Effect of Minho estuarine plume on Rias Baixas: numerical modeling approach

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ABSTRACT

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The Minho River, situated 30 km south from the Rias Baixas, is the most important freshwater source flowing into the Western Galician coast. This discharge is particularly important in driving the circulation and hydrography of this coastal region. To study this important issue, numerical modeling may constitute an important tool being used to understand the coastal plume effects under different conditions. The main purpose of this study is to implement and validate a marine model able to reproduce the propagation of the Minho estuarine plume. The chosen period for the validation was the spring of 1998, because a high Minho River discharge was reported as well as favorable wind patterns to spread the river plume towards the Rias Baixas. The numerical model MOHID was used through a downscaling approach with a three-level one-way nested scheme. The numerical predictions show good agreement with the observed water level in the entire domain. Also, the measured components of the velocity are well represented by the model, as well as the observed pycnocline, which is predicted for the observed depth. According to the model results, a buoyancy intrusion caused by the Minho river reverses the normal estuarine salinity longitudinal gradient of the Rias de Vigo and Pontevedra. Otherwise, this pattern is not observed in the Ria de Arousa. All these patterns are corroborated by *in situ* measurements. In summary, the validation results show that the model adequately reproduces the hydrodynamic and thermohaline patterns of the Western Galician coast.

ADDITIONAL INDEX WORDS: *River discharge, wind, MOHID, Western Galician Coast.*

INTRODUCTION

Estuarine plumes often discharge in the coastal zone and are essential for the transport of material across the land-sea interface, having a significant impact in coastal primary production. In the western coasts of the Northern Hemisphere, estuarine water usually spreads northward and alongshore in winter due to the influence of prevailing southwest winds as well as to high river runoff. When river discharge reduces and prevailing winds are from the northwest, the main feature of these coasts is the offshore extension of the plume. This pattern usually occurs in spring.

The Minho River is situated 30 km south of the Rias Baixas (NW Iberian Peninsula), and is the most important freshwater source flowing into this coastal region. The Minho River has a catchment area of 17080 km^2 and an annual average discharge of 300 m^{3}s^{-1}. The monthly average discharge oscillates between 100 m^{3}s^{-1} in August and 800 m^{3}s^{-1} in February. The buoyancy generated by the Minho plume can flood the Rias Baixas for long periods, reversing the normal estuarine density gradients (Fiedler and Laurs, 1990; Alvarez *et al.*, 2006). Several studies were already carried out to analyze changes in thermohaline variables, as the salinity decrease, inside the Rias Baixas (Mourino and Fraga, 1982; Alvarez *et al.*, 2006; Sousa *et al.*, 2011). According to these studies, these changes were related to the Minho River discharge, since the river runoff inside the estuaries was unable to generate the measured salinity values. In addition, these studies were carried out under a high Minho River discharge and wind patterns favorable to spread the river plume northward from the river mouth, toward the Rias Baixas. This buoyancy intrusion reversed the normal salinity gradient in the along axis direction in the Rias de Vigo and Pontevedra, but not in their neighbor Ria de Arousa. Thus, to study these important thermohaline processes, numerical models may constitute a reliable and useful tool to understand the complex structure of the oceanographic variables, and can therefore be used to research the coastal plume effects under different conditions. From its application may be evaluated the effect of the wind direction on a river plume under different conditions: upwelling or downwelling favorable winds.

In order to investigate the propagation of estuarine plumes some recent numerical studies have been performed worldwide. Choi and Wilkin (2007) in the Hudson River (USA), Otero *et al.* (2008) in the Northwest Iberian Peninsula, Marques *et al.* (2009) in Patos Lagoon (Brazil) or Vaz *et al.* (2009a) in the Tagus estuary (Portugal). Regarding the Minho River plume, numerical studies researching its spreading along the coast were not found, despite the importance of this plume on the NW Iberian Peninsula coastal dynamics.

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In this context, the aim of this paper is to describe the implementation and validation of a nesting numerical modeling methodology able to reproduce the propagation of the Minho estuarine plume towards Rias Baixas, using a downscaling approach. The 1998 spring period was chosen for the model validation, since it was reported a high Minho River discharge as well as favorable wind patterns to advect the river plume towards the Rias Baixas, and there was field data available to compare with the model predictions (Alvarez *et al.*, 2006).

