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Coupling watersheds, estuaries and regional ocean through numerical modelling for Western Iberia: a novel methodology

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Abstract An original methodology for integrating the water cycle from the rain water to the open ocean by numerical models was set up using an offline coupling technique. The different components of the water continuum, including watersheds, estuaries and ocean, for Western Iberia were reproduced using numerical components of the MOHID Water Modelling System (http://www.mohid.com). This set of models, when combined through this novel methodology, is able to fill information gaps, and to include, in a realistic mode, the fresh water inputs in terms of volume and composition, into a regional ocean model. The designed methodology is illustrated using the Tagus River, estuary and its region of fresh water influence as case study, and its performance is evaluated by means of river flow and salinity observations.

Keywords Western Iberia · Numerical modelling · MOHID · Watershed · River · Estuary · PCOMS · Tagus · ROFI · Regional ocean model · Offline coupling

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1 Introduction

River discharges exert a strong influence in their neighbouring coastal areas in many ways including the modification of water stratification Garvine and Whitney (2006), the introduction of significant fluctuations in circulation patterns and the modulation of upwelling events impact (Santos et al. 2007; Banas et al. 2009). They induce convergent areas near their discharge area, regulate the alongshore transport and exchange properties with the outer shelf while generating nutrient rich areas that provide food for fish larvae (Ribeiro et al. 2005; Santos et al. 2007).

Despite their importance, the incorporation of river and estuarine fluxes into regional ocean numerical models has been generally disregarded. One of the main reasons for this omission is the inherent difficulty of including the temporal variability associated to the estuarine inputs. This variability is related to several factors including, among others, the seasonal and interannual change in fresh water volume and its associated properties reaching the estuaries, the occurrence of drastic episodic events (i.e. droughts and floods), the fresh water mixing and the water properties evolution along the estuary subjected to the tidal cycle with residence times and tidal prisms specific for each estuary.

In recent times, due to an increase in the numerical modelling capacities and the need of operational forecast models with high accuracy in coastal areas, efforts have been made to include river discharges into the regional and coastal models. This subject is still an open subject of research, due to the number of existing uncertainties.

Starting at the watershed level, the river runoff reaching the coastal area is unavailable or unmonitored for many rivers. Nowadays, this is an increasing problem due to the global decline of the hydrometric networks (Mishra and

Coulibaly, 2009). For this reason, river climatologies are generally imposed as land boundary conditions in coastal or regional ocean models - thus ignoring the river variability in flow and properties. Moreover, for small rivers or poorly studied rivers, building a river climatology could also be regarded as a challenge.

Downstream, the method for including riverine inputs, regarding the complex and singularity of estuarine dynamics, into coarse regional ocean models, generally with horizontal grid resolution of km's, has been issued in several ways. For areas with a low tidal signal, i.e. the Mediterranean Sea, direct river discharge of volume and water properties could be regarded as a reasonable approximation (Estournel et al. 1997). However, for areas with a significant tidal signal, this approach is not realistic enough to represent the coastal processes and more complex solutions are needed. Herzfeld (2015) summarised some of the most typical methods to include river inputs into regional ocean models. In the horizontal plane, the most common methods are the following: the simple inlet method, consisting in making a "rectangular breach in the coastal wall with uniform inflow water properties, including density and discharge velocity" (Garvine and Whitney, 2006) and the point source method consisting in the addition of a volume flux of zero salinity water directly into one or more layers (Schiller and Kourafalou, 2010). Another common practice consists in adding fresh water discharges into non-realistic channels to induce an initial mixing (Lacroix et al. 2004). A more sophisticated method consists in including the desired estuary in the regional model domain. The latter approach tries to reproduce the estuary volume, bathymetry and dynamics by using refined grids on the estuarine and adjacent coast area. This approach seems to be adequate to study the Region of Freshwater Influence (ROFI) of isolated rivers (i.e. Banas et al. (2009) and Liu et al. (2009) for the Columbia River). Another subject of research is the vertical distribution of the river discharge. Herzfeld (2015) proposed a dynamic adjustment in order to obtain more realistic inputs in the coastal area.

In this paper, we present a novel numerical modelling methodology to include, in a realistic mode, the fresh water inputs, in terms of volume and water properties, from the rain water to its incorporation into a regional ocean model. The different interfaces encountered by the runoff water from the watersheds to the open ocean were reproduced using the different components of the MOHID Water Modelling System (http://www.mohid.com; Neves, 2013). The employed methodology is illustrated using the Tagus River, estuary and ROFI as a case study. The obtained modelling results were compared with in situ observations and with a state-of-the-art regional ocean model for the same study area.

1.1 Study area

The largest rivers of the Iberian Peninsula, with the exception of the Ebro River, discharge on the Atlantic coast draining on its way almost two-thirds of the territory. In Portugal, river mouths concentrate in the northern part of the territory (Fig. 1) while the Tagus River, the largest river of Iberia, reaches the coast almost isolated. Additionally, northern rivers present higher flows related to a latitudinal rain gradient, with mean annual precipitation values around 3000 mm in the Northwest of Portugal and below 1000 mm on the southern half of the territory (Portuguese Water Atlas, http://geo.snirh.pt/AtlasAgua/). Due to the scope of the present work, the methodology is applied focusing in the Tagus River, estuary and its adjacent area.

