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On residual circulation of the Ria of Vigo, using a 3-D baroclinic model

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ABSTRACT

The present paper studies circulation in the Ria of Vigo (northwest Spain) by means of a 3-D baroclinic model coupled with a Lagrangian model of dispersion. The model is examined to obtain the residual currents' underlying periodic tidal movements. These currents are related to the quality of water because they determine the residence time. The model is forced at the mouth of the estuary with the most important tidal harmonics, and at the innermost zone with the freshwater discharge due to the presence of the Oitaven River. Results show that the area under study has a two-layered circulation, where most of water enters the estuary through the southern mouth and leaves it through the northern one.

Key words: 3-D model, Ria of Vigo, estuarine circulation, particle tracking.

RESUMEN

Sobre la circulación de la ría de Vigo usando un modelo baroclínico 3-D

Se estudia la circulación de la ría de Vigo (noroeste de España) por medio de un modelo tridimensional baroclínico acoplado a un modelo lagrangiano de dispersión. Los resultados provenientes del modelo se utilizan para la obtención de la corriente residual que subyace a los movimientos periódicos de marea. Esta corriente se relaciona con la calidad del agua, pues determina su tiempo de residencia. El modelo es forzado en la boca de la ría a través de las constituyentes armónicas de marea más importantes y con el agua dulce introducida en la parte interior del estuario por el río Oitaven. Los resultados obtenidos muestran una circulación en doble capa, además de una entrada principal del agua por la boca sur y una salida de ésta por la boca norte.

Palabras clave: *Modelo tridimensional, ría de Vigo, circulación estuarina, seguimiento de partículas.*

INTRODUCTION

A ria is a transverse coast, resulting from a marine transgression, which interferes with a pre-existent relief of fluvial origin (Vidal-Romaní, 1984). Along the northwestern shoreline of the Iberian Peninsula (Noon, 1966), many inlets correspond to this general description.

Scales in coastal systems are so large that the usual study techniques, such as monitorisation systems, do not enable researchers to establish a complete description of the dynamics. Numerical models are a powerful tool in the understanding of the complex structure of velocity, density, and other oceanographic variables. These kinds of models have been applied to the study of some of the Galician rias by different authors. Thus, Pascual (1987a, 1987b) modelled the circulation driven by tide and wind in the ria of Arousa; Bermúdez, Rodríguez and Vilar (1991, 1994) carried out different numerical studies in the Pontevedra and Vigo Rias by means of a finite elements method, and Montero, Lloret and Ruiz-Mateo (1992) analysed the dispersion of pollutants in the area near the Vigo harbour by using an Eulerian method. All of these models are vertically integrated models (2-D models). On the other hand, some authors (Montero *et al.*, 1996; Gómez-Gesteira *et al.*, in press) use Lagrangian models coupled with 2-D Eulerian models to carry out dispersion studies in the Galician rias. When a vertically non-homogeneous water column exists, a three-dimensional (3-D) model must be used in order to obtain a realistic description.

Our aim throughout this paper will be the study of the circulation of water in the Ria of Vigo by analysing its residual current –defined as the current averaged during a period much longer than the period of the main tidal harmonics– and the dispersion of passive traces (particle-tracking model) (Maier-Reimer and Sünderman, 1982), which simulates the effect of an ideal water mass on the estuary. In this paper, a 3-D baroclinic model coupled with a Lagrangian model is used to calculate the residual current and the circulation and renovation of water masses in the Vigo Ria.

In the first section, we describe the area studied. In the next section, the Eulerian model used to calculate the hydrodynamic field and the Lagrangian (particle tracking) model are described. In addition, the model is calibrated using experimental data.

In the Results section, the residual circulation pattern is shown. Finally, the evolution of passive tracers is described. These results are commented in the Discussion section.