STUDY AREA

The Rias Baixas are flooded tectonic valleys located south of Cape Finisterre (NW coast of the Iberian Peninsula). The Rias Baixas considered in this study are, from south to north, the Ria de Vigo, the Ria de Pontevedra and the Ria de Arousa (Figure 1). They are connected to the open sea through two entrances, due to the existence of islands in its outermost area. Freshwater contributions come from four small rivers: the Verdugo River at the Ria de Vigo head, the Lérez River at the Ria de Pontevedra and the Umia e Ulla Rivers at the Ria de Arousa.

In the Rias Baixas, the tidal forcing is mainly semidiurnal, with a form number significantly lower than 0.25 (Varela *et al.*, 2005).

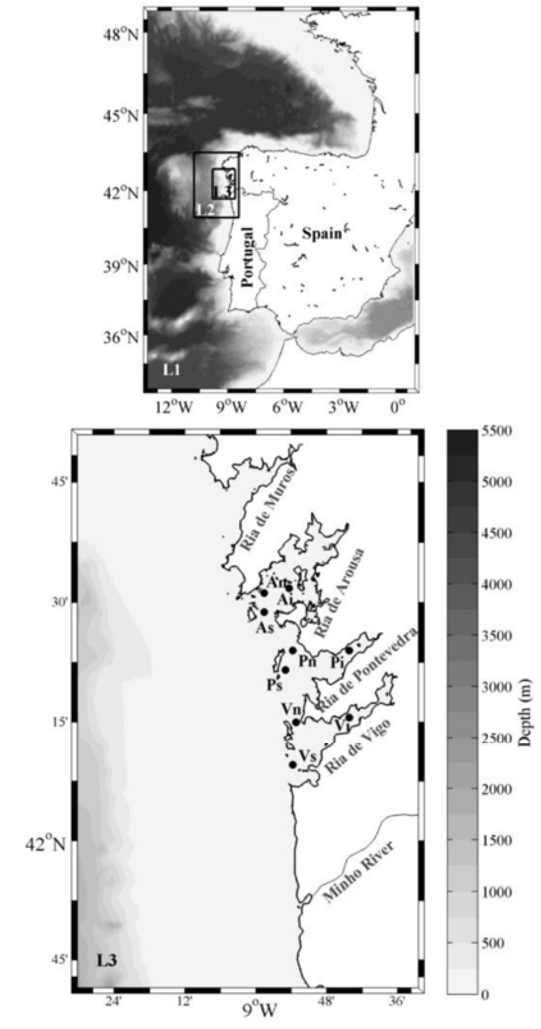

Figure 1. Topography (m) of study area with indication of the three nested grids and sampling stations position (black dots).

The Rias Baixas are mesotidal, with a tidal range from 2 to 4 m (Fraga and Margalef, 1979). The Rias Baixas behave as partially mixed estuaries with positive residual circulation, showing a two layer pattern with surface water outflow and bottom water inflow (Fraga and Margalef, 1979; Prego and Fraga, 1992).

MATERIAL AND METHODS

Data

The dataset used in this study comprises salinity data measured weekly at three sampling stations located at the southern (wider and deeper) and northern mouths and in the inner-middle areas of the Rias de Vigo, Pontevedra and Arousa during 1998 (Figure 1). These measurements were made using a conductivity-temperature-depth (CTD) instrument (Seabird19 and 25). Salinity calibration was previously performed by means of an "Autosal" salinometer. Current velocity data also integrates the available dataset, and was measured in the inner-middle part of the Ria de Pontevedra (42º23.51'N, 8º44.29'W) by means of an Electomagnetic Current Meter (Valeport Model 808) at six different depths during 5 min at each depth. The same protocol was repeated every 30 minutes during a tidal cycle. Amplitude and phase of the major tidal constituents obtained from harmonic analysis at Vigo (42º14.4'N, 8º43.8'W) and Villagarcia (42º36.0'N, 8º46.2'W) (available from Puertos del Estado) were also considered. Daily Minho River discharge was supplied by the "Confederación Hidrográfica del Norte" and Verdugo, Lérez, Umia and Ulla River discharges were obtained from estimations presented in Otero *et al.* (2010). The meteorological data comprises hourly air temperature, wind velocity, solar radiation and relative humidity around the Western Galician coast. These data result from the Weather Research and Forecasting Model (WRF) predictions with a spatial resolution of 5 km (Skamarock *et al*., 2008). Sea surface temperature (SST) data measured by the Advanced Very High Resolution Radiometer (AVHRR) sensors provided by the AVHRR/Pathfinder was also analyzed over the study period. SST daily data are available from 1986 to 2006 with a high spatial resolution of 4.5 km.