The Tagus River, 1000 km long, is the longest river of the Iberian Peninsula draining an area around 80,000 km^2, with 55,000 and 25,000 km^2 located in Spain and Portugal territory respectively. Its estuary, 320 km^2 wide, is the largest in Portugal and one of the largest in Europe (Fig. 2). The estuary area is inhabited by a population around 2.5 million, almost a quarter the overall Portugal population. Morphologically, the estuary can be divided in three main areas, a straight, narrow channel of 16 km long and 2 km wide with W-E orientation and maximum depths around 45 m; an inner bay 25 km long and 15 km wide oriented SW-NE with depths comprised between 5 and 10 m and the upper shallow estuary about 100 km^2 wide encompassing large mudflats and salt marshes separated by shallow channels. The Tagus River is the main source of fresh water in the estuary with flows typically varies between 50 and 2000 m^3 s^{-1}, although is affected by human activities and management (i.e. dams, agriculture, etc). The Sorraia and Trancão rivers, with mean river flow of 39 and 6 m^3 s^{-1} respectively, are other minor fresh water contributors to the estuary.

From the hydrodynamic point of view, the Tagus estuary is a semi-diurnal mesotidal estuary with tidal ranges varying from 1 m during neap tides up to almost 4 m during spring tides. The tide propagates up to almost 80 km landward from Lisbon, and the mean residence time of the estuary is around 25 days (Braunschweig et al. 2003). The combined effects of low average depth, strong tidal currents and low input of river water classify the Tagus estuary as a globally well-mixed estuary, with significant stratification only occurring during high river discharge periods.

2 Materials and methods

2.1 Numerical models

In order to reproduce the water continuum for the Portuguese coastal area, from the precipitation areas until its evacuation in

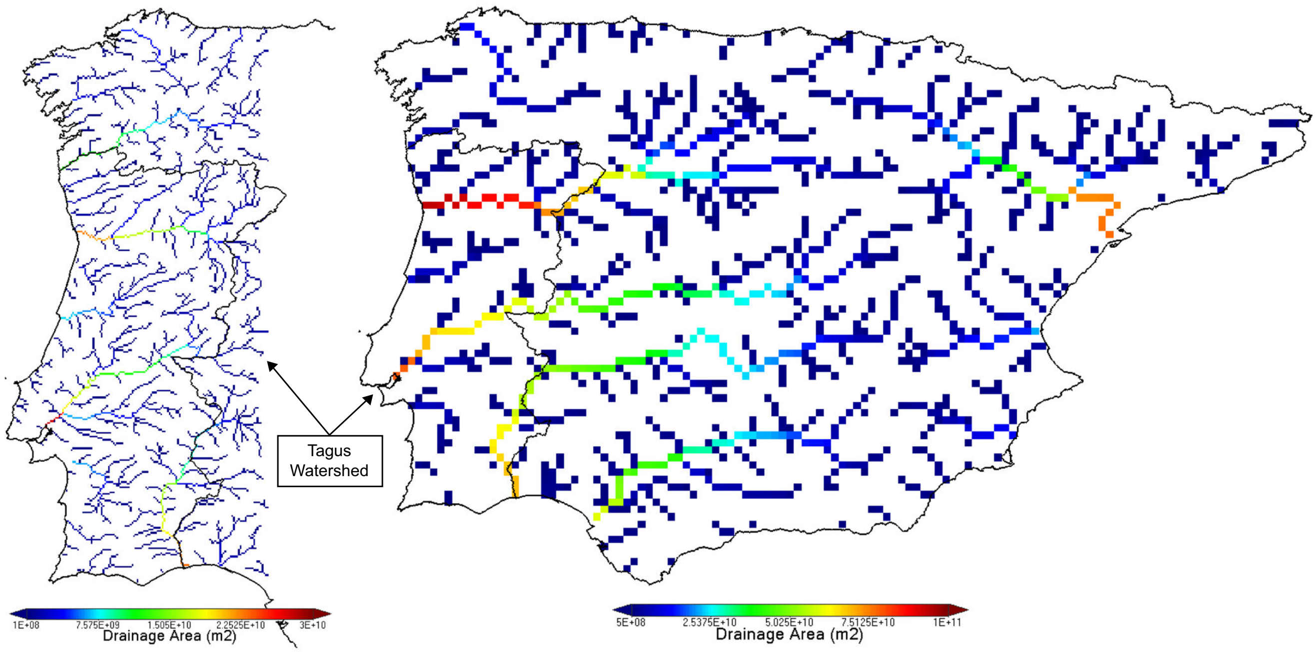

Fig. 1 Accumulated drainage area for the main water lines in the Western Iberian Peninsula (WI model domain, *left*) and in the Iberian Peninsula (IP model domain, *right*). Drainage networks were obtained with the MOHID Land model using 2 and 10 km horizontal resolution respectively

the open ocean, a system of coupled numerical models was designed to include the different temporal and spatial scales. Each system element—river catchment, estuary and open ocean was simulated through numerical models using the different components of the MOHID Water Modelling System (http://www.mohid.com; Neves, 2013).

The MOHID Water Modelling System is an open source modular finite volumes modelling system written in ANSI FORTRAN 95 using an object oriented programming philosophy integrating several numerical programs and supported by graphical user interfaces that manage all the pre- and post-processing operations. The core numerical models are MOHID Water and MOHID Land.

