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Water Exchange Mechanisms Between Ria de Aveiro and the Atlantic Ocean

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ABSTRACT

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The water exchange between the ocean costal waters and the Ria de Aveiro coastal lagoon has an important role in the environmental aspects inside the lagoon. A well-tested 3D coastal circulation model is applied to establish different scenarios of this interaction. The numerical experiments, employing lagrangian techniques, were devised to study the effect of the tide and wind driven flows on the patterns of the residual circulation in the neighborhoods of the entrance of the coastal lagoon, and to delimitate the ocean domain of influence of the Ria de Aveiro, where this exchange is important.

ADDITIONAL INDEX WORDS: *Numerical modeling, coastal circulation, water quality.*

INTRODUCTION

The Ria de Aveiro is a coastal lagoon with a complex morphology located in the Northern coast of Portugal that provides natural conditions for harbor, navigation and recreation facilities. The lagoon communicates with the Atlantic Ocean through a 500 m wide channel (see figure 1). The environmental aspects of the Ria de Aveiro depend mainly on the water exchanges with the coastal ocean, on the water flows due to river runoff and on the discharges of polluted waters originated by domestic and industrial wastes. Recently, a new submarine outfall was built 3 Km offshore the Aveiro coast and 3 Km north of the inlet channel. This outfall discharges into the ocean wastes coming from the municipalities bordering the Ria de Aveiro and also from a large pulp plant.

The recent work of SILVA *et al*. (2001) have characterized the transport and dispersion of effluent plume coming from the outfall from airborne remote sensing observations. The results show that during typical spring and summer conditions with moderate winds from the Northwest the near surface transport was alongshore in the southward direction frequently with an onshore component. Therefore impacts of pollutants released from the outfall can be expected in the near shore area to the south of the outfall and potentially within the lagoon.

In the present study we are concerned with the coastal circulation patterns close the inlet channel and how they drive the water exchange between the coastal lagoon and the shelf. This has a considerable interest to characterize the dispersion and transport of the pollutants released at the outfall and can provide useful information to understand the exchange of larvae between the two systems.

In order to investigate the conditions in which these water exchanges occurs it is important to understand and describe the hydrodynamic processes that control the water mixing in the coastal ocean and near the channel inlet. The coastal circulation is complex because is driven by a different ensemble of forcing mechanisms. The wind and the tidal flow are the two major driving forces in the shelf along the Western coast of Iberian Peninsula. In the foreshore and surf zone, swell waves also constitute an important factor in the near shore circulation, because they drive onshore and alongshore littoral drift to the south (SILVA *et al*., 2001). The circulation in the interior of the coastal lagoon and in the inlet channel is dominated by the tidal wave dynamics (DIAS, 2001).

To simulate the circulation in the coastal ocean and Ria the Aveiro systems a well-tested 3D numerical model is used. The numerical experiments were designed to study the effect of the winds and tidal forcing mechanisms on the water exchange between the coastal ocean and the Ria de Aveiro. For such purpose different wind regimes typical from this region were considered and realistic tidal currents and surface water level were imposed at the open oceanic boundaries. Spring tides and neap tides conditions were simulated. Lagrangian techniques were employed to establish patterns of residual circulation and to quantify the oceanic domain of influence of the lagoon.

COASTAL CIRCULATION MODEL

Coastal circulation models represent nowadays a powerful tool to address problems in environmental studies such as analysis of waste disposal, and transport and fate of contaminating materials and biological parameters.

The coastal ocean circulation model described in and the Atlantic Ocean. The model is a free surface, hydrostatic, discussing the transport processes between the Ria de Aveiro