The field data referred was used to examine the tidal wave and flow velocities characteristics, as well as the water properties inside the Rias Baixas and to set up and validate the numerical model. All datasets were considered from April to May 1998, covering the 1998 spring period under analysis.

Numerical model

In this study is used the MOHID (www.mohid.com), a three-dimensional free surface numerical model based on the Navier-Stokes equations, which are discretized using a finite volume approach. This method makes the solution independent of the mesh geometry, allowing the use of a generic vertical mesh. A more detailed description of the numerical algorithms can be found in Martins *et al.* (2001).

A downscaling methodology was developed to study the Minho estuarine plume dispersal, similar to the one followed by Leitão *et al.* (2005) and Vaz *et al*. (2009a), for simulating the Algarve coastal circulation and Tagus estuarine plume. In this case study a three level one-way nested model system was developed and implemented (Figure 1). The first domain (L1) is a 2D barotropic tidal driven model, which uses the FES2004 global solution as forcing (Lyard *et al.*, 2006), and has a variable horizontal resolution (0.02º – 0.06º). This domain was constructed based on the ETOPO1 global database. The second (L2) and third domains (L3) are 3D baroclinic models, with a horizontal resolution of 0.02º and 0.005º, respectively. The L2 and L3 bathymetries were constructed based on the General Bathymetric Chart of the Oceans (GEBCO), with some corrections on the continental shelf. A z-level vertical discretization was adopted, with L2 and L3 having 46 and 42 vertical layers, respectively.

To obtain the initial ocean stratification the second and third levels are forced at the open boundaries with monthly mean climatologies from Levitus (Antonov *et al.*, 2010; Locarnini *et al.*, 2010). The surface boundary condition is imposed using the high resolution results from the WRF model. These fields were interpolated into hourly fields for the two last model domains using triangulation interpolation in space and linear interpolation in time. At the surface, heat fluxes were imposed with parameterizations similar to those described by Chapra (1997). The sensible and latent heat fluxes are calculated using the Bowen and Dalton laws, respectively (Chapra, 1997). For the bottom boundary condition, a constant value of the bottom rugosity was considered. The 3D momentum (zonal and meridional velocities), heat and salt balance equations are computed implicitly in the vertical direction, while in the horizontal directions are computed explicitly. The advection of momentum, heat and salt is computed using a total variation diminishing (TVD) scheme with a Superbee limiter.

As landward boundary conditions, the freshwater inputs from Rias Baixas and the Minho estuary are considered. This last is imposed offline in L3 as momentum, water and mass discharges to the coastal model. These are computed with a 0.0065º – 0.001º horizontal resolution model for the inner part of the Minho estuary, also developed in the frame of this study.

The model was run from April to May, 1998.

RESULTS AND DISCUSSION

Environmental conditions

Figure 2 depicts the six-hourly wind speed at a point located close to the coast (42ºN, 9ºW), as well as the daily Minho River discharge for the period April-May 1998.

The wind pattern is variable, with strong fluctuations in direction and intensity. The most prevailing winds are northwesterly and northeasterly, with intensities higher than 5 m s^{-1}. The Minho River discharge shows an atypical pattern with high values during early May (1600 m^3 s^{-1}). This maximum discharge occurs concurrently with a north-northeasterly wind. According to the results obtained by Alvarez *et al*. (2006), this high Minho River discharge advects the river plume toward the Rias Baixas after a few days (9-13 May 1998), as does the favorable wind (wind blowing from the south).