The MOHID Land model is a 3D distributed, continuous, physically based, variable time step model using a finite volume approach based on mass and momentum balance equations for land areas (e.g. watersheds, agriculture plots and urban areas). The simulated processes include water and property transport in porous media, river runoff, erosion, evapotranspiration and vegetation growth and water quality

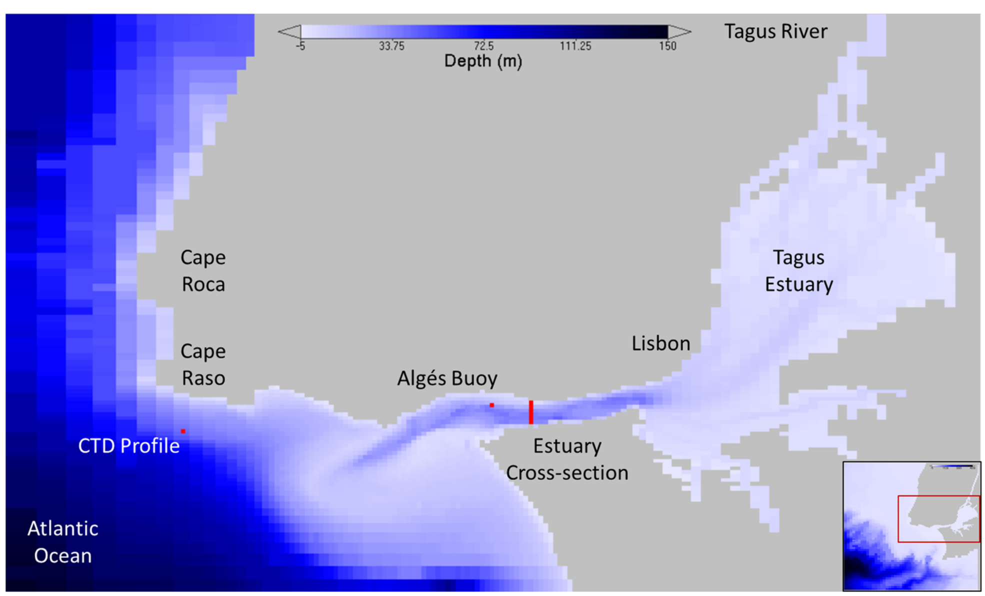

Fig. 2 Detail of the TagusMouth model bathymetry, full modelling domain in the box, where it can be identified the Tagus River discharge area, its estuary and the channel connecting to the adjacent coastal area. The *map* also indicates the locations of the Algés buoy, the CTD campaign and the latitudinal cross-section where the estuarine fluxes are calculated

processes, i.e. mineralization, nitrification, denitrification in porous media and rivers. The MOHID Water model is a 3D integrated model, capable of simulating a wide range of processes (e.g. hydrodynamics, transport, water quality and oil spills) in surface water bodies (oceans, coastal areas, estuaries and reservoirs).

At the watershed level, the MOHID Land model (Brito et al. 2015) estimates operationally water flow and associated properties (i.e. temperature, oxygen and nutrient concentrations) for the main river catchments discharging in the Western Iberian coast. Two domains with different horizontal resolution, 2 km for the West Iberia region (WI domain) and 10 km for the Iberian Peninsula (IP domain), were designed to represent adequately the Portuguese catchments and to include the spatial scale of the large trans-boundary rivers as the Tagus, Douro and Guadiana rivers (Fig. 1). Both domains were populated with topographic data from the NASA digital terrain elevation database and land use data from the Corine Land Cover 2006 – CLC2006 (EEA, 2007). Waterproofing and manning resistance were defined following van der Sande et al. (2003) and Chow (1959) suggested correspondences. Soil map distribution and hydraulic characteristics, necessary to estimate the van Genuchten model parameters, were obtained from the Joint Research Centre database (http://eusoils.jrc.ec.europa.eu/).

Currently, the watershed model applications disregard the effects of human consumption, water reservoirs or dam management that could modify the amount and timing of the water reaching the coastal zone. Methods to correct those effects are planned to be implemented in future versions of the model.

Downstream, several operational estuarine applications impose the watershed modelling results as land boundary conditions. In the case of the Portuguese estuaries, this type of input is used in the absence of automatic monitoring stations data and to complete the observations with non-monitored variables i.e. temperature, nutrient and oxygen concentrations, etc. The estuarine models are able to simulate the site-specific inner estuary dynamics and their connection with the open ocean waters.

The Tagus estuary and adjacent coast model application (Fig. 2, De Pablo et al. 2013), hereafter referred as TagusMouth, has a variable horizontal resolution ranging from 2 km off the coast up to 250 m in the estuarine mouth region comprised by the range of latitudes (38.16° N, 39.21° N) and longitudes (8.90° W, 10.02° W) resulting in a grid of 120 × 145 cells. The model domain limits and horizontal resolutions allow the model application to simulate accurately the estuarine plume dynamics while covering most of the Tagus ROFI.

As the Tagus River is the main source of fresh water in the estuary, its forcing can be considered as the main source of salinity variability. The closest river flow monitoring station to the Tagus estuary is the Almourol station (39.22° N, 8.67° W), located 70 km off the head of the estuary and part of the Portuguese river hydrometric observation network (http://snirh.pt). In the present study, four Tagus River forcing scenarios will be evaluated in the TagusMouth application: daily averaged river flows from the hydrometric station (Almourol Scenario), a monthly climatology built using several years of flow observations for that same station (Climatology Scenario), river flow calculated by the MOHID Land watershed model for the Iberian Peninsula (MOHIDLand_IP Scenario) and Western Iberia model domains (MOHIDLand_WI Scenario). Other minor sources of fresh water discharging in the estuary, i.e. Sorraia and Trancão rivers, were included using climatological flow values for all the modelling scenarios.