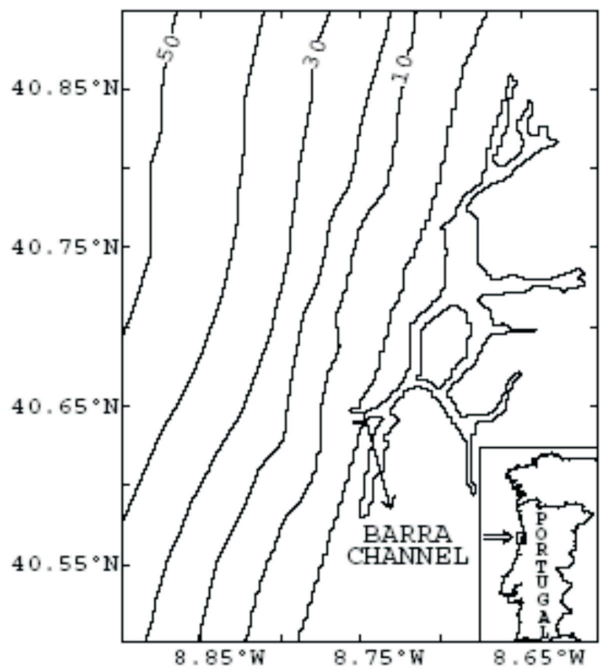

Figure 1. Geographic map of Ria de Aveiro and coastal region, illustrating the bathymetry.

HAIDVOGEL and BECKMAN (1999) called ROMS (Regional

Oceanographic Modeling System) is used as a framework for primitive equation 3D model that uses stretched terrain following coordinates in the vertical (*s*-coordinate system). In the *s*-coordinate system the number of grid points in the vertical is independent of the local depth, which enables a correct representation of the surface and bottom boundary layer across the entire slop shelf. In the horizontal plane, a curvilinear boundary following with lateral variable resolution grid can be considered. This feature enable the modeler to concentrate more resolution in some part of the domain and to adapt the grid to a complex coast line geometry. A comprehensive description of ROMS is given in the already mentioned paper.

Recent applications of the model ROMS to the Western Iberian continental shelf (PELIZ *et al*., 2003a; 2003b) have show the reliability of the model to reproduce the main features of the coastal circulation over the shelf, namely, wind driven and tidal flows.

CASE STUDY: RIA DE AVEIRO COASTAL OCEAN SYSTEM

To study the circulation patterns at the ocean entrance of the Ria de Aveiro coastal lagoon with the numerical model ROMS, a high-resolution 200 m regular computational numerical grid was set up. This grid encompasses the continental shelf up to 50 m depth and the Ria de Aveiro lagoon, from longitude 8º60W to 8º90W and latitude 40º50N to 40.90N (see figure 1). The dimensions of the computational grid are approximately 25 44 Km.

Realistic bottom topography of the continental shelf and of the Barra channel was considered, while in the interior of the Ria a constant water depth of 5 m was assumed. Therefore the circulation within the lagoon is not properly resolved. Ten vertical levels were considered in the whole computational domain.

A well-mixed ocean with a constant salinity of 35 PSU and temperature of 14ºC was assumed. The barotropic time step of the model was set to 1s and the baroclinic to 20 s in order to achieve numerical stability.

At the Northern, Western and Southern open boundaries, the tidal wave was imposed considering the harmonic semidiurnal components M2, K2, S2 and N2 and the diurnal P1, Q1, O1 and K1. In addition, the tidal ellipses corresponding to these frequencies were also imposed to improve the adjustment of the velocity field in the interior of the computational domain. These boundary values were obtained from the application of ROMS model to a larger domain, extending from the southern cape São Vicente up to the Northern boundary of the Iberian Peninsula (ALMEIDA and DUBERT, 2003).

A time period of 19 days was considered in the simulations. The computed values of the surface velocity at the entrance of the lagoon during spring tides oscillated between the maximum value of 1.8m/s, during flood conditions, and 2.5 m/s, during ebb conditions. At neap waters these values were 0.8 m/s and 0.9 m/s, respectively. These values are in agreement with the ones that were measured in identical tidal conditions. Moreover, the computed tidal prism of 50-140 10^6 m^3, corresponding to neap and spring tidal conditions, respectively, is also in agreement with the measured values of DIAS (2001), 40-140 10^6 m^3.

