A modelling study on the hydrodynamics of a coastal embayment occupied by mussel farms (ría de Ares-Betanzos, NW Iberian Peninsula)

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Key points

- A 3-D hydrodynamic model was implemented for a Galician ría
- The importance of different hydrodynamic forcing functions was studied
- The impact of mussel cultivation rafts on circulation was analyzed

Abstract

The Ría de Ares-Betanzos is a partially stratified estuary in the NW Iberian upwelling system where blue mussels are extensively cultured on hanging ropes. This type of culture depends to a large extend on water circulation and residence times, since mussels feed on suspended particles. Therefore, understanding the role of tides, continental runoff, and winds on the circulation of this embayment has important practical applications. Furthermore, previous works have stressed the potential importance of aquaculture leases on water circulation within coastal ecosystems, with potential negative feedbacks on production carrying capacity. Here we implemented and validated a 3D hydrodynamic numerical model for the Ría de Ares-Betanzos to (i)
evaluate the relative importance of the forcing agents on the circulation within the ría and (ii) estimate the importance of culture leases on circulation patterns at the scale of the mussel farms from model simulations. The model was successfully validated with empirical current velocity data collected during July and October 2007 using an assortment of efficiency criteria. Model simulations were carried out to isolate the effects of wind and river flows on circulation patterns. Model outputs suggest that (i) both under upwelling and downwelling winds, the residual circulation keeps positive with a strong influence from river discharge and a positive feedback from wind; and (ii) mussel cultivation areas may reduce residual velocities by as much as 35%, suggesting their potential feedbacks on food replenishment for cultivated mussels.

**Key words:** Hydrodynamic modeling; Galician rías, Aquaculture rafts, Mussel cultivation
1 Introduction

The Galician rías are flooded tectonic valleys on the northwest coast of the Iberian Peninsula (Fig. 1). They are the ground for 40% of the European and 15% of the World production of blue mussels, about $250 \times 10^6$ kg year$^{-1}$ [Labarta et al., 2004]. The cultivation system consist on hanging ropes (maximum length, 12 m) mounted on floating rafts (maximum size, 500 m$^2$) [Pérez Camacho et al., 1991] of which there are over three and a half thousand in the five rías where these structures are installed [Figueiras et al., 2002].

The large economic importance of these embayments, not only for mussel production but also for harbor, fishing, touristic and conservation activities, stimulated a large number of field studies on their physical, geochemical and biological features. Conversely, numerical modeling studies are scarce and focused mostly on circulation issues [Torres–López et al., 2001; Souto et al., 2003; Carballo et al., 2009]. Figueiras et al. (2002) reviewed some of the most important characteristics of these ecosystems justifying their high productivity. The subtidal circulation of the four Rías Baixas, to the south of Cape Fisterra (Fig. 1), is conditioned by the seasonal and short-term succession of upwelling and downwelling events on the adjacent shelf. The upwelling- favorable season starts between March and May and ends around early October [Alvarez-Salgado et al., 2000]. The upwelling-favorable season is characterized by the prevalence of northerly winds, with the Ekman pumping producing an inflow of upwelled water at the bottom of these embayments and a compensating outflow of surface waters (positive residual circulation). During the downwelling-favorable season, southerly winds prevail, provoking a reversal of this circulation pattern: Ekman pumping forces the
entry of shelf surface water into the embayment and a compensating outflow through
the bottom layer [Piedracoba et al., 2005a].

The Ría de Ares-Betanzos, to the north of Cape Fisterra (Fig. 1), is 4–7 times smaller
than the Rías Baixas and oriented differently. As a consequence, Ekman pumping on the
adjacent shelf has a lower impact on the subtidal circulation of this embayment and
continental runoff gains more importance compared with the Rías Baixas [Álvarez-
Salgado et al., 2011]. The Ría de Ares-Betanzos supports the production of 147 mussel
rafts, mostly concentrated along its southern margin (Fig. 1). This type of culture
depends to a large extent on water circulation and residence times, since mussel feed on
suspended living and non-living particles transported by water [Navarro et al., 1991;
Pérez-Camacho et al., 1995]. Previous works have stressed the potential importance of
aquaculture leases on water circulation within coastal ecosystems with potential
negative feedbacks on production carrying capacity [Grant et al., 1998; Grant and
Bacher, 2001]. Following Shi et al. [2011], suspended aquaculture leases in Sungo Bay
(China) may cause a reduction on the average speed of surface current by 40%,
decreasing the exchange of water with the adjacent sea. Current speed reductions may
have important feedbacks on bivalve production and exploitation since they have
implications on the dispersal of mussel larvae before settlement [Peteiro et al., 2011],
the availability of suspended food and the occurrence of harmful microalgae, which
limits the extraction of this resource [Álvarez-Salgado et al. 2008, 2011]. Therefore,
understanding the hydrodynamics of the Ría de Ares-Betanzos and the feedbacks from
cultivation leases on water circulation has important practical applications for the
sustainable management of this important culture.

Previous studies in the Ría de Ares-Betanzos have focused on phytoplankton diversity
and productivity [Blanco, 1985; Mariño et al., 1985; Bode and Varela, 1998], nutrient
distributions [Prego et al., 1999], the physico-chemical structure of the benthic environment [Sánchez-Mata et al., 1999] or the relationship between subtidal circulation and net ecosystem metabolism [Villegas-Ríos et al., 2011]. The latter authors implemented a 2-D transient box model to integrate physical, chemical and biological data and to estimate fluxes between the inner and outer parts of the ría. They concluded that, compared with the Rías Baixas, the subtidal circulation of the Ría de Ares-Betanzos is positive both under upwelling and downwelling conditions as a result of the larger relative importance of river flows [Villegas-Ríos et al., 2011].