MATERIALS AND METHODS

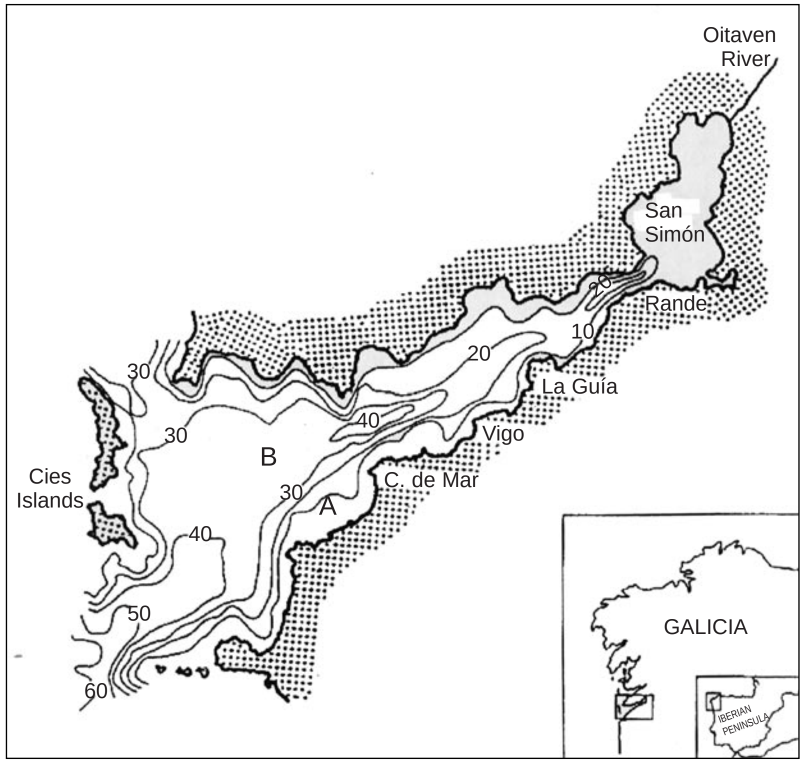
Area under study

The Rias Baixas are elongated estuaries that penetrate into the west coast of Galicia (northwest Spain) in a southwest-northeast direction The ria of Ria (figure 1) is the southernmost of the four Rias Baixas and is located between 42° 09' and 42° 21' N, 8° 36' and 8° 54' W. Its length is about 33 km on the main axis, and its mean width is over 4 km. The depth varies from 52 m in the mouth to a few centimetres on the sandbanks at the head of the estuary. The Ria of Vigo can be divided in three zones. The innermost zone includes San Simón Bay and shows the characteristics of a typical estuary, due to the effects of tides (~3.5 m of averaged tidal range) and the influence of the Oitaven River, with a mean annual discharge of 13 $m^3 s^{-1}$ and a mean winter discharge of 45 $m^3 s^{-1}$. The middle zone, which spreads from Rande Strait to Cape Mar, is under the influence of both continental and oceanic contributions. Finally, the outermost zone, which is under dominant oceanic influence, includes the area lying between Cape Mar and the Cíes Islands (Nogueira, Pérez and Ríos, 1997). The Estuarine Richardson number (Fischer *et al.*, 1979) is estimated from experimental data to be approximately 0.08 for an average river flow. Threfore, in a winter situation, the ría of Vigo is a partially-mixed estuary, with a two-layered residual circulation, due to the freshwater flow. In summer, stratification is maintained by the vertical distribution of the temperature (Mouriño, Fraga and Fernández Pérez, 1984; Prego and Fraga, 1992), in spite of the low river flow. This makes it similar to an estuary of type 3 (Bowden, 1980) or B (Beer, 1983). In table I a summary of the mean characteristics of Ria of Vigo is shown.

Table I. Physical characteristics of Ria of Vigo

Volume	3 275 hm^3
Mean width	4.8 km
Mean depth	21 m
Main axis length	32.5 km
Mean river flow	13 m^3/s
Winter mean river flow	43 m^3/s

Figure 1. Area under study (Ria of Vigo)



The model

The hydrodynamic model used in this case solves the Navier-Stokes (with hydrostatic and Boussinesq approximations), the equation of continuity, the salinity and temperature transport equation, and the equation of state (Leendertse and Liu, 1978):