To study the water exchanges between the coastal ocean and the lagoon, a set of particles was released at different levels in the water column (at the surface, at an intermediate level and near the bottom) in the domain adjacent to the entrance of the coastal lagoon. This domain extends from approximately 8,75ºW to 8,88ºW and from 40,55ºN to 40,71ºN. The distance between two adjacent particles is 1000 m. During the simulation period, two sets of particles were released: one after 1.92 days of the beginning of the simulation time, corresponding to spring water levels and another after 7.58 days corresponding to neap water levels.

Different typical wind conditions for the region in study were considered in the simulations: a Northerly and Northwesterly winds with a constant wind stress of 0.07 Pa (approximately 7 m/s wind speed). A third simulation was devised in order to describe the coastal ocean circulation in the absence of wind.

Therefore, 6 scenario tests cases were considered corresponding to different wind regimes and water tidal levels conditions. Within each scenario, we have analyzed the paths of the particles released at each grid point. This information was used in this study to establish the ocean domain of influence of the coastal lagoon. For this purpose, we have quantified which particles enter in the coastal lagoon after 2 days from their release time. On the other hand, the preferential paths of the particles that come out of the lagoon in ebb flow conditions were also analyzed. This information is also useful to establish the patterns of residual circulation that occur near the entrance of the coastal lagoon.

No wind forcing

This numerical simulation, when only the tidal forcing is considered, aimed to characterize the coastal circulation near the entrance of the coastal lagoon in low winds regime. Figure 2 and 3 illustrates the numerical results obtained in spring and neap tides, respectively. The domain where particles were released is indicated by the points in figures 2(a) and 3(a). The

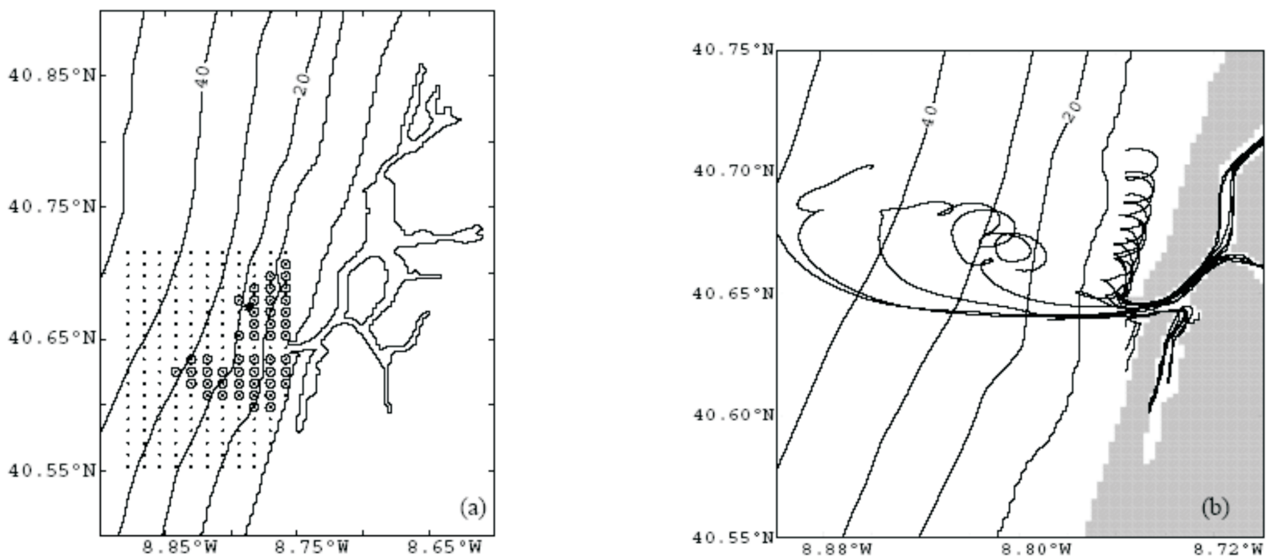

Figure 2. No wind forcing at spring tides (a) particles released; (b) the contour paths for the particles. In figure (a) * represents the outfall location.