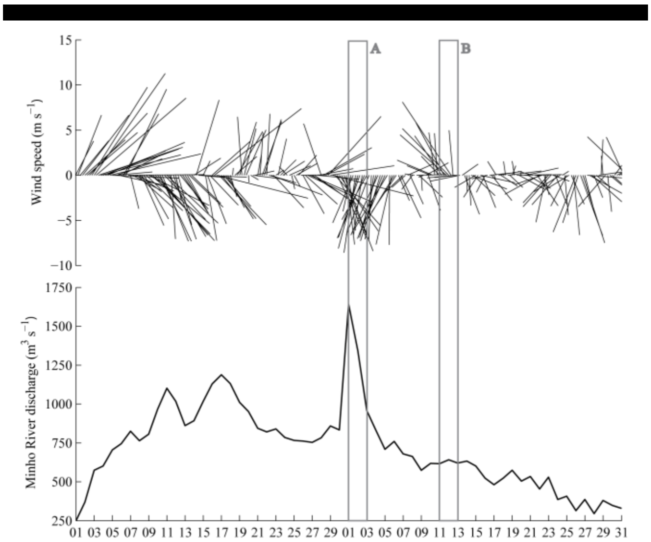

Figure 2. Time series of wind speed and Minho River discharge from April to May, 1998.

Taking into account Figure 2, and to evaluate the model accuracy in reproducing the Minho estuarine plume propagation, two scenarios were considered: the first when the wind is blowing from the north after high discharge (Figure 2, A) and the second when the river discharge reduces and the wind blows from the south to spread the river plume toward the Rias Baixas (Figure 2, B).

Model validation

The model validation is defined as a procedure consisting in comparing the model outputs with available data to prove the model skill under different conditions. In a first approach the model's predictions skill is assessed through a qualitative and quantitative comparison of the temporal evolution of sea surface elevation (SSE) and tidal currents data. Secondly, in terms of plume propagation, the model's accuracy is also evaluated, based on the scenarios described above (Figure 2, A and B), considering SST and salinity data.

Hydrodynamic analysis

To verify the model results, SSE outputs from a hydrodynamic simulation from 1 to 18 May (1998) are compared with predictions for Vigo and Villagarcia, determined by harmonic synthesis of local amplitude and phase data (Pawlowicz *et al.*, 2002) (Figure 3).

In general, there is a good agreement between the model results and predicted SSE for both stations, revealing the model's accuracy to reproduce the data. The time lag and elevation difference between model results and predicted data is considered negligible (about 0.05 m). To quantify the model's accuracy to reproduce the data, the root mean square (RMS) and the predictive skill are computed at each station, following the methodology proposed by Sousa and Dias (2007) and Dias *et al.* (2009). The values calculated for RMS are 0.06 m and 0.05 m for Villagarcia and Vigo stations, respectively. The skill is close to 1 for both stations, showing an excellent agreement between the model

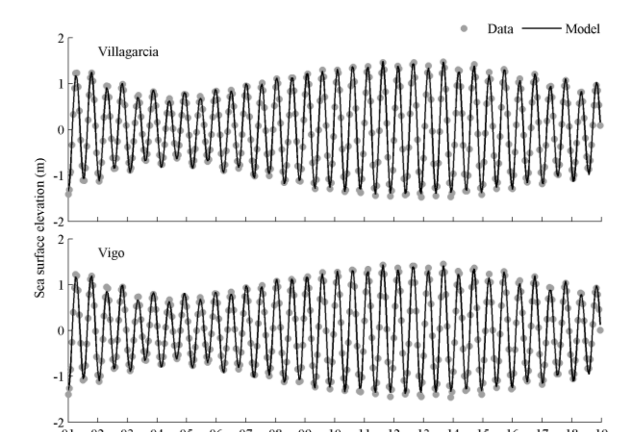

Figure 3. Model results and predicted sea surface elevation time series at Villagarcia and Vigo from 1 to 18 May, 1998.

results and the predicted data. These values are very similar to those obtained by Sousa and Dias (2007) and Vaz *et al*. (2009b) for the Ria de Aveiro lagoon and Dias *et al.* (2009) for the Ria Formosa.