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} + w\frac{\partial u}{\partial z} - fv = -\frac{1}{\rho_r}\frac{\partial p}{\partial x} + \frac{\partial}{\partial x}\left(A_H\frac{\partial u}{\partial x}\right) + \frac{\partial}{\partial y}\left(A_H\frac{\partial u}{\partial y}\right) + \frac{\partial}{\partial z}\left(A_V\frac{\partial u}{\partial z}\right) \quad [1]$$

$$\frac{\partial v}{\partial t} + u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} + w\frac{\partial v}{\partial z} + fu = -\frac{1}{\rho_r}\frac{\partial p}{\partial y} + \frac{\partial}{\partial x}\left(A_H\frac{\partial v}{\partial x}\right) + \frac{\partial}{\partial y}\left(A_H\frac{\partial v}{\partial y}\right) + \frac{\partial}{\partial z}\left(A_V\frac{\partial v}{\partial z}\right) \quad [2]$$

$$\frac{\partial p}{\partial z} + \rho g = 0 \quad [3]$$

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0 \quad [4]$$

$$\frac{\partial S}{\partial t} + \frac{\partial uS}{\partial x} + \frac{\partial vS}{\partial y} + \frac{\partial wS}{\partial z} = \frac{\partial}{\partial x}\left(K_H\frac{\partial S}{\partial x}\right) + \frac{\partial}{\partial y}\left(K_H\frac{\partial S}{\partial y}\right) + \frac{\partial}{\partial z}\left(K_V\frac{\partial S}{\partial z}\right) \quad [5]$$

$$\frac{\partial T}{\partial t} + \frac{\partial uT}{\partial x} + \frac{\partial vT}{\partial y} + \frac{\partial wT}{\partial z} = \frac{\partial}{\partial x}\left(K_H\frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(K_H\frac{\partial T}{\partial y}\right) + \frac{\partial}{\partial z}\left(K_V\frac{\partial T}{\partial z}\right) \quad [6]$$

$$\rho = (5890 + 38T - 0.375T^2) \,/\, (1779.5 + 11.25T - 0.0745T^2 - (3.8 + 0.01T)S + 0.698\,(5890 + 38T - 0.375T^2 + 3S)) \quad [7]$$

where (u, v, w) are the velocity components, (x, y, z) the Cartesian coordinates, f the Coriolis parameter, which is twice the vertical component of the Earth's rotation, g is the gravity acceleration, A_H and A_V the turbulent viscosity coefficients in the horizontal and vertical directions respectively, r the density, S and T the salinity and the temperature, K_H and K_V the horizontal and vertical components of the diffusitivity coefficient. To solve this system, the

Coriolis parameter is considered constant since the area under study is small.

If the equation of continuity [4] is integrated over the whole water column (between the surface level h and the bottom –h), the free surface equation is obtained

$$\frac{\partial \eta}{\partial t} = -\frac{\partial}{\partial x}\int_{-h}^{\eta} u dz - \frac{\partial}{\partial y}\int_{-h}^{\eta} v dz = -\frac{\partial \overline{U}}{\partial} x - \frac{\partial \overline{V}}{\partial y} \quad [8]$$

where U and V barred are the water column integrated velocities. Moreover, when the equation of the hydrostatic pressure [3] is vertical integrated, it is obtained

$$p(z) = p_{atm} + g\rho_r\ (\eta - z) + g\int_{z}^{\eta} \rho' dz \quad [9]$$

where $\rho' = \rho - \rho_r$; ρ_r is a reference density and ρ' the anomalous density. The equation [9] relates pressure at any depth with the atmospheric pressure at the free surface, the sea level and the anomalous pressure integrated between that level and the surface.