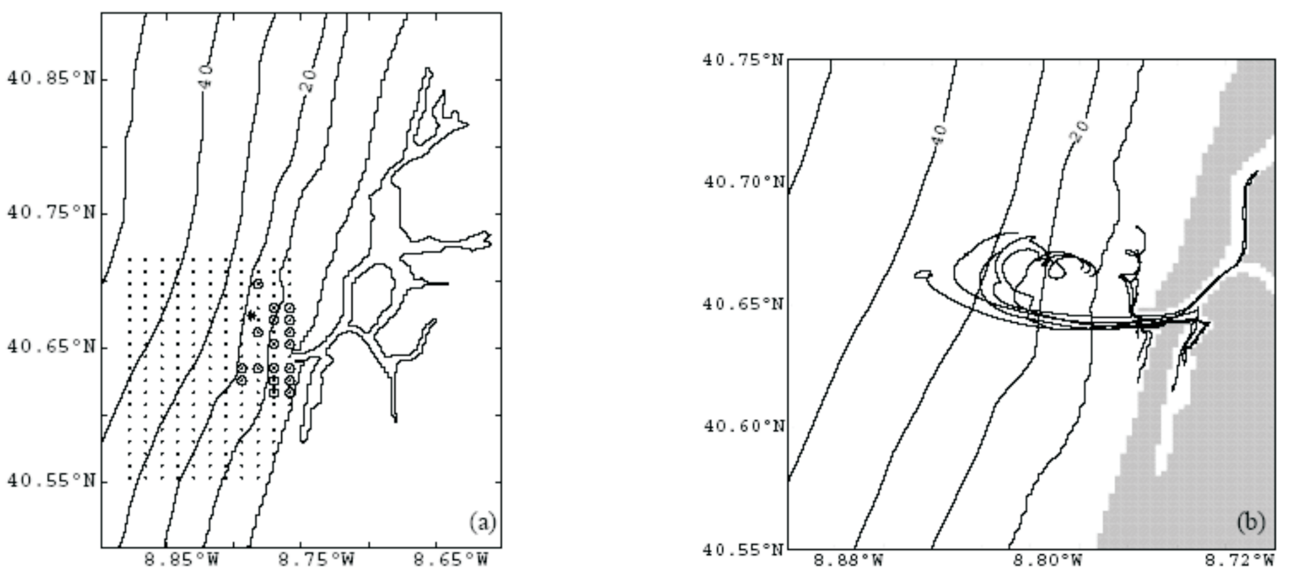

Figure 3. No wind forcing at neap tides (a) particles released; (b) the contour paths for the particles. In figure (a) * represents the outfall location.

solid circle lines around each mesh point indicate the initial positions of the particles that entered effectively in the coastal lagoon after 2 days of being released. Also, in these figures, the symbol represents the location of the São Jacinto submarine outfall. Figures 2(b) and 3(b) represent the paths of the particles that were driven offshore the lagoon in ebb flow conditions. For a better visualization, only paths of the particles released at a N-S line located at 8,76ºW that entered in the Ria are represented. Both figures show the numerical solutions obtained with the surface particles. The situation observed at the intermediate and near bottom levels do not differ substantially from the pictures observed at the surface, except when mentioned explicitly in the text.

In the absence of the coastal lagoon, the tidal circulation computed at each grid point consists in closed ellipses. The presence of an inlet, that communicates the costal ocean with the interior of the Ria de Aveiro, induces strong flow velocities at its entrance and changes significantly this picture.

During flood conditions, a suction effect is observed at all mesh points, driving the particles into the Ria de Aveiro. As shown in figures 2(a) and 3(a), within a time scale of 2 days, this region of suction extends well into the inner shelf. In spring tide conditions this region extends from approximately 40,60ºN to 40,70ºN in latitude and up to 7 Km in the offshore direction. The location of the submarine outfall is within the coastal ocean domain represented. In neap tide conditions the dimensions of this region are lower due to a decrease of the flow velocities in the Barra channel: it extends from approximately 40,62ºN to 40,68ºN in latitude and up to 3 Km offshore. It should be stressed that the results presented are phase dependent, in the sense that they depend on the existing flow conditions (flood/ebb flows) at the entrance of the channel when the particles pass just in front of it. This explains that some particles initially located near the entrance of the Ria were advected offshore and were not quantified for the coastal domain represented.