The Portuguese Coast Operational Modelling System (hereafter referred as PCOMS; Mateus et al. 2012) is the regional ocean model application and is composed of two nested domains: the West Iberia (2D) and the Portugal (3D) domains covering the Iberian Atlantic coast and its contiguous ocean. Both domains present a constant horizontal resolution of 0.06° (≈ 5.2 km) populated with bathymetric information derived from the EMODnet Hydrography portal (http://www.emodnet-hydrography.eu). The West Iberia domain covers the area limited the following range of latitudes (33.48° N, 45.90° N) and longitudes (4.20° W, 13.50° W) resulting in a grid of 207 × 155 cells with maximum depths reaching 5600 m. The Portugal domain covers the area comprised by the latitudes (34.38° N, 45.00° N) and the longitudes (5.10° W, 12.60° W) resulting in a grid of 177 × 125 cells and maximum depths around 5300 m. The Portugal domain is located centred in the West Iberia domain, leaving 15 cells of difference in every direction, that downscales the Mercator-Océan PSY2V4 North Atlantic solution (Drillet et al. 2005) (Fig. 3). Tides are forced along the ocean boundary of the West Iberia (2D) model domain, using the global tide solution FES2004 (Lyard et al. 2006). Hereafter, the 3D Portugal model domain would be referred as PCOMS.

The PCOMS and the Tagus Mouth model applications are fully 3D baroclinic–hydrodynamic and ecological model applications operated by the MOHID Water model. They share a common vertical discretisation consisting on a mixed vertical geometry composed of a sigma domain with seven layers from the surface until 8.68 m depth, with variable thickness decreasing up to 1 m at the surface, on top of a Cartesian domain of 43 layers with thickness increasing towards the bottom. The TagusMouth model application receives open ocean boundary conditions from a PCOMS version without river inputs as described in Campuzano et al. (2012).

Each component of this set of models was forced with the higher horizontal resolution meteorological model available for its domain. Meteorological model applications provide 3D fields that include relevant model forcing variables (i.e. precipitation, solar radiation, wind modulus and direction,

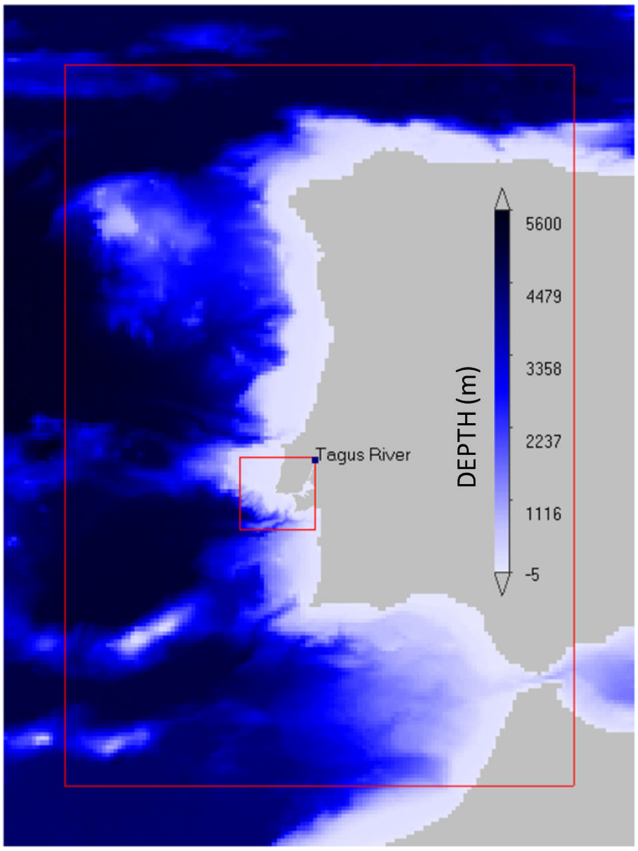

Fig. 3 Bathymetry of the PCOMS regional ocean operational system and TagusMouth domains. The full domain correspond to the 2D West Iberian domain while the *outer box* indicates the 3D Portugal domain limits and the *inner box* indicates the TagusMouth domain limits

relative humidity, air temperature, etc.) and whose surface layer is interpolated for each modelling domain by triangulation. The MOHID Land IP domain, was forced using WRF model results (Skamarock et al. 2005) with 12 km horizontal resolution generated by Meteogalicia (http://www.meteogalicia.es). The MOHID Land WI and the MOHID Water PCOMS domains used, as atmospheric boundary conditions, MM5 modelling results (Grell et al. 1994) with a horizontal resolution of 9 km provided by the IST meteorological group. The TagusMouth MOHID Water application was forced using 3 km horizontal resolution WRF model results also provided by the IST meteorological group (http://meteo.tecnico.ulisboa.pt/; Trancoso, 2012).

To evaluate the presented methodology, the regional ocean model would be compared with results from a state-of-the-art regional model covering the study area: the operational IBI (Iberian Biscay Irish) Ocean Analysis and Forecasting system (hereafter referred as CMEMS-IBI; http://marine.copernicus.eu/). This is the regional ocean model of the European Commission Copernicus Programme based on a NEMO model application run at 0.028° (≈ 2.40 km) horizontal resolution and operated by Puertos del Estado and Mercator-Océan that includes high frequency processes (i.e. tidal forcing, surges and high frequency atmospheric forcing, fresh water river discharge, etc.). The CMEMS-IBI model application includes the Tagus estuary with an inlet in their domain that simulates the estuary morphology.

2.2 Coupling the Estuary-Ocean Interface

In order to include the estuarine fluxes into a regional ocean model with coarser horizontal resolution, a novel methodology was designed. Flow time series (positive during ebb conditions and negative during flood conditions) and properties concentration (i.e. temperature and salinity) are extracted for each cell of a defined 2D cross-section. For the TagusMouth case study, a meridional cross-section was defined in the estuarine channel (Fig. 2). The vertical correspondence between the PCOMS and the TagusMouth model grids allows to add directly each estuarine layer fluxes in the corresponding layer of the PCOMS domain providing the implementation of an effective off-line 2D boundary condition.