The Eulerian model used (MOHID3D) was developed by the Lisbon Technical Institute (Santos, 1995), and has been widely applied to different oceanic and coastal areas. The model provides sea level, velocity, heat, salt and density fields. The numerical scheme is a semi-implicit one, and follows the S21 discretisation (Abbot, Damsgaard and Rodenhuis, 1973), which avoids the time-step limitation required by the Courant-Friederich-Lewy criterion, particularly important in models including the propagation of external gravity waves in a free surface. Moreover, the time-levels of the S21 discretisation make it possible to centre in time the Coriolis term, solving this source of numerical instability (Fletcher, 1991). The vertical shear stress is integrated using an implicit scheme, which avoids unwanted numerical restrictions in the choice of the time step, another cause of instability. Horizontal advection, diffusion and baroclinic pressure components are solved explicitly. An upwind-centred hybrid scheme is used in the discretisation of the advection term in order to guarantee low numerical diffusion and the transportativity property. The heat and salt transport equations are explicitly discretised because it is assumed that variations in temperature and salinity fields are slower than free-surface oscillations. Vertical velocity is calculated through the equation of continuity.

An Arakawa C grid is used for spatial discretisation (Arakawa and Lamb, 1977). The chosen vertical coordinate is an s-coordinate (Phillips, 1957), which is bottom- and free-surface fitted. To guarantee that the layers are far apart enough to prevent numerical instability in very shallow zones, a double s-coordinate is used (Deleersnijder and Beckers, 1992) instead of a single one.

A mixing-length model is used to obtain the vertical diffusion coefficient, following the well-known Prandtl's expression:

$$A_V = l_m^2 \left|\frac{\partial U}{\partial z}\right| \quad [10]$$

where l_m is the mixing length and U is the module of the velocity, parametrisated following Leendertse and Liu (1978):

$$l_m = H\chi \frac{x_3}{H}\left(1 - \frac{x_3}{H}\right)^{\frac{1}{2}} \exp\ (-\alpha R_i) \quad [11]$$

where $x_3 = z + h$, h is the depth from hydrografic zero, $H = h + \eta$, the total depth of the column, $\chi \approx 0.4$ is the Von Karman constant, $\alpha \approx 0.8$ and R_i is the Richardson Number. The horizontal diffusion coefficient is assumed to be constant.

The horizontal velocity normal to the shore and the vertical velocity at the bottom are zero, while tangential components are computed assuming a free-slip condition. In the open sea boundary, sea level is imposed from tidal harmonic analysis. The river boundary is simulated through a 2-D vertical model, considering the upstream edge far enough from the tidal influence. The freshwater flux is imposed as a boundary condition in the model. The free surface moment transfer depends on wind stress, i.e. is considered to be zero in this study. A relaxation time is supposed in order to impose heat and salt open boundary conditions from empirical measurements outside the estuary, while they are directly imposed at the river boundary. Heat and salt fluxes on the bottom and the free surface are considered to be negligible in this case.

The Eulerian residual current is calculated at every time step from the velocity field provided by the hydrodynamic model (u), following the formula

$$u_R = \frac{1}{T}\int_0^T u\ dt$$

where T is a period much longer than the main tidal harmonic period, as noted above. The residual current is related to the capacity of renovation of the water since it is the underlying current under the oscillatory movement of the tide.

As mentioned above, a particle tracking model (PARTIC) (Neves *et al.*, 1990; Leitão, 1996) was coupled with the hydrodynamic model to describe the movement of passive tracers. Throughout our simulations, a fully Langrangian formulation was considered. The main advantage of this formulation is its greater accuracy in describing localised pollution spots with respect to an Eulerian transport model, where the existence of sharp gradients would be numerically eroded by the artificial diffusion. Besides, the method provides considerable time saving, because it only follows the track of the dumped particles, in contrast to Eulerian transport models, which calculate the concentration of some property everywhere, independently of the existence of that property at that point. It is assumed that the velocity of each particle (u_P) can be split into a large-scale organised flow, characterised by a mean velocity (u), provided by the hydrodynamic model, and a smaller-scale random fluctuation (u_F) such that $u_p = u + u_F$ with $u_F = R \times u \times c$, where $R \in [-1, 1]$ is a random number and c a free parameter that we will consider to be 0.2 (Neves *et al.*, 1990).

The model is applied to studying the Ria of Vigo during March 1997. The size of the grid used was 162×116 nodes, one level in the upper sigma frame of reference and six levels in the lower one. The space-step of the grid is 200 m. The model is forced with tide imposing the sea surface level at the open ocean boundary, by baroclinic forcing, and with river inflow.

