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Integrated High-resolution Numerical Model for the NW Iberian Peninsula Coast and Main Estuarine Systems

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ABSTRACT

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The NW Iberian Peninsula (NWIP) coast includes a large diversity of estuarine systems such as Rias, river estuaries and coastal lagoons, being characterized by a high primary production, responsible for the significant fisheries and aquaculture productivity of the region. Thus, the main objective of this study is the development of a novel integrated high-resolution circulation and hydrographic coastal model designed with Delft3D-flow and applied for a large and complex area integrating the NWIP continental shelf and main estuarine systems. A domain decomposition technique was adopted to resolve the complex geomorphology in the study area. This approach allows local refinement in estuarine systems with the capability of two-way communication of water level, currents and hydrographic properties between those areas and the coastal ocean. The model was successfully validated using sea surface elevation, salinity and water temperature data from various observational sources, including remotely sensed images. Numerical calculations show good agreement with the observed water level in the entire domain. In addition, measured salinity and water temperature are well reproduced by the model. Results from two real events (summer 2005 and winter 2012-2013) were compared with remote sensing products, revealing that predictions adequately represent the hydrographic patterns observed. Results showed a complex interaction among estuarine systems as well with the adjacent coast, in addition to the accuracy of the integrated high-resolution numerical model developed in reproducing the hydrodynamic and thermohaline patterns of the NWIP coast and main estuarine systems.

ADDITIONAL INDEX WORDS: *Estuary-near-shelf systems interaction, sea surface elevation, salinity, water temperature, harmonic analysis, MODIS, Delft3D.*

INTRODUCTION

Physical processes in estuaries are forced by tides, freshwater inflow, wind stress and exchanges between atmosphere-ocean, as well as by the interaction with the adjacent shelf where coastal phenomena such as upwelling and river plumes dispersion occur. These processes determine the estuarine circulation, salinity and water temperature patterns, which are critical physical factors for the local ecosystems.

The NWIP coast includes four estuarine systems called Rias Baixas (Rias de Muros, Arousa, Pontevedra and Vigo) in the northern area, and the estuaries of major rivers flowing into this coast (Minho, Lima and Douro) and Ria de Aveiro coastal lagoon in the south (Figure 1). The area is located in the northernmost limit of the Eastern North Atlantic Upwelling System (Wooster *et al*., 1976), where the alongshore winds interact with the coastal topography to generate upwelling-downwelling processes. On the other hand, river plumes propagation, mostly from Douro and Minho estuaries, dominates surface layers. This mechanism can modify the density inside the estuaries located up north or south of the river mouth, altering the estuarine circulation. Therefore, extreme river discharges and upwelling/downwelling events affect the dynamics of these coupled estuary-near-shelf systems, primarily of the Rias Baixas (Otero *et al*., 2013; Sousa *et al*., 2014; Mendes *et al*., 2016). The great primary productivity generated by the entrance of upwelled water into these estuaries promotes its high commercial interest (Blanton et al., 1987; Prego et al., 2001). Primary production, biological diversity and estuarine circulation were also studied in the Minho, Lima, Douro and Ria de Aveiro estuaries (Vieira *et al*., 2000; Queiroga *et al*., 2003; deCastro *et al*., 2006; Costa-Dias *et al*., 2010; Vale and Dias, 2011). Most of the previous studies are only focused on each estuary independently and did not consider the full interaction with the adjacent shelf circulation processes. Thus, the interaction between the hydrodynamic and thermohaline properties of all estuarine systems along this coastline and the local coastal circulation has not been assessed. A single high-resolution 3D model including all these areas is essential to resolve the NWIP coast and main estuaries dynamics in an integrate way. This potentially requires a model system with the capability of wide geographic coverage (from regional oceanic influences into local estuarine dynamics) and of high spatial resolution in the regions of major interest.

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In this context, the main purpose of this study is to implement and validate an integrated estuarine and coastal high-resolution model designed with Delft3D-flow, which aims to simulate simultaneously a complex area integrating the continental shelf with Rias Baixas, Minho, Lima, Douro and Ria de Aveiro estuarine systems.