In this work, a 3D hydrodynamic model of the Ría de Ares-Betanzos was implemented and validated and, thereafter, used to: (i) evaluate the relative importance of local winds, tidal and river forcing processes on the circulation, providing a further test to the explanations advanced by Villegas-Ríos et al. [2011] for the persistent positive residual circulation; and (ii) assess the importance of culture leases on residual circulation.

2 Methods

2.1 Study site

The Ría de Ares-Betanzos is the largest of six bays located between Cape Fisterra and Cape Prior, in the NW coast of the Iberian Peninsula (Fig. 1), with a surface area of 72 km², a volume of 0.75 km³ and a length of 19 km. It consists of two branches: Ares, the estuary of river Eume and Betanzos, the estuary of river Mandeo with long-term average flows of 16.5 and 14.1 m³s⁻¹, respectively [Prego et al., 1999; Sánchez-Mata et al., 1999]. The two branches converge into a zone that is freely connected to the adjacent shelf through a mouth that is 40 m deep and 4 km wide.
2.2 Available data

Field data used in this work is described in Villegas-Ríos et al. [2011] and it was obtained in July and October-November of 2007. An acoustic Doppler (ACDP) current profiler was moored at stn 3 (Fig. 1) and covered the periods from 3 to 26 July and from 15 October to 20 November. Furthermore, continuous vertical profiles of salinity and temperature were recorded at stns A1, A2, B1, B2, 4 and 5 in the periods 9–23 July and 10–29 October (stn 5 was sampled only in October). These data was used for model initialization and validation.

Data on air temperature, relative humidity and light intensity from the meteorological station of Ferrol (Fig. 1) were downloaded from the web side of the Galician Weather Forecast Agency Meteogalicia (http://www.meteogalicia.es). Flows from rivers Eume and Mandeo were obtained as described in Villegas-Ríos et al. [2011]. Wind velocity and direction as well as river flows for the two periods under study are depicted in Fig. 2. Tide harmonics for A Coruña were obtained in SHOM [1984]. These data was used for model forcing (see below).

2.3 Hydrodynamic model

The model is based on the horizontal equations of motion (1 and 2), the equation of continuity (3 and 4), the equation of transport (5) and the hydrostatic and the Bousinesq assumptions [Pond and Pickard, 1983]:

\[
\frac{\partial u_x}{\partial t} + \frac{\partial u_x}{\partial x} + \frac{\partial u_y}{\partial y} + \frac{\partial u_z}{\partial z} - v_x \frac{\partial^2 u}{\partial x^2} - v_y \frac{\partial^2 u}{\partial y^2} - v_z \frac{\partial^2 u}{\partial z^2} = - \frac{\partial P}{\rho \partial x} - \frac{C_f |u| |u|}{2H} \frac{Cd |u| u d |u|}{2H} + \frac{\partial \tau_x}{\rho \partial z} + f v_y
\]  (1)
\[
\begin{align*}
\frac{\partial v}{\partial t} + \frac{\partial vv}{\partial y} + \frac{\partial vu}{\partial x} + \frac{\partial vw}{\partial z} - v_x \frac{\partial^2 v}{\partial x^2} - v_y \frac{\partial^2 v}{\partial y^2} - v_z \frac{\partial^2 v}{\partial z^2} &= - \frac{\partial P}{\partial \zeta} - \frac{Cf |v|}{H} - \frac{Cd |v| d |l|}{2\nu} + \frac{\partial \tau_y}{\partial \zeta} - f u_x \\
\frac{d \xi}{dt} &= \frac{\partial u_x}{\partial x} + \frac{\partial v_y}{\partial y} + \frac{\partial w_z}{\partial z} \quad (3) \\
\frac{\partial u_x}{\partial x} + \frac{\partial v_y}{\partial y} + \frac{\partial w_z}{\partial z} &= 0 \quad (4) \\
\frac{\partial S}{\partial t} + \frac{\partial u S}{\partial x} + \frac{\partial v S}{\partial y} + \frac{\partial w S}{\partial z} &= \frac{\partial \left( A_x \frac{\partial S}{\partial x} \right)}{\partial x} + \frac{\partial \left( A_y \frac{\partial S}{\partial y} \right)}{\partial y} + \frac{\partial \left( A_z \frac{\partial S}{\partial z} \right)}{\partial z} \quad (5)
\end{align*}
\]

Where, \( u, v \) and \( w \) are the components of the current velocity (West-East \( x \), South- North \( y \) and Bottom-Up \( z \), respectively) (in m s\(^{-1}\)); \( P \) is the hydrostatic pressure (in N m\(^{-2}\)); \( \rho \) is the seawater density (in kg m\(^{-3}\)); \( \nu \) is the eddy diffusivity (East-West \( x \), North- South \( y \) and Bottom-Up \( z \), respectively) (in m\(^2\) s\(^{-1}\)); \( Cf \) is the rugosity coefficient (dimensionless); \( Cd \) is the body drag coefficient (dimensionless); \( d \) and \( l \) are the width and height of the body against which drag is calculated (in m); \( \tau \) is the wind stress (in N m\(^{-2}\)); \( f \) is the Coriolis parameter (in s\(^{-1}\)); \( \xi \) is the surface elevation/ water level (in m); \( H \) is the water depth (in m); \( S \) is the concentration of any dissolved or particulate property (in kg m\(^{-3}\)); and \( A \) is the diffusivity of the mentioned property along each of the three dimensions (in m\(^2\) s\(^{-1}\)).
Equation 3 is applied at the surface, where flow divergence/convergence may change surface elevation. Equation 4 is applied below the surface, where the balance of inflows and outflows at any control volume must be zero.