During the ebb, the flow consists of a jet that extends a few kilometers offshore as represented by the paths of the particles in figures 2(b) and 3(b). Due to the action of the Coriolis force the trajectories of these particles are deviated in the clockwise direction and afterwards, during flood conditions, are again driven into the lagoon, performing a vortex movement. The simulations show that these particles are continuously entering and leaving the coastal lagoon at subsequent times. This established residual flow is not favorable to the renewal of the waters within the coastal lagoon. It should be noted that the path of the particles released at intermediate and near bottom levels do not show such a well-organized motion, probably because the flow velocities during the flood conditions at those levels are not so strong.

Northerly winds

The numerical simulations performed with a steady northerly wind show a southward circulation pattern at all levels. This revels that wind forcing is the main forcing mechanism in the shelf, as it controls the shelf circulation through the development of analongshore-southward coastal current. The dynamics of this flow is well studied in the literature (ALLEN *et al*., 1995). It results from the response of the ocean to the offshore Ekman transport, coastal divergence, and hence the generation of a pressure gradient (water level gradient) with lowers values of sea level at the coast. This generates a southward geostrophic jet, which advects the particles in the southward direction. However, in the surroundings of the entrance of the channel this pattern is modified by tidal induced velocities, driving the particles in and out of the Ria, as described above.

Figures 4 and 5 are analogous to the ones presented before: they illustrate the numerical results obtained in this test case in spring and neap tides, respectively.

The analysis of figures 4(a) and 5(a) give a clear indication that the particles that were released northward of the Barra channel, at least up to 40,71ºN, are mainly the ones that enter in the Ria. The spring and neap tidal results are different in the offshore extension to which this effect is visible: in spring tidal conditions some particles released 3000m offshore enter in the Ria, while in neap tides this distance reduces to 1000 m. This different behavior can be interpreted in light of the strength of the onshore flow velocities developed at the Barra channel during flood conditions low, as described before. Note that the location of the submarine outfall is within the coastal ocean domain represented for the spring tidal condition.

Figures 4(b) and 5(b) show the preferential paths of the particles that leave the lagoon and that have been released in the N-S line located at 8,76ºW. It is seen that these particles are driven offshore due to the strong offshore ebb flow jet and are afterwards advected southward, more or less in paths aligned with the bottom topography, responding to northerly wind forcing. Note that the strength of the ebb induced circulation near the entrance of the coastal lagoon lead to different paths of the surface particles as they move southward: in spring tide conditions the particles move southward in paths more located offshore than in neap tide conditions. However, in the case of neap tides, we have observed a different behavior for the