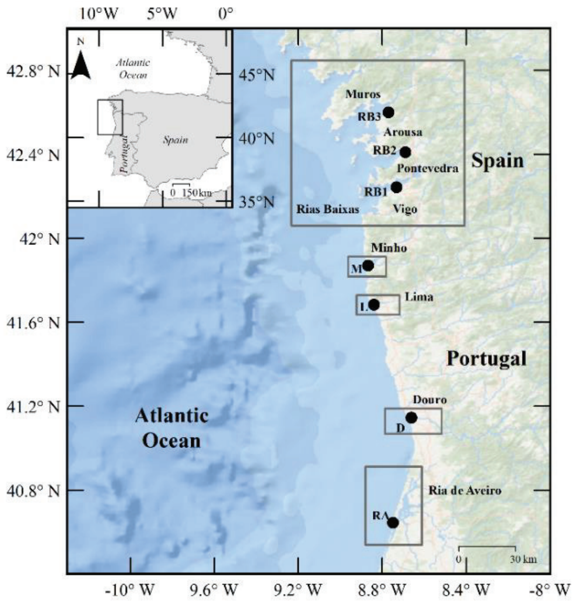

Figure 1. Map of the NWIP with the location of the main estuarine systems and sampling stations position (black dots).

METHODOLOGY

In this section, the general overview of integrated high-resolution circulation and hydrographic coastal model is presented as well as the validation procedure.

Numerical model

A 3D integrated high-resolution numerical model was setup using the Delft3D-Flow modeling system. To resolve the complex geomorphology of the NWIP continental shelf and main estuarine systems a domain decomposition technique was adopted, allowing the necessary local refinement. Thus, the model was divided into five domains (Figure 2). They were connected by internal domain decomposition boundaries with the capability of two-way communication of water level, currents and hydrographic properties. Ria de Aveiro and Douro were covered by domains with a grid resolution varying from 45 to 80 m. Minho and Lima estuaries were combined into a single domain with ~60 m grid resolution. Rias Baixas were also represented by a single domain with a spatial resolution of ~250 m, while the grid representative of the continental shelf has a lower resolution of ~1500 m (with a ratio of 1:4 compared to the grids developed for the estuarine systems). Thirteen vertical sigma layers were used for all domains, with refined surface layers, to improve the ability of the model to resolve the vertical mixing.

The bathymetric data for the estuarine systems was collected from several databases: Ria de Aveiro was obtained from Polis and Aveiro Harbor Administration; Douro, Minho and Lima estuaries were provided by the Instituto Hidrográfico updated with topographic data from an available Digital Terrain Model for the adjacent offshore area while Rias Baixas and adjacent shelf area were obtained from the General Bathymetric Chart of the Oceans.

The model uses tidal data from OSU TOPEX/Poseidon Global Inverse Solution as oceanic open boundary conditions, consisting in sea surface elevations determined from thirteen constituents with a spatial resolution of about 25 km. Transport conditions were also imposed from daily results obtained from the Atlantic Iberian Biscay Irish Ocean Physics Reanalysis with a spatial resolution of 10 km. The surface boundary condition was imposed using hourly results from the Weather Research Forecasting (WRF) model (www.wrfmodel.org) with a spatial resolution of 12 km. An ocean heat transport model was applied, taking into account air temperature, relative humidity and ocean cloudiness. This model provides the possibility to apply the required space and time dependent heat flux forcing. Freshwater inputs for Ria de Aveiro, Douro, Minho, Lima and Rias Baixas were considered, corresponding to a total of twelve freshwater points discharging in these estuarine systems.

The time step defined for this application is 30 seconds. For the all-estuarine systems, the horizontal and vertical eddy viscosities were 5 $m^2\ s^{-1}$ and 0.00001 $m^2\ s^{-1}$, respectively, while for the adjacent continental shelf the horizontal eddy viscosity was 15 $m^2\ s^{-1}$. The k-ε model was used for 3D turbulence. A constant manning value of 0.024 was assumed for bottom roughness, except for Ria de Aveiro where a spatial variable friction coefficient (Lopes and Dias, 2015) was used due to the shallowness of the lagoon.