The generic algorithm is:

\[ v_{ijk}^{t+1/2} \rightarrow \xi_{y j}^{t+1/2} \rightarrow u_{ijk}^{t+1} \rightarrow w_{ijk}^{t+1} \rightarrow V_{x j}^{t+1} \text{ and } \xi_{y j}^{t+1} \rightarrow S_{y j}^{t+1} \]

The resolution is semi-implicit following an Alternate Direction Implicit (ADI) scheme. Equations 1 and 2 are used to replace the velocity terms in the equation of continuity (3). One of the velocity terms is explicit and the other is implicit. Equation 3 is integrated vertically to estimate surface elevation implicitly \((\xi_{y j}^{t+1/2})\), without the need to know vertical velocities at this time and with vertical diffusivities cancelling each other out. Obtained elevations at \(t+1/2\) (half time step) are used in the pressure term of equations 1 and 2, to calculate horizontal velocities (again, one of the velocity components is calculated explicitly and the other is calculated implicitly). The pressure term has a barotropic parcel that results from differences in water elevation and a baroclinic parcel that results from water density differences. Afterwards, vertical velocities are calculated with the continuity equation from the bottom till the surface. At the surface layer, the numerical solution of equation 3 is used to obtain a final estimate for the water level \((\xi_{y j}^{t+1})\). Calculated velocities are then used in the transport equation to calculate the concentration of dissolved or particulate substances (5).
In this model there are two drag terms: the first drag term in both equations 6 and 7 is bottom drag (computed implicitly for stability) whereas the second drag term results from drag exerted by a body within the water (for example: aquaculture leases). The former term is computed only for bottom cells, whereas the latter is computed for cells where mussel rafts are located. This drag is calculated as described in Morrison et al. (1950):

\[ D = \frac{1}{2} \rho u^2 C_d d l \]  

(6)

Where, \( C_d d \) and \( l \) were defined above.

To get a force per unit of mass (acceleration), similar to the other parcels of both equations, it is necessary to divide this equation by the mass of the water contained in a certain volume, obtaining:

\[ D = \frac{1}{2} \frac{C_d u^2 \rho d l}{\rho V} \Rightarrow \frac{C_d u^2 d l}{2V} \]  

(7)

The implementation of this drag term was necessary to take into account the drag effects of the hanging ropes from mussel rafts. Each raft has approximately 500 ropes descending to a depth of up to 12 m. Each rope has a diameter of up to 12 cm, when loaded with mussels. \( C_d \) may have values between 1 and 2 for flows approaching a
cylinder [Fernandes et al., unpublished]. Additionally, the effect of the ropes has to be adjusted to the grid resolution of the model, i.e. defining the ropes density per horizontal grid cell.

In this model, flows are solved at the sides of the grid cells, whereas surface elevations and concentrations are calculated at the cells center. Horizontal advection terms are calculated using an upwind scheme, whereas diffusion terms are based on a central differences scheme. Vertical advection is computed with the Lax-Wendorf Total Variation Diminishing (TDV) advection scheme described in James [1996], to reduce numerical diffusion and allow a better simulation of vertical stratification. Horizontal diffusivities are used as a calibration parameter, whereas vertical diffusivities are computed with a mixing length model following Nihoul [1982] and Santos [1995].

The model is forced by tidal height at the sea boundaries, local winds and fresh water flows. It includes a wet-drying scheme for intertidal areas, which consists of stop using the advection term when depth is lower than a threshold value to avoid numerical instabilities. Below this threshold the model computes all remaining terms – pressure, bottom drag and Coriolis – while water depth is larger than 0.05 m. When this limit is reached, computations do not take place in a given cell until a neighbor cell has a higher water level, allowing then the pressure term to start ‘filling’ the ‘dry’ cell. Furthermore, the model may add and remove surface layers during the simulation: if water depth of the surface layer becomes smaller than a predefined threshold, this layer is added to the second one. When the depth of this second layer becomes large enough is it divided in two and the former surface layer is restored. This way it is possible to maintain a high resolution near the surface without numerical problems arising when depth becomes too small.
The model was implemented with EcoDynamo [Pereira et al., 2006], an object-oriented modeling software written in C++. There are different objects to simulate hydrodynamic, thermodynamic and biogeochemical processes and variables. The shell interface allows the user to choose among different models and to define the respective setups – time steps, output formats (file, graphic and tables), objects to be used and variables to be visualized. The list of objects, variables and parameters of model equations are stored in specific files. Objects may communicate among them for data exchange. In the present work the following objects were used: (i) Tide object, to simulate water level at the sea boundaries, using harmonics for A Coruña (cf. – Methodology – Available data); (ii) Air temperature object, storing air temperature data; (iii) Wind object, storing wind velocities and directions; (iv) Light object, storing solar radiation data; (v) Water temperature object, for water temperature calculation following the equations described in Portela and Neves [1994]; (vi) Three-dimensional hydrodynamic object, to solve the hydrodynamic equations mentioned above. The first four objects act as forcing functions for both water temperature and hydrodynamic calculations.

