume water presents a salinity variations noisier than the salinity variation at station 3. When the river inflow increases, surface salinity decreases. Typical values of surface salinity are about 30/31 psu under a river runoff between 200 and 500 m^3s^{-1}. When the river inflow is lower than 200 m^3s^{-1}, surface salinity increases reaching, at these locations, 35 psu, which is an oceanic value. This noisier salinity signal at Station 2 could be due to the tidal effect. Nonetheless this should be confirmed using long time series of surface salinity that are not available at this time.

These results confirm that the plume salinity is a quasi-linear function of the river discharge on time scales higher than the tidal cycle and ranges from 35 psu at discharge rates under 200 m^3s^{-1} to values of about 30 psu at discharge rates between 200 and 500 m^3s^{-1}.

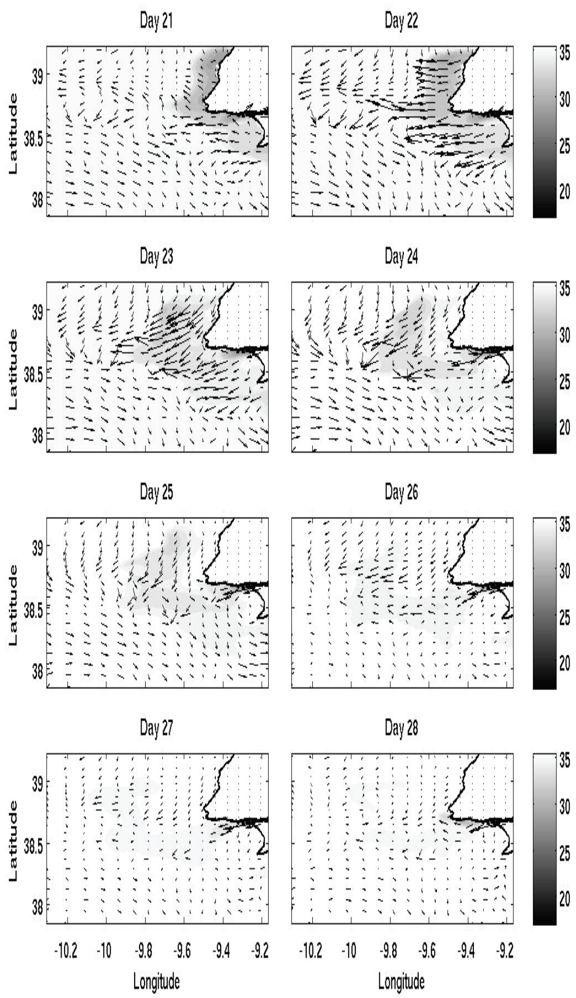

Figure 5: Surface salinity and current vectors for the days covering the winter upwelling event. Color is salinity [psu]. The considered initial state is the graph of Day 21.

PLUME RESPONSE TO FAVORABLE UPWELLING WINDS

In this section, the penetration of the estuarine plume onto the near-shelf under the influence of favorable upwelling winds is examined.

After 20 of January, the Estremadura Coast (domain D3) was under the influence of winds blowing from the north which are favorable to the occurrence of upwelling events. The end of January was characterized by strong northern winds which reach a maximum of 12 ms^{-1} on 25 of January. At the western Portuguese coast, when northward wind blows, Ekman surface flow is droved toward the west. Low salinity water, from the coast, is advected offshore mixing with oceanic waters. On the other hand, on the coast, high salinity water from the bottom is advected toward the surface increasing salinity concentration.

Figure 5 depicts surface salinity and surface current velocity at domain D3 during this winter upwelling event. Initial state is considered on January 21 when the plume is fully developed along the west coast of Estoril (Figure 5, Day 21). In fact, in this day estuarine water flows out the estuary and follow toward the north close to the shore, as trapped by the bathymetry. The width of the plume is about 10 kilometers (from the coast).

Starting from day 21, northward winds increase their magnitude (see Figure 2a for reference), inducing an advection of plume water toward the west, in the cross-shore direction. On day 22, the plume displacement is about 20 km (from the coast), increasing to a maximum of about 40 km on day 24. Near the coast, surface salinity increases from values close to 30 psu (on day 21) to values of about 35 (on days 26 and 27) when the plume water was completed advected offshore.

Surface current shows a pattern that also indicates transport toward the west, with a maximum, outside the Tagus ROFI, close to 1 ms^{-1}, as visible in figures depicting Days 22, 23 and 24 results.

On day 22, surface currents present a well defined east-west direction, corresponding to a period in which the wind blows steadily from north. As the wind direction changes current velocity changes its direction to southwest (as depicted on days 23 and 24 figures). Maximum wind magnitude is reached around day 25, leading to the maximum displacement of the plume on days 25 and 26. The advection of plume waters induces mixing of low saline water with oceanic water, leading to a decrease of surface salinity as the plume is being advected and then an increase of surface salinity as mixing with upwelled water from the shelf occurs.

After day 26, a relaxation of the wind magnitude is felted, being visible that low salinity water from the estuary begins to flow following the coastline, forming a buoyancy front toward the north. Surface currents are also weaker at these days, with values lower than 0.2 ms^{-1} (out of the coastal zone).

CONCLUSIONS

This work intends to be a first step in order to study and characterize the Tagus estuarine plume as it propagates itself out of the estuary. A baroclinic nested model with realistic low and high frequency forcing is used to address this topic.

The model was validated against data measured at the estuary ROFI, revealing a good agreement in water temperature. However, the salinity results reveal that the model underestimates mixing below 15-20 meters depth. On the other hand, the pycnocline depth is well reproduced by the model.

The effect of the river flow intensity over salinity in the adjacent coastal area was illustrated by doing a simple exercise of directly comparing the surface salinity at three different locations and the river runoff. Near the Tagus Estuary mouth, surface salinity is clearly modulated by the freshwater runoff and also by the tide. In the limit of the estuary ROFI (at Guia), surface salinity varies smoothly and in phase opposition to the freshwater discharge. At the west coast of domain D3, surface salinity follows a similar variation as the one observed at Guia.

The response of the river plume to favorable upwelling winds was also examined. As expected, northern winds induces an offshore Ekman transport, with low salinity water from the plume being advected westward. Near the coast, the surface salinity ranges from 30 psu (plume waters) to oceanic values of 35 psu when the plume is totally advected and the upwelled water from the shelf reach the surface. A maximum displacement of 40 kilometers is observed from the surface salinity results. A relaxation of the northern winds pushes back the coastal jet toward the coast, propagating plume water, from the estuary, northward along the Estremadura coast.

Although the main scope of this paper is to provide some insight on the Tagus estuarine plume main features, further studies should also address the water temperature results. In fact, model results show that a plume of low temperature water from the estuary is not completely visible. This could indicate that heating of estuarine waters by solar radiation, which in turn are advected to the near coast, may influence surface water temperature at the coast. These questions will be addressed in future studies.

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