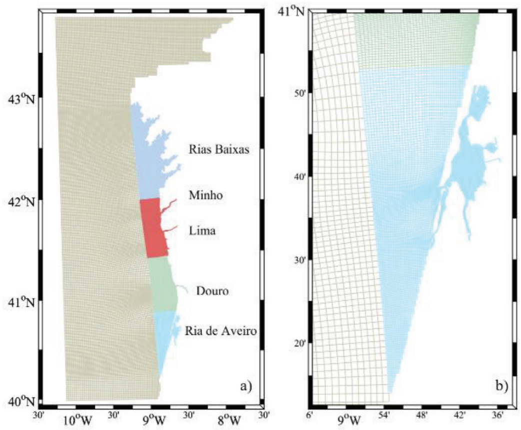

Figure 2. Integrated computational grid for NWIP coast, showing the five domains adopted in the grid decomposition (a). Detail of the grid domain decomposition design (b).

Model validation

The validation of the integrated estuarine and coastal high-resolution circulation and hydrographic model is performed in two steps, namely: tidal wave propagation and salt and heat transport processes. The last one is assessed over two distinct periods (summer 2005 and winter 2012/2013). For both simulations, three months of the simulation are considered as spin-up.

Predicted sea surface elevation (SSE) was compared with *in-situ* data sampled during 30 days (Figure 1, black dots) to verify the accuracy of model predictions for the estuarine systems. Next, the root mean square error (RMSE) and predictive skill was computed for stations shown in Figure 1 to quantify the model accuracy in reproducing *in-situ* data. Harmonic analysis of the predicted SSE time series for each station was also performed, using the software T_TIDE (Pawlowicz *et al*., 2002). Finally, harmonic constants for the main tidal constituents determined from model predictions and *in-situ* measurements were compared. Predicted and observed salinity and water temperature were also compared to evaluate the accuracy of the salt and heat transport models. Salinity and water temperature was sampled with Acoustic Doppler Current Profiler (ADCP) fixed near the bottom during two tidal cycles (Figure 1).

The model accuracy in reproducing local sea surface temperature (SST) patterns was also quantified and analyzed, comparing predicted SST horizontal fields with remotely sensed images for July 2005 and January 2013. These were obtained from the Moderate-resolution Imaging Spectroradiometer (MODIS) L2 products (oceancolor.gsfc.nasa.gov/). For the spatial comparison, model data was interpolated to the satellite grid (1 km) using a linear interpolation.

RESULTS

Table 1 shows the SSE RMSE, ΔError relative to the local mean amplitude and skill calculated for the stations shown in Figure 1. In general, it was found an adequate fit between model predictions and observations, revealing the ability of the model to accurately reproduce *in-situ* data. RMSE values range from 4 cm to 8 cm for Ria de Muros (RB3) and Ria de Aveiro (RA), respectively. The average RMSE is 6 cm. Considering the ΔError, values range from 1.7% to 4.0%, showing an excellent agreement between predictions and observations following the classification proposed in Dias *et al*. (2009). Predictive skills are close to 1 for all stations.

Table 1. *RMSE (m), ΔError (%) and Skill values for the stations shown in Figure 1.*

Station	RMSE (m)	ΔError (%)	Skill
RA	0.079	3.95	0.997
D	0.062	2.49	0.999
L	0.056	3.26	0.998
M	0.058	3.20	0.999
RB1	0.049	2.08	0.992
RB2	0.045	1.70	0.999
RB3	0.040	1.77	0.999

The tide is semi-diurnal with low diurnal inequality, with average form number of about 0.07. For the M_2 constituent, ranges from 1 cm at Ria de Aveiro and Rias Baixas to 8 cm at Lima estuary whose amplitudes are the largest, the difference between datasets. The results show that M_2 amplitude decreases northwards while its phase increases, in agreement with Quaresma and Pichon (2013) results. The most significant phase difference is about 2.3° in Rias Baixas. The mean amplitude difference for the principal solar semi-diurnal constituent (S_2) is ~1 cm, whereas the mean phase lag is ~5 minutes. For K_1 and O_1 constituents, the amplitude and phase agreement are good for all stations (about 1 cm for amplitude and 15° for phase).

Figure 3 shows predicted and observed salinity and water temperature for some stations located at the estuaries mouths (RA, D and M, Figure 1). These variables are strongly influenced by freshwater discharges and the validation of the salt and heat transport model becomes a challenging issue. Comparison between predicted and observed water temperature shows that heat transport is well represented in Ria de Aveiro and Douro stations, with differences around 0.5°C. For salinity, the differences are higher compared to the water temperature. Nevertheless, the highest discrepancies between model predictions and measurements are observed in Minho station (4.5 and 1.5°C for salinity and water temperature, respectively).