The horizontal spatial resolution of the model grid used in this work is 150 m, the vertical resolution is between less than 1 m at the surface and up to c.a. 15 m at the bottom layer corresponding to 107 lines x 121 columns x 15 vertical layers. Fig. 1 depicts a GIS image showing a chart of Ría de Ares-Betanzos, the location of sampling stations used for model initialization and validation and a white line with the limits of the model domain. A detail on the bathymetry used in the model is also shown.
2.3.1 Simulations

Simulations were run for 9–31 July and for 15 October–20 November 2007 for comparison with field data and also with residual flow estimates obtained by Villegas-Ríos et al. [2011] with a transient 2-D kinematic box model. Two simulations, hereafter named as “standard” were used for model validation. These simulations were forced with available meteorological data for the study period to be as realistic as possible. Afterwards, simulations were run without river flows or without wind or with a wind blowing always from the north or always from the south. Furthermore, simulations were run without taking into account the body drag exerted by the hanging ropes of mussel rafts. In all cases, only one condition was tested at each time. Comparing standard simulations with those without river flows allows estimating the relative importance of continental runoff in establishing the positive residual circulation pattern. Comparing standard simulations with those without wind and with those with a wind oriented in the North-South direction allows understanding the relative importance of local wind forcing on the observed residual circulation. Finally, comparing standard simulations with those without mussel rafts body drag allows estimating the effect of the mussel farms on the circulation of the ría. Table 1 synthesizes the set of simulations carried out in this study and corresponding abbreviations.

Validation

For the purposes of model validation, field data collected in July and October 2007 were used to compare with July and October standard simulations (see above and Table 1). Current velocity time series obtained at stn 3 (Fig. 1) were compared with model results. A correspondence had to be established between water layers monitored by the ACDP current meter and model layers. Accordingly, model predicted velocities were
averaged for layers: (i) 1 till 5 for comparison with current meter surface layer data; 6 to 8, for comparison with current meter intermediate layer data; (iii) 9 to 12, for comparison with current meter deeper layer data. Furthermore, vertical temperature and salinity profiles available for the same periods were also compared with those obtained with the model. However, since there was no available salinity and water temperature data along the sea boundary for the simulation period, it was not possible to do a realistic simulation for these variables. Therefore, available data for the outermost station (stn 4, refer Fig. 1) at the starting simulation dates were assumed for the whole simulation period.

The overall correspondence between data records and simulated values was analyzed using Model II linear regression analysis, as suggested by Laws and Archie [1981], with the major axis regression method as recommended by Mesplé et al. [1996] and described in Sokal and Rohlf [1995]. ANOVA was used to test the variance explained by the model. Furthermore, several efficiency criteria were used: the root mean square error (RMSE), the Nash-Sutcliffe efficiency (E) [Nash and Sutcliffe, 1970], the index of agreement (d) [Wilmott, 1981], their modified versions E1 [Wilmott, 1981] and d1 [Krause et al., 2005], respectively, and the cost function (CF) (OSPAR commission, 1998). Whenever available in the literature, qualitative criteria were adopted (Table 2).

### 3 Results

#### 3.1 Model performance

Predicted and observed $u$ and $v$ velocity components at stn 3 for the standard October simulation are shown in Fig. 3 for the intermediate layers. Model simulations fitted well with the measured data for the intermediate and deeper layers but not for the surface
ones. Similar results were obtained for the July standard simulation (not shown). A synthesis of model II linear regression analysis between empirical and simulated data for both velocity components is presented in Table 3 together with the results obtained for the assortment of efficiency criteria defined in the methods section. With the exception of results obtained for the surface layers, the slopes of the regression lines tend to be close to one and the y-intercepts tend to be close to zero. Deviations of the former from one would suggest that differences between model predictions and observations are proportional to variable values, whereas deviations of the latter from zero indicate a bias that would affect model results equally for all values of the variables being simulated. In spite of the poor fit between model and observed results at the surface layer, with the simulations generally overestimating the current velocities, the variance explained by the model was very large compared to the unexplained variance (p << 0.001 for all simulations). RMSE was < 5 cm s\(^{-1}\) except in a few cases. Results obtained with the various efficiency criteria suggest that the model behaved poorly for the surface layers but the performance was generally good, very good or even excellent for the intermediate and the deeper layers for, at least, two efficiency criteria. However, concerning CF, all simulation results were good or very good, even for the surface layers. The d and d1 criteria lack a quality scale, to the best of our knowledge. However, considering that its values may range from zero to one (the best possible result) and that all obtained values for the intermediate and deeper layers are equal or larger than 0.6, model results seem, at least, reasonably good according to this index of agreement.

Observed and predicted (standard simulations) vertical profiles of water temperature and salinity are shown in Fig. 4 for July 19\(^{th}\) (stns 4, 3, A1 and B1). The water column was thermally stratified in July with temperatures ranging from almost 20°C at the surface to nearly 15°C at 25–30 m depth, both for observed and predicted results. There
was also haline stratification, with surface water values around 34.5 and deeper water values (at c.a. 30 m) around 35.5. Surface salinities at inner stations A1 and B1, under the direct influence of rivers Eume and Mandeo, respectively, were slightly lower than values observed at the other stations. In what concerns October data (not shown), considering both the observed and predicted results, the water column was well mixed with a temperature difference between the surface and the deeper layers of less than 0.5°C. Salinity was almost vertically homogeneous, with a maximal difference of c.a. 0.5 units in station A1.