The comparison between harmonic constants determined from model results and observed data is another quantification method used to evaluate models accuracy. Thus, this methodology was also applied in this study, to compare the harmonic constants for the Villagarcia and Vigo. The software *t_tide* (Pawlowicz *et al.*, 2002) was used to analyze the model predicted time series shown in Figure 3. Table 1 shows amplitudes and phases of the harmonic constants M_2, S_2, O_1 and K_1 for Villagarcia and Vigo, determined from model results and from observed data. The agreement between values is very good, for the semi-diurnal and diurnal constituents, which are the major tidal constituents in the Rias Baixas (Marta-Almeida and Dubert, 2006). For the M_2 constituent, whose amplitude is the largest, the difference between datasets is 0.01 m. In Villagarcia, the phase difference is 2.6º, which means that the average delay between the observed and predicted tide is about 5.5 minutes for this constituent. For Vigo, the average delay is lower (about 2.5 minutes), revealing a good phase agreement. For the diurnal constituents the amplitude and phase agreement may be considered good for both stations. The results from the harmonic analysis show that the tide should be classified as semidiurnal (Form Number ≈0.07) and that constituents M_2 and S_2 together determine about 90% of the astronomic tide in Western Galician coast. This last result is in accordance with previous studies (Marta-Almeida and Dubert, 2006).

Regarding the vertical structure, the model's accuracy was also verified using current meter data taken at inner-middle part of the Ria de Pontevedra during three hours (Figure 4). The comparison between the observed and model predicted velocity indicates that the model reproduces the real variability and trends of the velocity vertical structure on this region, with small differences in the intensity and phase of the series. The highest discrepancies between model predictions and field data were found at 22 h, but it may be justified by a casual malfunction of the current meter or by an insufficient vertical discretization. The RMS values range from 0.012 to 0.040 m s^{-1} in the zonal and 0.014 to 0.040 m s^{-1} in the meridional component. For both components, the bias is close to zero, indicating that datasets are in concordance.

Although the errors are not negligible, especially for the meridional velocity component, the validation results show that the model developed in this study reproduces accurately the hydrodynamic behavior on Rias Baixas. Thus, the model presented here constitutes a useful tool to study the tidal dynamics in the Western Galician coast.

Plume propagation verification

The wind and river runoff affects the dispersal of estuarine

Table 1. Comparison between amplitudes and phases from model results and observed data for M_2, S_2, O_1 and K_1 for Villagarcia and Vigo tide gauge stations.

	Tide gauge	*Amplitude (m)*		*Phase (º)*	
		Data	*Model*	*Data*	*Model*
M_2	Villagarcia	1.06	1.07	83.07	80.47
	Vigo	1.02	1.03	80.25	79.06
S_2	Villagarcia	0.44	0.41	100.89	97.32
	Vigo	0.42	0.40	97.66	95.78
O_1	Villagarcia	0.06	0.07	323.22	323.59
	Vigo	0.06	0.07	318.96	332.52
K_1	Villagarcia	0.05	0.08	32.86	42.98
	Vigo	0.06	0.08	47.87	42.60

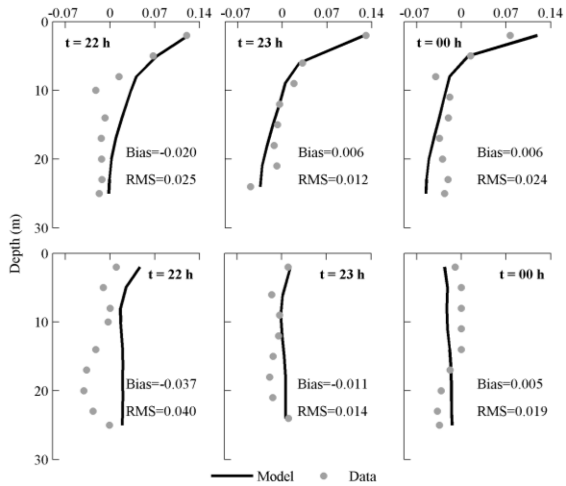

Figure 4. Observed and model predicted zonal (upper panel) and meridional (lower panel) velocity currents (m s^{-1}) profiles for the Ria de Pontevedra on May 12, 1998.

plumes, influencing the transport and mixing of plume waters (Choi and Wilkin, 2007). Thereby, it is important to evaluate the model accuracy to reproduce the Minho estuarine plume under different conditions.

One way of validating the accuracy of model´s results spatial variability consists in comparing model predicted SST horizontal fields with satellite measurements. For the spatial comparison, model data were interpolated for the satellite grid (4.5 km) using a cubic interpolation. The modeled SST is calculated by daily averaging the model predictions at each grid cell. Thus, Figure 5 shows SST patterns obtained from model predictions and satellite data for scenarios A and B.