Figure 4 compares SST patterns obtained from predictions and satellite imagery data on 31 July 2005 and 4 January 2013. These days were chosen as representative of summer and winter seasons. A good agreement between predicted and satellite SST product is observed, with both patterns showing the expected main features of the water temperature field in the NWIP coast, which is characterized by higher temperatures offshore decreasing landward.

Table 2. *Harmonic analysis results comparison between observed and predicted SSE data for RA, D, M, L, RB1, RB2 and RB3 stations.*

Station		M_2 Amplitude (m)	M_2 Phase (°)	S_2 Amplitude (m)	S_2 Phase (°)	O_1 Amplitude (m)	O_1 Phase (°)	K_1 Amplitude (m)	K_1 Phase (°)
RA	Data	0.95	78.88	0.36	100.45	0.05	315.35	0.06	44.75
	Model	0.96	79.87	0.36	97.09	0.05	318.80	0.06	52.28
D	Data	1.04	75.34	0.45	93.63	0.06	320.38	0.06	44.08
	Model	1.08	74.16	0.47	89.85	0.06	320.89	0.06	49.67
L	Data	1.00	76.59	0.50	114.32	0.07	320.25	0.06	73.90
	Model	1.08	75.48	0.50	111.65	0.06	321.48	0.06	77.11
M	Data	0.98	84.88	0.43	122.96	0.05	323.35	0.05	64.63
	Model	0.99	83.04	0.45	115.52	0.06	328.88	0.05	80.33
RB1	Data	1.13	75.45	0.43	97.53	0.06	330.38	0.04	16.09
	Model	1.12	77.74	0.44	95.65	0.06	322.44	0.06	48.50
RB2	Data	1.12	76.45	0.43	98.69	0.06	331.98	0.05	26.66
	Model	1.13	78.29	0.44	96.31	0.06	322.83	0.06	49.17
RB3	Data	1.16	78.26	0.44	100.29	0.06	331.44	0.05	32.80
	Model	1.15	79.15	0.45	97.35	0.06	323.01	0.06	49.85

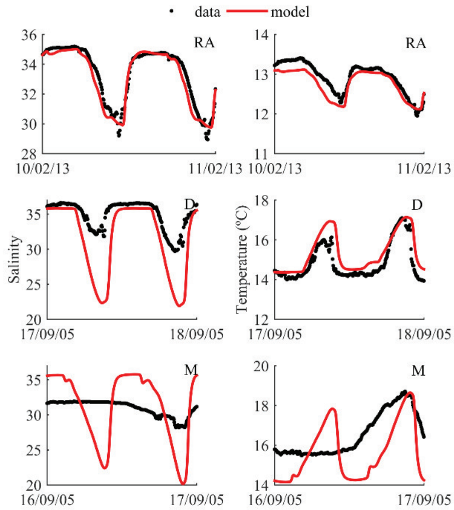

Figure 3. Observed and predicted salinity and water temperature time series for Ria de Aveiro, Douro and Minho stations.

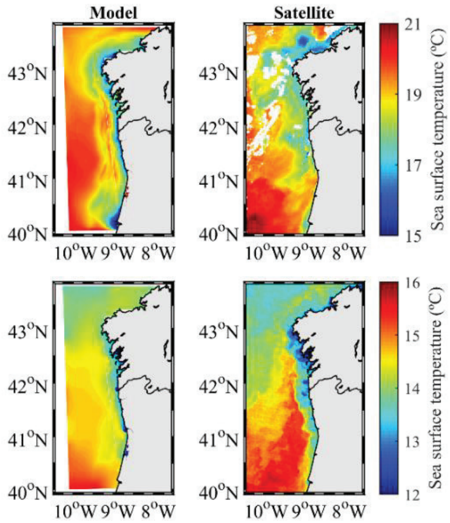

Figure 4. Sea surface temperature obtained from model predictions and satellite imagery on 31 July 2005 (upper panel) and 4 January 2013 (lower panel).