3.2 Standard residual circulation patterns

Figs. 5 and 6 show residual velocities for the surface and bottom layers of the Ría de Ares-Betanzos in July and October, respectively. These values were calculated from predicted velocities integrated for the upper eight and for the lower seven layers. Previously, we verified that residual velocities showed opposite directions in these two sets of layers. Predicted residual circulation patterns are clearly positive in July, with a marked water inflow below layer 8 (c.a. 10 m depth) and outflow at shallower depths. The most remarkable feature of the simulated surface circulation of the ría in this period (Fig. 5a & b) is the cyclonic gyre that develops in the confluence zone between the estuaries of the rivers Eume and Mandeo, in the middle ría, which produces a weak inflow of surface water through the southern side of the ría and strong outflow through the northern side. It is also remarkable that the freshwater excess introduced by both rivers preferentially leaves the ría through the northern side. This means that the outflow of the River Mandeo should displace first north along the eastern side of the ría, meet the River Eume flow and, then, both turn left to leave the ría. The simulated flow in the bottom layer shows a marked divergence just below the cyclonic gyre of the surface
layer with part of the water entering the Eume and the other part the Mandeo estuary (Fig. 5b). This divergence is the probable reason behind the surface cyclonic circulation. Although less well-defined, a similar residual circulation pattern was produced by the standard October simulations (Fig. 6a & b).

Figures 7 and 8 depict the average residual flows (in m$^3$ s$^{-1}$) calculated with the current velocities produced by the various simulations for the periods (16-23 July 2007 and 15-28 October 2007) and the boundaries covered by the inverse 2D box model of Villegas-Ríos et al. [2011]. Earlier dates were not used for comparisons to allow an initial model spin-up of, at least, five days. Those boundaries were chosen for the sake of comparison of the results of the numerical and the inverse models and to get a simplified picture of the 2-layer residual circulation of the embayment. Flows calculated for the July standard simulation (Fig. 7a) were higher than those for the October standard simulation (Fig. 7b). The magnitude of the flows was larger at the boundary located on the sea side with some values above 200 m$^3$ s$^{-1}$. Residual flows across the inner boundaries are much lower than those predicted for the outer boundary, with the lowest values for the inner northern boundary.

3.3 Effect of continental runoff and local winds on the residual circulation pattern

Removing river flows has a large decreasing effect on residual flows in July (up to 50% reduction; Fig. 7c), but not in October (Fig. 7d). Removal of the local wind forcing has a strong effect both in July (Fig. 8a) and October (Fig. 8b). In July, the effect was stronger than the removal of river flows. Forcing the model with northerly winds would have almost no effect in July but an important effect in October (Fig. 8c & d), with an increase in the residual flows at the northern inner boundary by almost 100% in comparison with the standard simulation. Regarding the results obtained with southerly
wind forcing, there was an important increase in residual circulation across the outer boundary both in July (Fig. 8e) and October (Fig. 8f). In the case of the latter, there was also a remarkable decrease in the residual circulation across the inner northern boundary associated with a change in the direction of the surface flow.

### 3.4 Effect of mussel farms on the residual circulation pattern

The percentage of reduction in residual velocities (Fig. 9), calculated from the differences between the simulation without mussel farms and the standard simulation, for the study period in July, suggests that body drag exerted by the mussel rafts may lead to a slowness of the residual currents of almost 40%.

### 4 Discussion

The model reproduced reasonably well the velocity field at the intermediate and bottom layers. However, despite the good results obtained with some validation criteria, such as the cost function, the agreement between measured and modeled currents was not so satisfactory for the surface layer. Such a disagreement cannot be imputed exclusively to the performance of the model. It is well known that the ability of the DCM12 to measure the current in the surface layer is negatively affected in such a way that the most energetic tidal harmonics were not found in the surface layer (1–5 m), as could be expected, but in the second one [Míguez, 2003; Piedracoba et al. 2005a]. Whether this is a natural physical process (wind/wave induced turbulence at the surface layer) or an instrumental artifact is not clear yet. Because the DCM12 was designed to reduce the side-lobe effect [Aanderaa et al. 1995, Aanderaa Instruments, 1999], this can cause artificial effects on surface measurements that lead to under estimate of surface
velocities [van Haren, 2001]. It is also remarkable that the vertical stratification is reasonably well reproduced by the model both for temperature and salinity.

Exchange flows calculated by Villegas-Ríos et al. [2011] across the three boundaries defined in Figure 7 with a 2-D kinematic box model were significantly higher than the outputs of the standard simulations. Although a 2-D positive residual circulation pattern was shown by both the inverse and the numerical model, the values of the former were from twofold (in July) to tenfold (in October) larger than the latter. It should be noted that the 2-D box model of Villegas-Ríos et al. [2011] was based on the integration of simplified versions of the equations of continuity (4) and salinity conservation (5):

\[
\overline{Q}_S = \overline{Q}_B + \overline{Q}_R + \overline{P} - \overline{E} \tag{8}
\]

\[
V \frac{\Delta S}{\Delta t} = \overline{Q}_B \overline{S}_B - \overline{Q}_S \overline{S}_S \tag{9}
\]