Thermohaline, velocity and sea-level data were collected during 1997 as part of the Ordenación Integral del Espacio Marítimo Terrestre de Galicia, an in-depth study of the Galician Rias supported by the Fisheries Council of the Galician Regional Government. The initial conditions of heat and salt fields were obtained by interpolation of the empirical measurements in each grid node. Salinity and temperatures at the ocean boundary were imposed using a decay law, which simulates a boundary station placed 10 km far from the boundary model. These values were obtained from the measurements. The model was run during a relaxation time to smooth unreal gradients and the velocity field. The spin-up time was three days. During this period, the time-step was increased and the horizontal turbulent diffusion coefficient decreased to 30 s and 50 m²/s, respectively. Eighteen tidal harmonics, from data obtained by the Instituto Hidrográfico de la Marina (IHM), were used to describe tidal elevation at the open boundary. The tide is mainly semidiurnal, and has a range of about 3.5 m. The mean freshwater flow in the wet season was considered as the river boundary condition (Prego and Fraga, 1992) (table II).

Table II. Numerical characteristics

Computational time-step	30 s
Computational grid mesh	200 m
Grid size	$162 \times 116 \times 6$
Turbulent diffusion coefficient	50 m²/s
Imposed river flow	43 m³/s

The model was calibrated using experimental measurements of sea level and current velocity by the Instituto Español de Oceanografía. The agreement between observed and modelled values in a fixed point of the estuary is shown in figure 2.

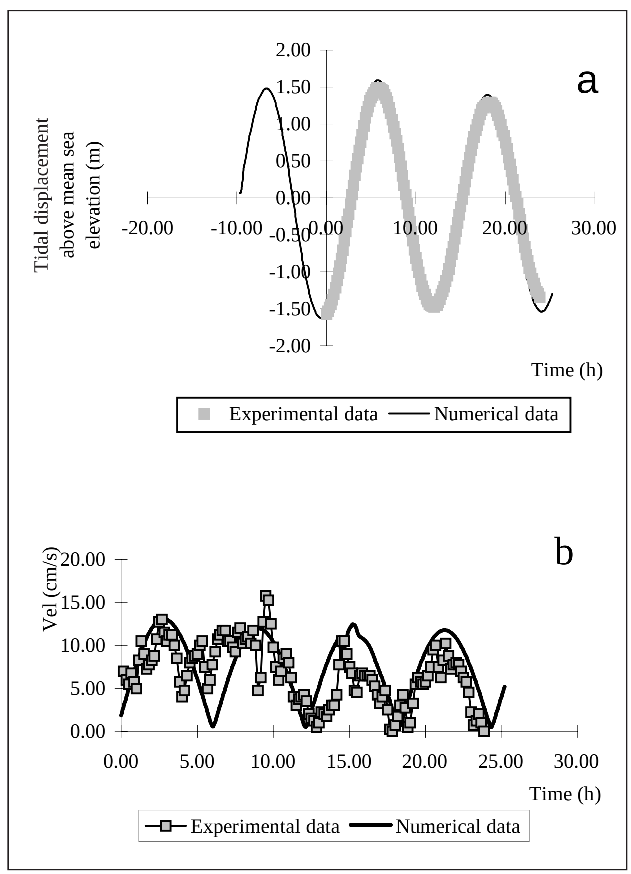


Figure 2. Model calibration using experimental data. (a): tidal displacement above mean sea elevation at 42° 12.319' N, 8° 48.589' W (station A in figure 1); (b): current at 42° 13.479' N, 8° 49.813' W and 20 m deep (station B in figure 1)

RESULTS

Figure 3 shows the residual circulation pattern corresponding to the Ria of Vigo calculated during the period covering 13-20 March 1997. This period (7 days) is long enough to filter the main tidal current. Therefore, the residual current pattern reflects the river runoff, the thermohaline circulation, and the coupling between tidal current and bathymetry. Typical residual currents of around 4-6 cm/s are observed in both patterns. Figure 3a,b show the existence of a two-layered circulation, where water enters the estuary through deep layers (figure 3a represents the bottom layer) and leaves the estuary through upper layers (figure 3b represents the top layer). Figure 3a shows a more intense incoming current through the southern mouth, and figure 3b a more intense outgoing current through the northern mouth.