For 31 July 2005, there is a satisfactory agreement pattern between observations and predictions, although the adjustment tends to decrease offshore and at the south of Ria de Aveiro (Figure 4, upper panel). An upwelling phenomenon is observed in model predictions between the Ria de Aveiro Lagoon and the Rias Baixas, where colder waters emerge from deeper. This feature is also observed in satellite images, with smaller offshore extension and lower magnitude to the south of Ria de Aveiro (-2 °C). For 4 January 2013, predicted and measured SST show a meridional gradient, characterized by high temperatures (15-16 °C) at the south decreasing northward. Moreover, the estuarine plumes can be identified in both model predictions and satellite imagery, through the cold water mass (13 − 14 °C) along the NWIP coast. The predictions of the plume propagation were found excellent and the SST deviation in the northward coastal band does not exceed 1°C. The RMSE and skill were also computed to quantify the difference between datasets. A RMSE of 0.36 °C and 0.45 °C was found for summer and winter periods, respectively, as well as and an average skill of 0.7 in both seasons.

DISCUSSION

The analysis of Tables 1 and 2 reveals that the model reproduces the hydrodynamic behavior of the study area. The RMSE and predictive skill values obtained are very similar to those obtained in previous numerical modelling works (Vale and Dias, 2011; Mendes *et al*., 2013; Sousa *et al*., 2014; Lopes and Dias, 2015) showing that the estuaries hydrodynamic models accuracy is excellent. Harmonic analysis results show that phase and amplitude of major tidal constituents are also well reproduced by the estuarine models. The best model predictions were found for the stations located on the Rias Baixas, with amplitude errors of 2 cm for both semidiurnal constituents. Both in amplitude and phase, the highest differences between model predictions and observed data correspond to Lima and Minho estuaries. Amplitude and phase differences for the semi-diurnal and diurnal constituents are lower than those achieved by Sousa *et al*. (2014), revealing the importance of refining the model spatial resolution.

Considering the water temperature, a good agreement between predicted and observed data is achieved, revealing a fair representation of the water temperature time evolution and amplitude variation, except at Minho station where the RMSE value is 1.56 °C (~10% of the mean water temperature value). Both water temperature and salinity data only represent the second tidal cycle (Figure 3). The *in-situ* data do not reproduce the variability of the thermohaline properties, which can be explained by a malfunction of the ADCP instrument. At Ria de Aveiro station, the results for salinity are better than those achieved by Tomas *et al*. (2014), that obtained a RMSE of about 4. For Douro station a RMSE of about 18% of the mean salinity value was obtained, despite data and salinity predictions presented a similar trend. This discrepancy is due to inaccuracies in the freshwater discharge imposed in the land boundary of the model. Nevertheless, this result is in line with those obtained by Azevedo *et al*. (2010).

The model adequately reproduced the SST patterns over the NWIP coast both for summer and winter seasons, especially close to the mouths of the estuaries (Figure 4). Results are similar to those obtained in previous numerical modelling works (Mateus *et al*., 2012; Marta-Almeida *et al*., 2012), revealing that the fully integrated estuarine and coastal high-resolution model reproduces adequately the coastal wind-forced circulation. However, the model tends to underestimate SST, with a maximum difference of 0.5 C (offshore) between observations and predictions. This temperature difference can derive from an inappropriate atmospheric forcing prescription leading to some limitations in simulating the wind field near the coast, in agreement with findings by Vaz *et al*. (2015) in their study about Tagus estuary-coastal interaction. Nevertheless, it is necessary to keep in mind that the satellite SST products have an error induced by the algorithm used to derive the bulk temperature from water leaving radiances. The products for the two days analyzed have a standard deviation of about 0.35ºC, which could be significantly higher for data close to the coastal line. Considering that differences between model predictions and MODIS data have the same order of the magnitude of the standard deviation of satellite product, it is reasonable to assume that the model simulates adequately the thermodynamics of the top sea layer.

CONCLUSIONS

The results obtained in this study reveal that the integrated high-resolution model for the NWIP coast and main estuarine systems was successfully implemented. An excellent agreement between predicted and measured SSE was accomplished, revealing that the numerical model accurately reproduces the tidal propagation inside the estuaries. Salinity and water temperature was evaluated against *in-situ* and remote sensing data. The model accurately predicts horizontal and vertical local structures of water temperature and salinity, showing its high ability in reproducing the heat and salt transport over the shelf and the main estuarine systems of NWIP coast.

In summary, this implementation proves to be a useful and suitable tool to perform future studies about essential aspects of local circulation and extreme phenomena as well as climate change impact in this coastal region and the referred estuarine systems in a fully integrated way.

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