Where \(\overline{Q}_B\), \(\overline{Q}_S\), \(\overline{Q}_R\), \(\overline{P}\) and \(\overline{E}\) (m\(^3\) s\(^{-1}\)) are, respectively, the horizontal bottom and surface subtidal flows at the open boundary of each of the 3 boxes defined in Figs. 7 and 8, continental runoff, precipitation and evaporation, between two consecutive surveys. \(\overline{S}_S\) and \(\overline{S}_B\) (kg m\(^{-3}\)) are the salinities at the bottom and surface layers of each boundary, averaged over two consecutive surveys. To obtain \(\overline{S}_S\) and \(\overline{S}_B\), they used the salinity profiles collected on each survey and assumed that this salinity was representative for the whole cross section that defines the boundary of each box. This is equivalent to assume that the water flow is homogeneous throughout each cross section. However,
the standard model simulations (Fig. 5 & 6) predicts a marked lateral gradient in the residual circulation, mainly in the middle ría, where the predicted flows through the northern side of the embayment are an order of magnitude stronger than through the southern side. Furthermore, there are cases where there is an inflow of surface water through the southern side resulting in the cyclonic gyre previously described.

Considering that and were negligible during both study periods [Villegas-Ríos et al., 2011] 8 may be simplified to:

\[ Q_S = Q_B + Q_R \] (10)

Inserting 10 into 9 and solving for:

\[ Q_B = \frac{V \Delta S + Q_R S_S}{\Delta t} \left( S_B - S_S \right) \] (11)

Equation 11 implies that very small differences in bottom and surface salinities will lead to very high bottom flow estimates and, consequently, to very high surface flow estimates. Therefore, when water is weakly stratified, as in October 2007, higher flow estimates are more likely to be obtained. Therefore, our guess is that the disagreement between the results of the kinematic and the numerical model should be more due to the
assumptions made to run the kinematic model than to a failure of the numerical model to reproduce the circulation pattern of the ría.

In support of the model results there are some indirect evidences: i) despite that almost 100% of the adult mussels are located in the mussel farms of the southern side of the ría, the site where mussel seeds are collected more efficiently is, surprisingly, the northern outer side of the ría [Peteiro et al., 2011]. The surface circulation pattern predicted by the model would explain this dislocation between the site of massive gamete production and the site of massive larvae settlement; ii) despite the closeness of the mussel farm area of Arnela to the mouth of the River Mandeo, surface salinities at that site are not coupled to the Mandeo river flow [Isabel et al., in prep.]. This is consistent with the preferential displacement of the freshwater discharged by the River Mandeo to the North, to meet the outflow of the river Eume suggested by the model simulations; iii) If the current velocity profile in the central segment of the ria were representative of the whole cross section, the renewal of this embayment would be from two to tenfold faster than predicted by the model, which would be hardly compatible with the observed warming of the surface layer and the recurrent closure of mussel cultivation areas because of the occurrence of harmful microalgae characteristic of highly stratified sites with very low flushing rates [Álvarez-Salgado et al., 2011].

Concerning the modeled residual flows, differences between input and output values are expected to be matched by river flows. However, when inputs and outputs are compared in Figs. 7 and 8 there are situations when the former are larger than the latter. This is not the result of some violation of the conservation law, but just the result of the net changes in water height along the periods used to calculate residual flows. In fact, tests conducted for longer periods when initial and final heights were similar confirmed that the model is conservative.
The comparison of July 2007 simulations with and without river flows (cf. Table 1) suggests the importance of the latter in the intensity of residual circulation during that period. However, a similar comparison with the October 2007 simulations suggests the opposite. This is an obvious consequence of the larger river flows in July 2007 (average $= 5.7 \text{ m}^3 \text{ s}^{-1}$) compared with those of October 2007 (average $= 2.8 \text{ m}^3 \text{ s}^{-1}$) (c.f. – Fig. 2).

The comparison of July and October simulations with and without the wind effect suggests the strong effect of the wind forcing, especially in the July simulation. Therefore, it may be concluded that it is hard to generalize on the relative weight of these two potentially important forcing mechanisms that will change as a function of their respective magnitude. However, within the ranges covered by the present study periods and model simulations it seems that local wind have the potential for a larger effect on the intensity of input/output residual flows than the river outputs.

When the standard simulations are compared with those with a persistently meridional wind (Figs. 5-8), model results suggest that southerly winds have a stronger effect on residual circulation, increasing the intensity of the input/output flows across the outer boundary. Again, the differences in the patterns obtained for July and October are a result of the large differences in wind velocity for both periods. In the case of October, northerly winds seem to have an effect of blockage of the residual circulation along the outer boundary (Fig. 6): both surface and bottom residual velocities under persistent northerly wind produce a strong south-westward current along the outer boundary of the model, preventing the exchange between the ría and the adjacent shelf. However, it is important to keep in mind that this effect could be merely an artifact resulting from the close location of the sea boundary that prevents the integration of mesoscale effects on model dynamics rather than a real phenomenon. Possibly, the orientation of this ría implies an influence of meridional winds slightly different from that observed for the
Rías Baixas, that are perpendicular to the shore (Fig. 1). In Ares-Betanzos, a perfectly meridional northerly wind would force the water towards the south-western margin, possibly explaining the above mentioned blockage of the circulation. Such an effect would not be observed with a perfectly meridional southerly wind because most of the north-western boundary is open and, therefore, the model does not receive the feedback of the interaction of water circulation with land boundaries.