The results show that wind plays an important role in the dispersion of the Minho estuarine plume. When the wind blows southwards (Figure 5, scenario A), the main feature is the offshore extension of the plume. Otherwise, northward wind (Figure 5, scenario B) spreads the river plume towards the Rias Baixas, confining it close to the coast. In this case the plume reaches the mouth of the Ria de Pontevedra, influencing its inner physical properties.

Both the measured and predicted SST patterns show approximately the expected main features of the temperature field in the region under analysis, which is characterized by higher temperatures offshore that decrease toward the coast (Figure 5).

In both scenarios there is a satisfactory agreement between the observations and predictions of the plume, although the adjustment quality tends to decrease offshore and close to the river mouth (Figure 5, scenario B). More specifically, in the area of spread of the plume it should take into account the existence of a small satellite land mask near shore and the satellite coarse resolution. These results are very similar to those obtained in previous numerical modeling works (Otero *et al.*, 2008; Marta-Almeida *et al.*, 2012), revealing that the numerical model developed reproduces adequately the plume propagation.

The difference between satellite and model predicted SST was determined to evaluate and quantify the model accuracy (Figure 5). The difference distribution shows negative values in the northwestern Galician coast for both scenarios, meaning that the model underestimates SST in this region. However, the lowest values (close to zero) are observed in the area of spread of the

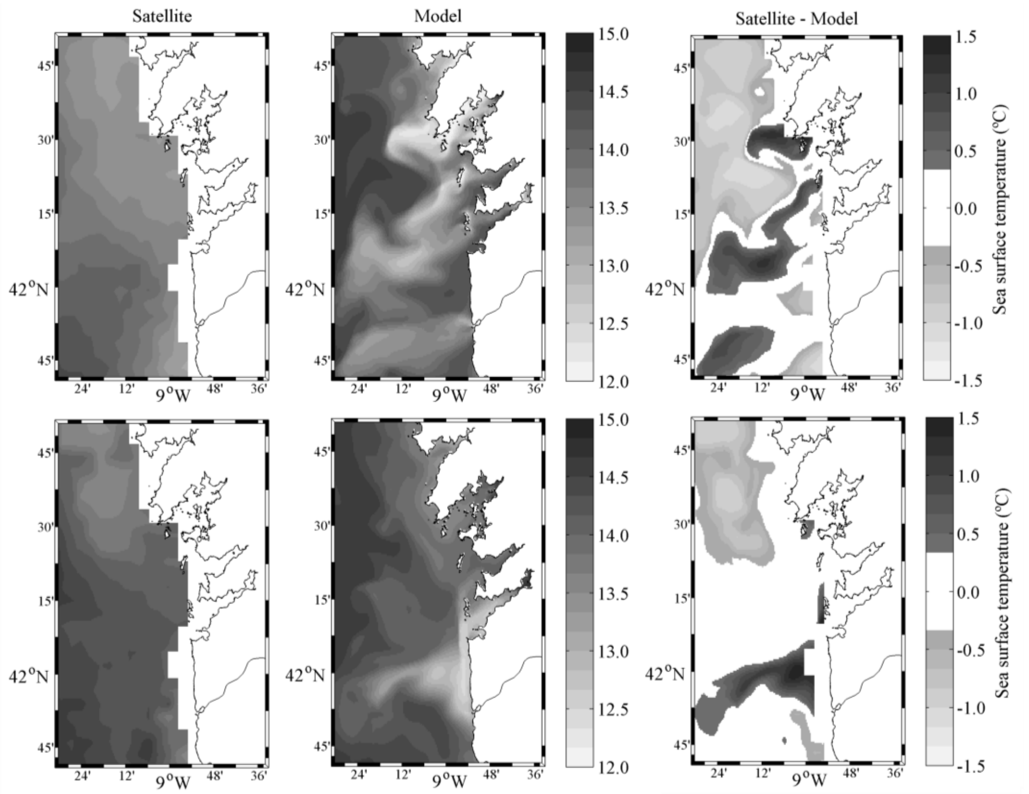

Figure 5. Sea surface temperature maps obtained from satellite data, model predictions and respective difference for scenario A (upper panel) and B (lower panel).

plume, revealing a good fit between predictions and measurements in the reproduction of the estuarine plume. Nevertheless, it is necessary to keep in mind that the model temperature is the average of the surface layer, whose thickness is about 1 m, while the satellite data refers to the skin temperature. Considering that the temperature measured by the satellite is higher, it is reasonable to assume that the model simulates adequately the thermodynamics of the top sea layer. These differences between model and satellite data are consistent with values described in the literature, where differences of the order of 1-1.5 ºC are found.