Additional information about estuary circulation and water exchange among different areas may be provided by the Lagrangian technique described previously. Two rejection boxes corresponding to different regions in the estuary were filled with particles with a homogeneous vertical distribution.

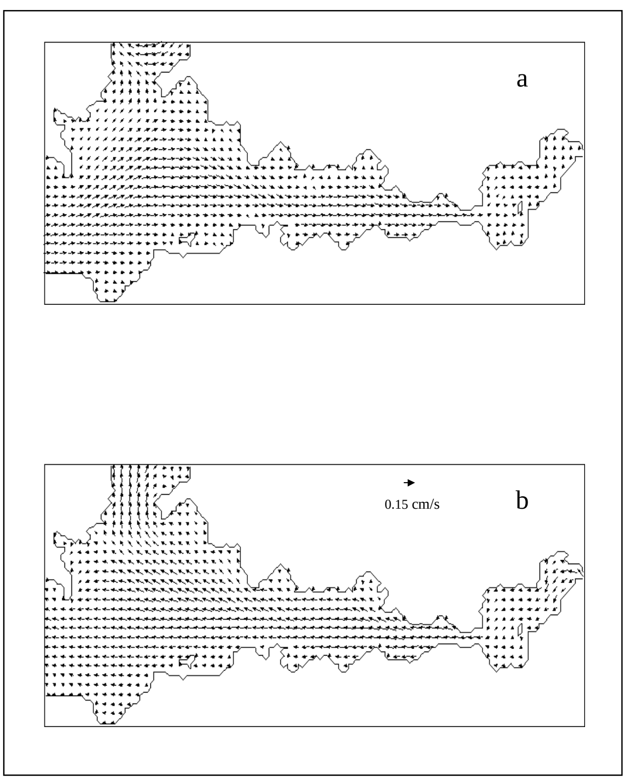


Figure 3. Circulation pattern after 7 days. (a): bottom layer; (b): top layer

Darker particles were dumped into San Simón Bay, and lighter particles into the rest of the estuary (figure. 4). No passive tracers were dumped into the outermost part of the estuary, since their further movement could be affected by the imposed boundary conditions. After 1 day, the initially homogeneous vertical distribution was strongly changed, as depicted in figure 5a,b. The bottom layer (figure 5a) showed the existence of a region without tracers near the mouth of the estuary. This tongue corresponds to the entrance of oceanic water through the lower layers. The same situation can be observed near Rande Strait, with lighter particles entering San Simón Bay. On the other hand, particles placed at the top layer tended to leave the estuary (figure 5b). In addition, when comparing both figures, a more intense jet can be seen leaving San Simón Bay (figure 5b) than entering it (figure 5a). After 4 days, the oceanic water tongue had advanced through the bottom layer up to Rande Strait, and a large amount of lighter particles had entered San Simón Bay (figure 5c). The outgoing jet previously observed in figure 5b had advanced toward the northern mouth of the estuary through the top layer (figure 5d). This difference between layers and between both mouths of the estuary is in good agreement with the residual pattern described in figure 3.

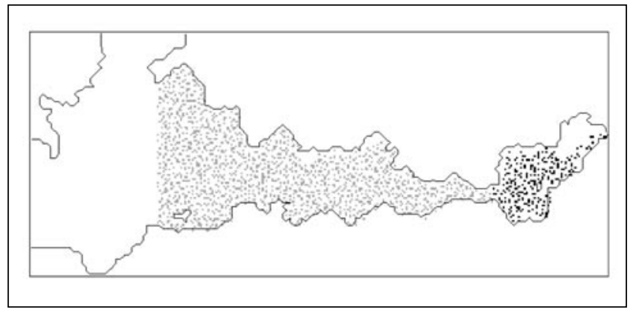


Figure 4. Initial distribution of Lagrangian particles at any depth

DISCUSSION

The analysis of the residual current pattern and the passive tracers circulation makes it possible to observe some general features of the Vigo Ria, namely, its two-layered nature and different behaviours at both mouths of the estuary.