The impact of mussel cultivation on hydrodynamics may correspond to large reductions in residual current velocities (up to 40%) suggesting the potential for mussel rafts to influence water flows and, therefore, water and food renewal for the cultivated species. This is a potentially negative feedback to the cultivation process, in line with findings by other authors. Grant et al. [1998] applied the methodology of drag calculation within a kelp forest, described by Jackson and Winant [1983], to estimate drag exerted by mussel rafts in Saldanha Bay (South Africa). Grant and Bacher [2001], working with a two-dimensional vertically integrated finite element model to simulate current velocities in Sungo Bay (China), used Manning coefficients of 0.03 and 0.15 for non-aquaculture and aquaculture areas, respectively, to account for the slow down effects of aquaculture structures on the flow. The same approach was followed by Duarte et al. [2003] for the same ecosystem. Shi et al. [2011] estimated that body drag exerted by kelp cultivation in Sungo Bay may cause a 40% reduction in average speed of surface current, using a similar approach to the one described in the present study. Delaux et al. [2011] used 2D high resolution computational fluid dynamics model to investigate the influence of block spacing and angle in suspended shellfish long-line cultures and obtained flow reductions of up to 25%.
5 Conclusions

In this work a 3D hydrodynamic model was implemented to Ría de Ares-Betanzos and validated with empirical data on current velocities and vertical salinity and temperature profiles. Results from model simulations suggest the existence of a cyclonic gyre that develops in the confluence zone between the estuaries of the rivers Eume and Mandeo, in the middle ría, consistent with empirical evidence on mussel larval dispersion. Furthermore, residual circulation seems to be always positive with a bottom inflow and a surface outflow, irrespective of local wind regime and as a probable result of river flows and the geographic orientation of this system, unlike what has been observed in Rías Baixas to the south of Cape Fisterra. Substantial reduction of the subtidal circulation of the Ría de Ares-Betanzos has been predicted because of the presence of mussel farms, not only locally, but at the scale of the whole embayment. A reduction of the flow would affect negatively the carrying capacity of the mussel farms and would favor the occurrence of harmful microalgae that proliferates in stratified slow moving environments. On this light, and claiming the principle of precaution, a cornerstone of the sustainable exploitation of marine living resources, we suggest incorporating this kind of numerical models to the scientific advice of policymakers involved in the regulation of extensive aquaculture.

6 Acknowledgements

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7 References


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Table 1 – Model simulations and corresponding abbreviations.

<table>
<thead>
<tr>
<th>Period</th>
<th>Simulation</th>
<th>Abbreviation</th>
</tr>
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<tbody>
<tr>
<td>July</td>
<td>Standard</td>
<td>July-St</td>
</tr>
<tr>
<td></td>
<td>Without rivers</td>
<td>July-1</td>
</tr>
<tr>
<td></td>
<td>Without wind</td>
<td>July-2</td>
</tr>
<tr>
<td></td>
<td>With northerly wind</td>
<td>July-3</td>
</tr>
<tr>
<td></td>
<td>With southerly wind</td>
<td>July-4</td>
</tr>
<tr>
<td></td>
<td>Without body drag due to the mussel rafts</td>
<td>July-5</td>
</tr>
<tr>
<td>October</td>
<td>Standard</td>
<td>October-St</td>
</tr>
<tr>
<td></td>
<td>Without rivers</td>
<td>October-1</td>
</tr>
<tr>
<td></td>
<td>Without wind</td>
<td>October-2</td>
</tr>
<tr>
<td></td>
<td>With northerly wind</td>
<td>October-3</td>
</tr>
<tr>
<td></td>
<td>With southerly wind</td>
<td>October-4</td>
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Table 2 – Measures of reliability synthesized in Allen et al. [2007].

<table>
<thead>
<tr>
<th>Measure</th>
<th>Excellent</th>
<th>Very good</th>
<th>Good</th>
<th>Poor</th>
</tr>
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<tr>
<td>Nash Sutcliffe model efficiency (E) [Nash and Sutcliffe, 1970] and Maréchal [2004] for quality level criteria</td>
<td>&gt; 0.65</td>
<td>0.65-0.5</td>
<td>0.5-0.2</td>
<td>&lt; 0.2</td>
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<tr>
<td>Cost function (CF) [OSPAR Commission, 1998]</td>
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<tr>
<td>Cost function with quality criteria according to Radach and Moll [2006]</td>
<td>≤ 1</td>
<td>1-2</td>
<td></td>
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Table 3 – Model validation. For each of the two standard simulations (cf. Methodology) and for each velocity component (west-east ($u$) and south-north ($v$)) parameters of the Model II regressions between predicted and observed data are given together with the significance of the variance explained by the model. Root mean square error (RMSE), Nash Sutcliffe model efficiency (E) [Nash and Sutcliffe, 1970], index of agreement (d) [Wilmot, 1981], their modified versions E1 and d1 () and the Cost function (CF) [OSPAR Commission, 1998] are shown in the following columns. Quality levels are based on data presented in Table 1.