Figure 4 represents schematically the fluxes' calculation performed in the estuarine model application, that are later imposed in estuary-ocean interface. H, in the diagram, represents the constant bathymetric depth for a horizontal cell related to the hydrographic zero while $h_{t.}$ corresponds to the free surface that varies in time mainly due to the atmospheric and astronomic tides. h'_{t} is the sum of both the permanent and the variable heights that is decomposed in several layers according to the vertical geometry of the model. Thus, each cell vertical dimension $h_{a,\mathrm{t}}$ (a representing the number of the vertical layer) would evolve in time while the cell horizontal dimensions (δx and δy) are constant. With these values, the instantaneous volume for each cell ($V_{a,\mathrm{t}}$) can be obtained, and by multiplying it with the cross-section velocity, the corresponding instantaneous flow ($F_{a,\mathrm{t}}$) would be obtained. The flow value has positive sign during ebb periods and negative during flood periods. The instantaneous concentration ($\mathrm{Ce}_{a,\mathrm{t,i}}$) for any water property i (i.e. temperature, salinity, nutrients, etc.) associated to the instantaneous flow corresponds to the estuarine value calculated by the model at each cell centre.

The MOHID Water model allows to input positive and negative flows, and by following this approach, the tidal intermittent fluxes coming from the estuarine models can be included into the regional ocean model. This methodology could be applied to 2D or 3D estuarine models. Currently, it is implemented in an offline delayed mode by obtaining a set of time series that are independent from the receiving model. This approach also allows to calculate the estuarine fluxes from previous modelling results and to couple several operational estuarine models with different time steps to a single regional ocean model. Additionally, this method would allow to provide land boundary conditions to other regional ocean models simulating the same study area. In future versions of the application, this methodology could be implemented in an

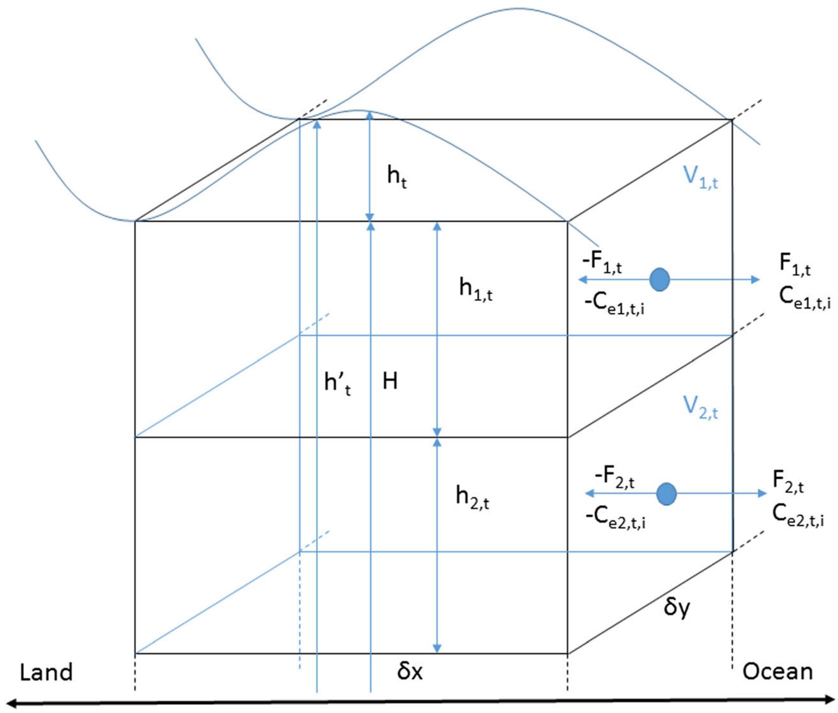

Fig. 4 Diagram representing the flow and concentration calculations performed in the estuary model cross-section cells that is imposed as land boundary conditions in the regional ocean model. δx and δy correspond to the cell horizontal dimensions while the cell horizontal dimensions while H corresponds to the constant depth for each cell. $h_{t.}$ corresponds to the instantaneous value of the free surface that varies in time and h'_t is total depth that is decomposed in several layers $h_{a,t}$ (a representing the number of the vertical layer from top to bottom) according to the vertical geometry of the model. $V_{a,t}$ is the instantaneous volume that multiplied by the instantaneous velocity provides each cell instantaneous flow ($F_{a,t}$). $Ce_{a,t,i}$ stands for the estuarine concentration for each water property i (i.e. temperature, salinity)

online coupled mode by using the Open Modelling Interface framework (OpenMI) as was previously done in other MOHID model applications (i.e. Pina et al. 2015).

2.3 Operational modelling

This set of numerical models is integrated and synchronised through the Automatic Running Tool (ART) software, a software for the automation of model simulations developed at IST that is currently used by many operational applications (Ascione Kenov et al. 2014; Brito et al. 2015). The ART tool is a standalone application, independent, compiled and able to run in any Windows operative system. This tool can be seen as the "heart" of an operational framework, controlling the execution of other auxiliary standalone applications or even scripts (e.g. conversion of file formats, interpolation and specific downloading procedures), and adapting automatically the configuration files and launching those applications (Fig. 5). The ART tool pre-processes the boundary conditions from different sources needed to run the model; executes the MOHID Water and Land model applications using the configured files, and coordinates the sequence described in this study. After each estuarine model has finished, it executes the River Out software. A software designed specifically to extract and calculate the fluxes and concentrations (as described above) for all the cells comprised between two defined coordinates and to store them in an organised manner. Those fluxes are latter accessed by the ART software controlling the PCOMS regional model and incorporated through pre-configured files. The operational tool finally stores, graphs and distributes the model results via OPeNDAP, ftp, smartphone and webpages during the post-processor operations. This software can either be used to automatise real time nowcast/forecast solutions, hindcast scenarios or mixed solutions (hindcast + nowcast + forecast).