Figure 5 shows that in scenario B the Minho estuarine plume reaches the Rias Baixas. To investigate this freshwater intrusion, the salinity vertical profiles predicted by the model were compared with salinity measurements at the sampling stations shown in Figure 1 (Figure 6).

The salinity profiles corresponding to *in situ* measurements reveal an abnormal salinity gradient in the along axis direction of the Rias de Vigo and Pontevedra. The southern mouths of the Rias are less saline than the internal part. This difference is more significant in the Ria de Vigo. On the contrary, the Ria de Arousa shows a completely different salinity gradient, with saltier water near the mouth than in the inner part of the estuary. A similar pattern can be observed in the model predictions.

An overestimation of the salinity in the southern mouth of the Ria de Vigo is observed from the analysis of Figure 6. Nonetheless, the pycnocline is always well reproduced by the model for all the stations, being predicted for the same depth.

The maximum RMS values (1.27) between model results and measurements are observed in the Ria de Vigo. For the other stations, RMS values range between 0.15 and 0.33. Bias shows positive values for almost all stations, indicating that the model predictions overestimate salinity. The highest values of bias (about -1.19) are also observed in the Ria de Vigo. These values could be explained by an improper prescription of the landward boundary

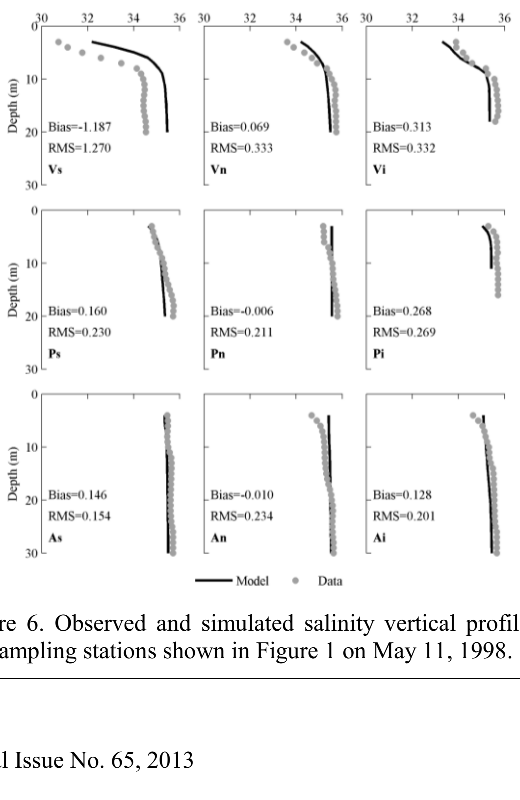

Figure 6. Observed and simulated salinity vertical profiles for the sampling stations shown in Figure 1 on May 11, 1998.

condition or a malfunction of the CTD instrument.

These results reveal that the model accurately reproduce the thermohaline patterns on Rias Baixas, as well as the effect of the Minho estuarine plume in these costal regions.

CONCLUSIONS

The results obtained in this study reveal that the nesting methodology adopted to develop the model for the Western Galician coast was successful, given that the model predictions reproduce accurately the local hydrodynamics and thermohalime patterns. Regarding SSE, the RMS values were 5% lower than the amplitude of the observed data and the predictive skill was close to 1. The measured velocity currents were also well represented by the model, with RMS values lower than 0.040 m s^{-1} both in the zonal and in the meridional component. The model predictions slightly overestimate salinity, with maximum RMS values lower than 1.27, whereas the lowest difference between SST model predictions and satellite data (close to zero) are observed in the plume propagation area.

Model results reveal an important effect of the Minho estuarine plume on Rias Baixas. The freshwater intrusion caused by the high Minho River discharge was found to reverse the normal salinity gradient at the Rias de Vigo and Pontevedra, but not in Ria de Arousa, which is in accordance with local observations.

In summary, the methodology proposed in this paper appears to be useful and accurate enough to simulate the dynamics of the estuarine Minho Plume along the Galician coast, as well as its effects on Ria Baixas.

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