<table>
<thead>
<tr>
<th>Simulation</th>
<th>Velocity component</th>
<th>Model II regression</th>
<th>RMSE</th>
<th>E</th>
<th>d</th>
<th>E1</th>
<th>d1</th>
<th>CF</th>
</tr>
</thead>
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<tr>
<td></td>
<td></td>
<td>Slope</td>
<td>Y-intercept</td>
<td>F (explained variance)</td>
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<td>July 2007 Surface layers</td>
<td>$u$</td>
<td>5.67</td>
<td>0.02</td>
<td>Poor -4.17</td>
<td>0.49</td>
<td>Poor -1.44</td>
<td>0.34</td>
<td>Good 1.84</td>
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<tr>
<td></td>
<td>$v$</td>
<td>1.99</td>
<td>-0.02</td>
<td>Poor -0.75</td>
<td>0.62</td>
<td>Poor -0.41</td>
<td>0.42</td>
<td>Good 1.08</td>
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<tr>
<td>Intermediate layers</td>
<td>$u$</td>
<td>1.18</td>
<td>-0.02</td>
<td>Good 0.27</td>
<td>0.82</td>
<td>Poor 0.13</td>
<td>0.61</td>
<td>Very good 0.68</td>
</tr>
<tr>
<td></td>
<td>$v$</td>
<td>0.82</td>
<td>0.02</td>
<td>Very good 0.63</td>
<td>0.89</td>
<td>Good 0.42</td>
<td>0.69</td>
<td>Very good 0.47</td>
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<tr>
<td>Bottom layers</td>
<td>$u$</td>
<td>0.65</td>
<td>0.01</td>
<td>Excellent 0.70</td>
<td>0.89</td>
<td>Good 0.50</td>
<td>0.71</td>
<td>Very good 0.41</td>
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<tr>
<td></td>
<td>$v$</td>
<td>0.56</td>
<td>-0.01</td>
<td>Excellent 0.69</td>
<td>0.87</td>
<td>Good 0.49</td>
<td>0.68</td>
<td>Very good 0.42</td>
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<td>0.12</td>
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<td>0.52</td>
<td>Poor -0.19</td>
<td>0.51</td>
<td>Good 1.01</td>
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<tr>
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<td>$v$</td>
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<td>-0.01</td>
<td>Poor 0.48</td>
<td>0.48</td>
<td>Poor 0.43</td>
<td>0.43</td>
<td>Very</td>
</tr>
<tr>
<td></td>
<td>October 2007</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
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<tr>
<td>Intermediate layers</td>
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<td>-0.71</td>
<td>-0.13</td>
<td>good</td>
<td>0.85</td>
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<tr>
<td></td>
<td>u</td>
<td>1.12</td>
<td>-0.01</td>
<td>P &lt;&lt; 0.001</td>
<td>0.05</td>
<td>Good</td>
<td>0.34</td>
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<tr>
<td></td>
<td>v</td>
<td>1.41</td>
<td>0.01</td>
<td>P &lt;&lt; 0.001</td>
<td>0.03</td>
<td>Poor</td>
<td>0.28</td>
<td></td>
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<tr>
<td>Bottom layers</td>
<td></td>
<td>0.97</td>
<td>0.00</td>
<td>P &lt;&lt; 0.001</td>
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<td>Very good</td>
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<tr>
<td></td>
<td>u</td>
<td>1.17</td>
<td>0.00</td>
<td>P &lt;&lt; 0.001</td>
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<td>Good</td>
<td>0.45</td>
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</tr>
<tr>
<td></td>
<td>v</td>
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</tbody>
</table>
**Figure captions**

Figure 1 – Galician ría with a detail of ría de Ares-Betanzos, showing monitoring stations (triangles), the location of mussel rafts (small white dots), model domain (continuous line) and rivers Eume and Mandeo. A raster image with the bathymetry and model grid is also shown (see text).

Figure 2 – Wind velocity and direction and river flow data used to force the model for the periods covered by the simulations (see text).

Figure 3 – Predicted and observed $u$ (east-west) and $v$ (north-south) velocity components over a period of 550 h, from October 16th till November 7th 2007 at station 3 (cf. Figure 1) between c.a. 6 and 12 m depth.

Figure 4 – Predicted and observed vertical profiles of water temperature and salinity in 19th July 2007, at several stations depicted in Figure 1 (3, 4, A1 and B1), nine days after simulation started.

Figure 5 – Residual velocities predicted by the model for the simulations July – St, July-3 and July-4 (cf. – Table 1) integrated for the upper eight layers (left maps) and for the bottom seven layers (right maps) (see text).

Figure 6 – Residual velocities predicted by the model for the simulations October – St, October-3 and October-4 (cf. – Table 1) integrated for the upper eight layers (left maps) and for the bottom seven layers (right maps) (see text).

Figure 7 – Predicted daily averaged residual flows ($m^3 s^{-1}$) for both the July and the October simulations (July-St, July-1, October-St and October-1) (cf. – Table 1), for part of the period covered by the work of Villegas-Ríos et al. [2011] and for the boundaries of their box-model. Surface and bottom values were integrated for the upper eight and for the lower seven layers, respectively.
Figure 8 – Predicted daily averaged residual flows (m$^3$ s$^{-1}$) for both the July and the October simulations (July-2, July-3, July-4, October-2, October-3 and October-4) (cf. – Table 1), for the part of the period covered by the work of Villegas-Ríos et al. [2011] and for the boundaries of their box-model. Surface and bottom values were integrated for the upper eight and for the lower seven layers, respectively.

Figure 9 – Percent differences in residual velocities integrated over time and depth between simulations with and without mussel raft body drag (see text). Upper panel and lower panels: average results integrated for the upper eight layers and the lower seven layers, respectively.
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