3 Results and discussion

River flow was used as indicator to evaluate the performance of the watershed model applications while salinity concentrations was the selected indicator for the estuarine and regional ocean model applications. An additional difficulty to validate the proposed methodology is the scarcity of continuous salinity observations in the estuarine and coastal areas that

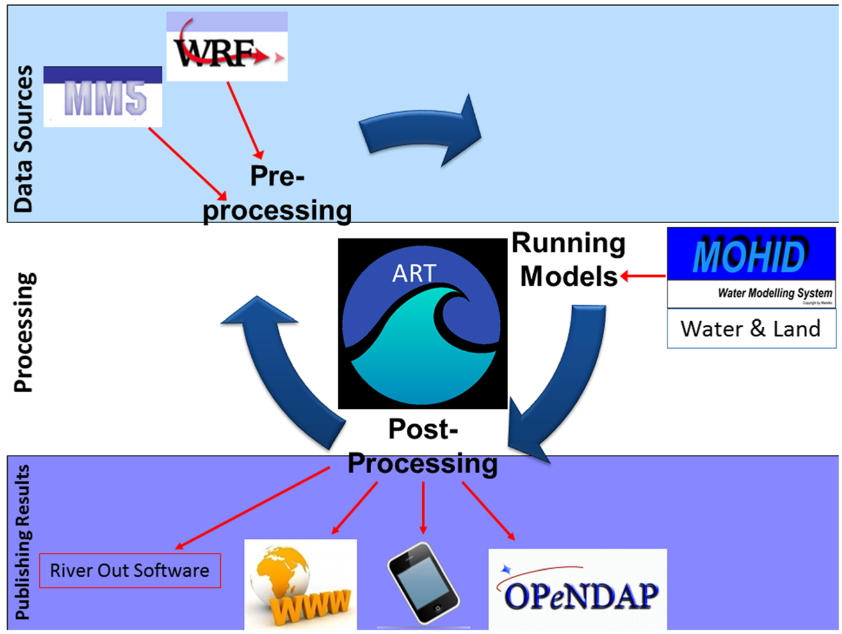

Fig. 5 General scheme of the Automatic Running Tool (ART) where it can be distinguished the pre-processing, modelling and post-processing cycle of operations including only the elements used for the MOHID Land and MOHID Water applications used in this work. The River Out software is executed during the post-processing operations of the estuarine model application

currently cannot be compensated by satellite imagery for these resolutions.

3.1 Watershed modelling

In order to provide an insight of the advantages of using watershed modelling, the Tagus River modelling results obtained with the MOHID Land IP and WI domains were compared with the streamflow measured by the Almourol hydrometric station and with the climatology derived from the same station data (Fig. 6). Both model domains show a good agreement in terms of flow and peak timing, though it can be observed that following dry periods the model overpredicts flow values. That effect could be related to watershed management through dams' retention, irrigation, human consumption, etc. On the other hand, the main weakness of river climatologies is its incapacity to include the interannual variability compared to model applications that are in agreement with the main trends. Statistically, the coefficient of determination (R^2) between the observed data with the IP domain, the WI domain and the climatology, for the period 2011–2013, is 0.59, 0.34 and 0.06 respectively. The coefficient of determination for the model applications are of the same range of magnitude to similar studies i.e. Yang et al. (2014) obtained R^2 around 0.6 for three watersheds with drainage area between 30 and 300 km^2. That area is much smaller than the 25,000 and 80,000 km^2 area drained for the Tagus River by the MOHID Land WI and IP model applications respectively. Please refer