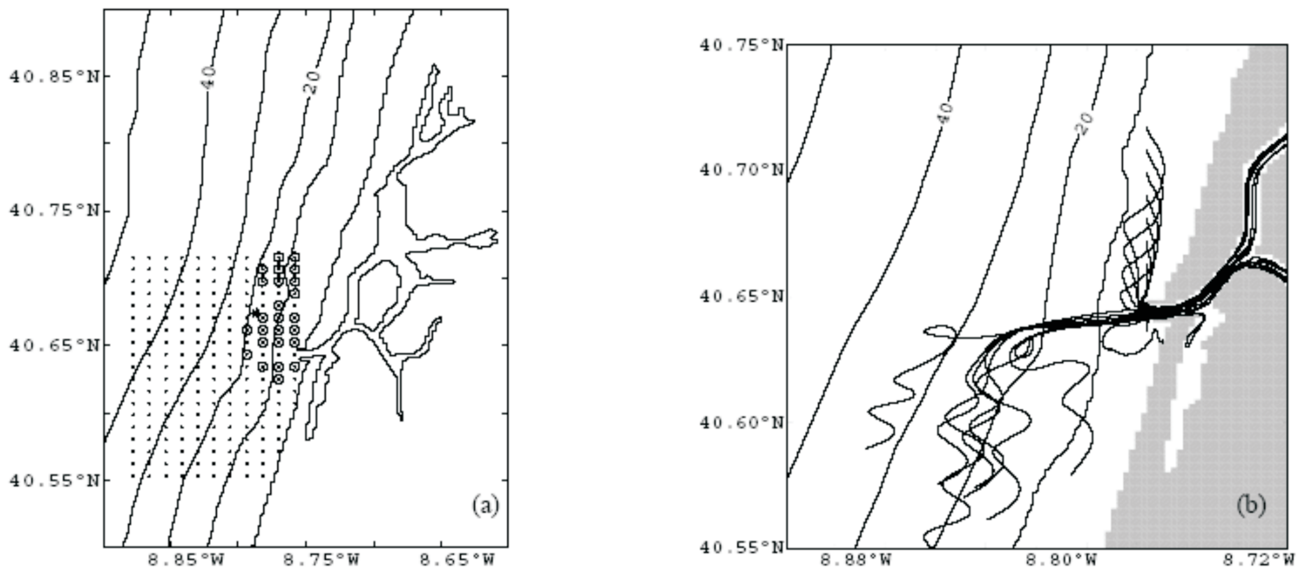

Figure 4. Northerly wind forcing at spring tides (a) particles released; (b) the contour paths for the particles. In figure (a) * represents the outfall location.

particles that were released at the intermediate and near bottom levels. These move southwards preferentially between the bathymetric of 10 and 20 m. This fact gives an indication that during neap tides the surface circulation near the entrance of the Ria is to a more extent dominated by the wind driven flow.

The flow patterns described implies a residual transport, first from the area depicted in figure 4(a), north of the inlet channel, into the Ria de Aveiro, and afterwards to the south.

Northwesterly winds

The numerical simulations performed with a steady northwesterly wind give similar results to the ones presented before for the Northerly wind. In this case, the coastal domain of particles that effectively interact with the lagoon is slightly deviated to the left, when compare to the one depicted in figure 4(a), and aligned with the wind direction. Also, the paths of the particles that are driven offshore the lagoon during ebb flow is very similar to the ones represented in figure 5(b): the particles are advected offshore and southeastward impinging on the coast.

DISCUSSION AND CONCLUSION

The circulation patterns at the coastal ocean near the Ria de Aveiro, were simulated with a 3D numerical ocean model. Different scenario test cases were considered corresponding to different wind regimes and tidal conditions. Lagrangian techniques were employed to delimitate the ocean domain of influence of the Ria de Aveiro and to identify patterns of residual circulation in the coastal ocean.

The results obtained have shown that the flow patterns in the neighborhood of the Barra channel are mainly driven by flood and ebb tidal currents, while offshore, when wind forcing is considered, wind driven currents are predominant. These general flow characteristics give rise to a suction effect during flood tidal conditions that drive the particles released at different levels into the coastal lagoon and to the development of an offshore jet at ebb tide, that extends well into the shelf. The occurrence of spring and neap tides modify the magnitude of the currents at Barra channel and therefore the extent in the offshore direction where these two flow patterns are felt.