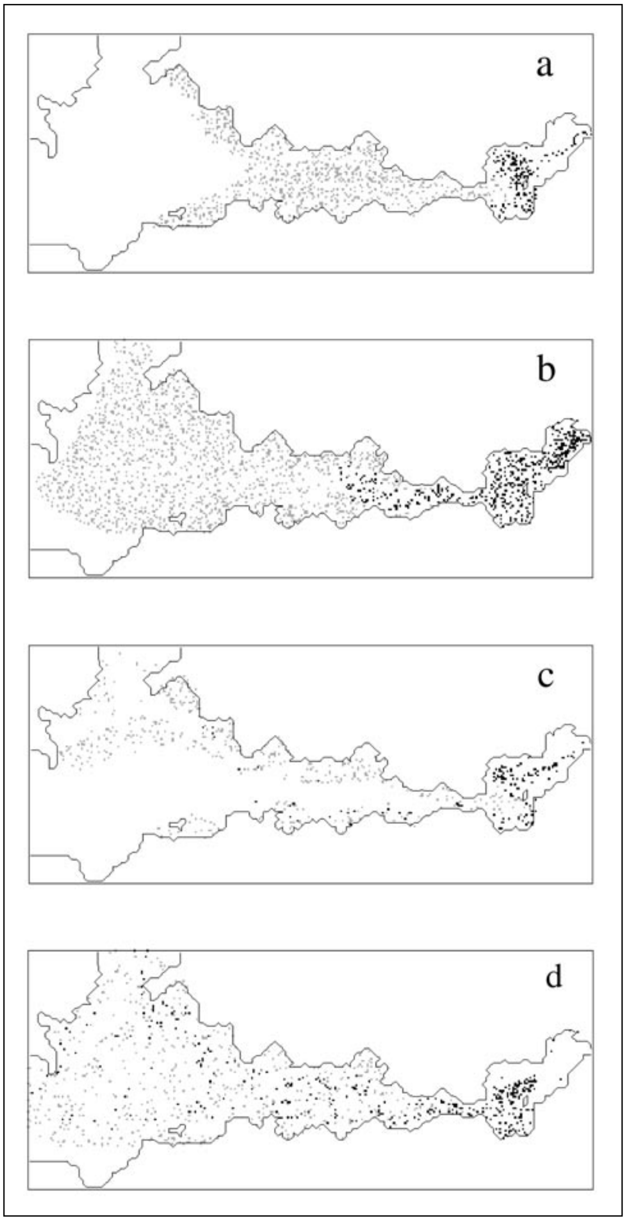


Figure 5. Time evolution of Lagrangian particles. (a): bottom layer after 1 day; (b): top layer after 1 day; (c): bottom layer after 4 days; (d): top layer after 4 days

The observed two-layered circulation pattern is mainly due to density stratification, in good agreement with experimental data (Prego and Fraga, 1992). On the other hand, calculations performed with vertically-integrated models (Gómez-Gesteira *et al.*, in press) in absence of baroclinic forcing showed a less intense residual current and the appearance of lateral eddies due to the coupling between bathymetry and tidal forcing.

The different circulation through both mouths of the estuary is due to the gyre induced by Coriolis force balanced with the vertical density distribution and enhanced by the bathymetry (the southern mouth is deeper than the northern one) (Pritchard, 1989).

This is the first attempt to use a 3-D baroclinic model to study the circulation in a Galician ria. However, these results need to be viewed with some caution since the data available for model initialisation and validation are still preliminary. Winds have not been taken into account explicitly in the model, since in the inner part of the rias they are intermittent and directionally variable so they do not contribute to the long-term distribution of the current. To our knowledge, the only contribution of wind is that of the quasi-steady northerly wind in the May-October period on the Galician Shelf, a period which is not covered by the simulations carried out in the present paper.

Direct measurement of water properties is a laborious and expensive task. Therefore, numerical models can provide very valuable general information, especially in areas, like the one under study, subjected to high human pressure.

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