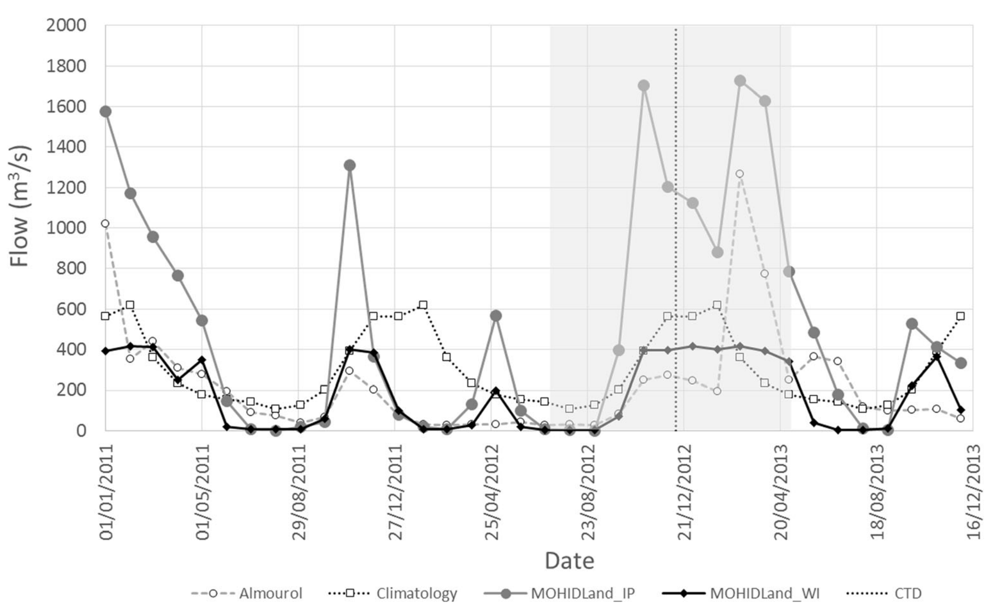

Fig. 6 Monthly averaged Tagus River flow for the period 2011–2013 observed by the Almourol hydrometric station (*white circle marks* and *dashed line*), river climatology (*white square marks* and *dotted line*) and obtained with the MOHID Land IP (*grey circle marks* and *solid line*) and WI (*black diamond marks* and *solid line*) model domains. The *grey area* corresponds to the period monitored by the Algés coastal buoy. The *vertical dotted line* indicates the date when the CTD campaign took place

to Brito et al. (2015) for a broader description of the watershed modelling results.

3.2 Estuarine modelling

To evaluate the effect of the Tagus River forcing in the TagusMouth estuarine application, the period from 1 October 2012 to 30 April 2013 was simulated using as boundary conditions the four defined scenarios: Almourol, Climatology, MOHID Land_IP and MOHID Land_WI (Fig. 6). The simulation period was selected due to the availability of a continuous salinity record measured by a monitoring buoy in Algés (38.694° N, 9.237° W) deployed by the SimTejo water utility (Fig. 2), hereafter referred as Algés buoy. The Algés buoy due to its location, in the vicinity of the estuarine mouth, was able to record the salinity concentration in the estuary–ocean interface during the simulation period.

Figure 7 represents the mean daily salinity values observed by the Algés buoy, located at the estuarine mouth, along with the salinity values in the corresponding model domain cell for each TagusMouth modelling scenario. In April 2013, the Algés buoy was able to observe the effect of an extreme rain event in the salinity values with salinity concentrations reaching values under 10. Modelling results obtained using the Almourol Scenario, thus the most realistic scenario, were able to adequately reproduce that event which allow us to gain confidence in the TagusMouth model application. This scenario shows a high correspondence in time and magnitude in the whole simulated period and indicates that the TagusMouth model setup and parameterisations are able to represent adequately the Tagus estuary dynamics and, therefore, can serve to quantify the output fluxes. The coefficient of determination (R^2) between the Algés buoy observations and the Almourol modelling scenario for the modelled period was 0.89 with a root mean square error (RMSE), expressed in salinity units, of 2.55. When the buoy observations are compared with the scenarios using the MOHID Land results, the R^2 and the RMSE are 0.58 and 5.67, respectively, for the IP domain and 0.40 and 4.31, respectively, for the WI domain. The MOHID Land IP scenario, even if generally overestimating the river flow, follows quite well the Tagus River flow general trends and is able to reproduce the peaks associated to extreme events. The MOHID Land WI scenario presents on average a lower error than the IP scenario; however, it is not able to reproduce extreme events thus its correlation is penalised for the analysed period. Finally, the climatology scenario presents the lowest R^2, 0.20, and a RMSE similar to the WI domain, 4.71. Consequently, it could be concluded that the climatology scenario had the worst performance for modelling the estuarine concentrations at the estuary-ocean interface for the modelled period.

3.3 Ocean modelling

Following the methodology described above, the fluxes and concentrations for each of the four TagusMouth modelling