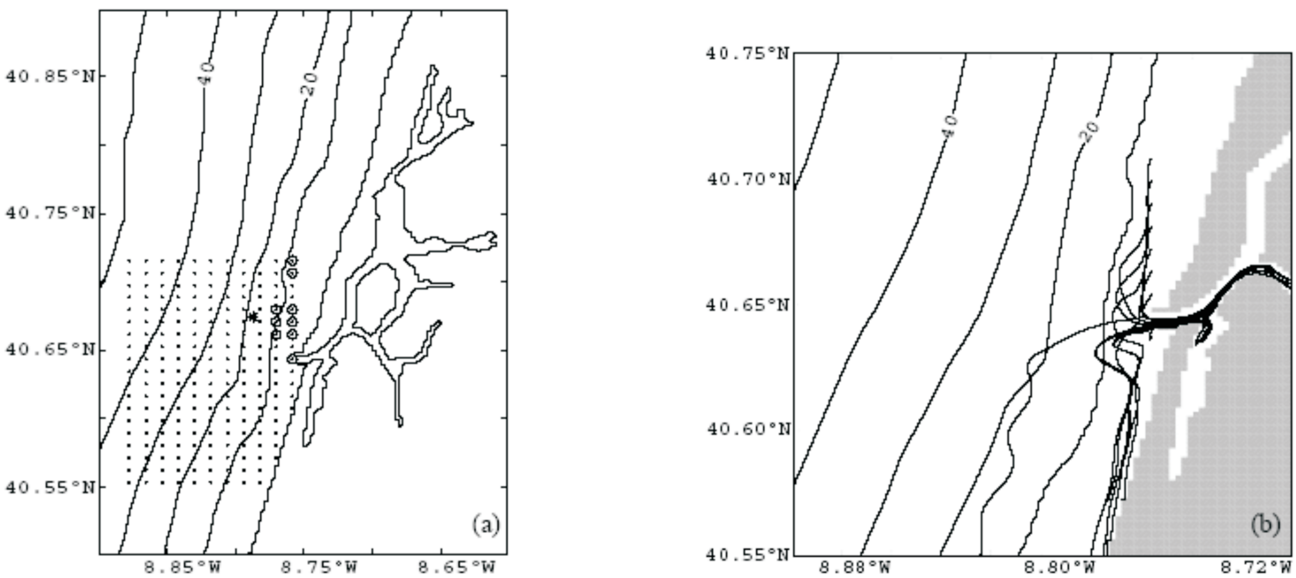

Figure 5. Northerly wind forcing at neap tides (a) particles released; (b) the contour paths for the particles. In figure (a) * represents the outfall location.

The coastal domain of influence of the Ria de Aveiro was delimitated for each of the scenarios by analyzing the paths of the particles released within a time scale of two days. The offshore extension of this domain is greater in the case of low winds regime (up to 7 Km in spring tidal conditions). In the simulations performed with northerly and northwesterly steady winds, the domain is polarized in the wind direction.

Figures 2(a) and 4(a) also show that in spring tidal conditions the sewer outfall is located within the domains depicted. Therefore, within the time scale considered, we shall expect a transport of surface contaminated materials into the lagoon.

Finally, the analysis of the path of the particles that are driven offshore the lagoon during ebb tidal flow is also elucidative for the establishment of the residual transport patterns in the coastal ocean/Ria system. In the simulations performed with no wind, the particles are retained in a vortex like flow developed northwest of the Barra channel. This residual flow pattern is not favorable to the renewal of the waters within the coastal lagoon. A distinct situation was observed when wind forcing was considered. In this case, the simulated flow patterns imply a residual transport first from the north of the inlet channel into the Ria de Aveiro, and afterwards to the south.

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LITERATURE CITED

ALLEN, J.S.; FEDERIUK, J. and NEWBERGER, P.A.,1995. Upwelling circulation on the Oregan continental shelf. Part I: Response to idealized forcing, *J.Phy.Oceanogr.*, 25, pp.1843-1866.

ALMEIDA, M. M. and DUBERT, J., 2003. Tidal dynamics in the western Iberian peninsula: a first approach, *4th Symposium on the Iberian Atlantic Margin*,Vigo, Spain.

DIAS, J.M., 2001. Contribution to the study of the Ria de Aveiro hydrodynamics. PhD Thesis, University of Aveiro, Portugal.

HAIDVOGEL, D.B. and BECKMANN, A., 1999. *Numerical ocean circulation modeling*. Imperial College Press, Series on environmental science management, vol. 2.

PELIZ, A.; DUBERT, J.; HAIDVOGEL, D. B. and LE CANN, B., 2003. Generation and unstable evolution of a density-driven Eastern Poleward Current: The Iberian Poleward Current, *J. Geophys. Res*., 108(C8), 3268, doi: 10.1029/ 2002JC 001443.

PELIZ, A.; DUBERT, J. and HAIDVOGEL, D. A., 2003. Subinertial Response of a Density Driven Eastern Boundary Poleward Current to Wind Forcing, *J.Phy.Oceanogr.*, 33, pp.1633-1650.