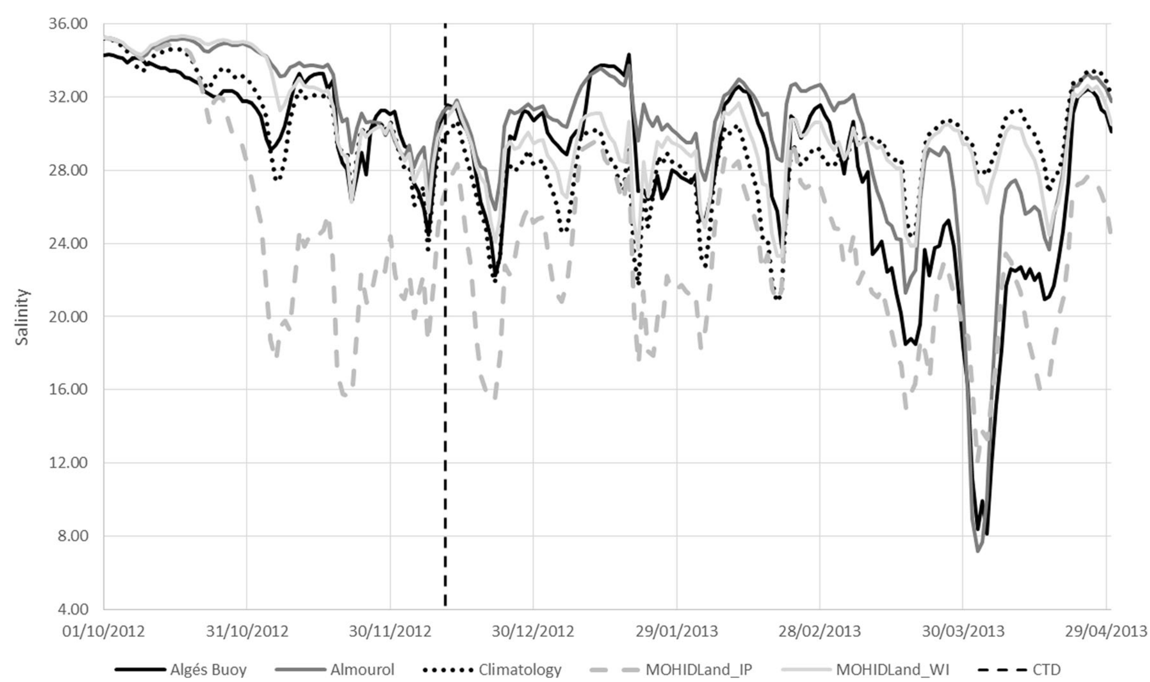

Fig. 7 Salinity values at the location of the Algés monitoring buoy for the simulation period observed by the monitoring buoy (*solid black line*) and modelled by the TagusMouth model application for the four forcing scenarios: Almourol station (*solid dark grey line*), Tagus River climatology (*dotted black line*), MOHIDLand_IP (*dashed light grey line*) and MOHID Land_WI Domain (*solid light grey line*). The *vertical dashed dark line* indicates the date when the CTD campaign was performed

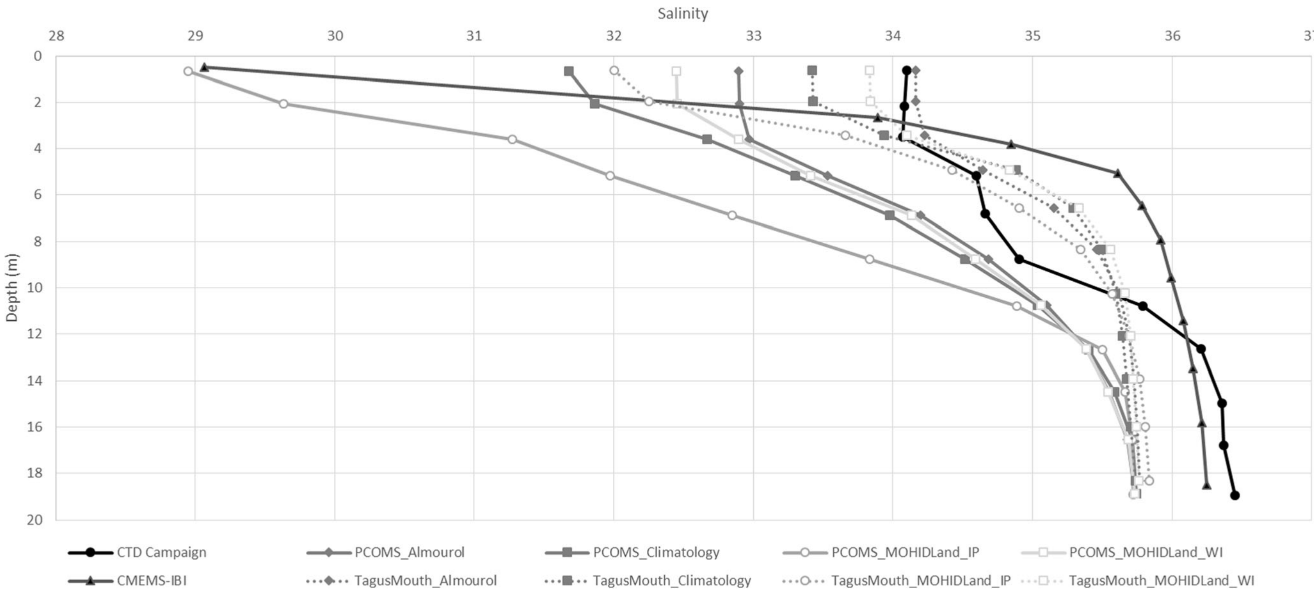

Fig. 8 CTD salinity profile above 20 m depth observed during a coastal campaign on 11 December 2012 at 12 h and the salinity profiles obtained with the four modelling scenarios for the PCOMS and TagusMouth modelling domains and the salinity profile from the CMEMS-IBI model for the same date

scenarios were obtained at the defined meridional cross-section (Fig. 2). Those fluxes were imposed in the corresponding land-ocean boundary cell in an off-line coupled mode with a time step low enough to incorporate the tidal signal. In this study, a fixed time step of 900 s was used. Due to the difference of horizontal resolution between the PCOMS and the TagusMouth grids, both grids at the estuary-ocean interface present different depth values at that boundary cell, and the vertical implementation of the estuarine fluxes was limited to the first 10 m which is the depth of the receiving grid cell.

In order to evaluate the adequateness of this novel technique to represent the ROFI for the Tagus River, modelling results for both the PCOMS and the TagusMouth model applications were evaluated using a salinity profile obtained during a CTD campaign that took place in coastal waters near the estuarine mouth (Fig. 2) during the simulated period (11 December 2012 12 h). Additionally, the salinity profile was also compared with modelling results from CMEMS-IBI model for the same date, along the four modelling scenarios.

To compare the level of agreement between the observations and the modelling results, the salinity result at the closest depth of the modelling levels was selected for the top 20 m (Fig. 8). The salinity profile shows a salt wedge of estuarine water in the top 12 m increasing up to 36 in deeper waters. During that monitoring campaign, a flow under 300 $m^3\ s^{-1}$ was measured in the Tagus River, almost half of the climatological value for that period, while the MOHID Land WI and IP domains calculated river flows around 400 and 1200 $m^3\ s^{-1}$, respectively (Fig. 6). The differences in river flow do not produce a high impact in the salinity values detected at the estuarine mouth with only 1 salinity unit for the Almourol, MOHID Land WI and river climatology scenarios (Fig. 7). That could be due to the volume of the Tagus estuary tidal prism compared to the magnitude of the river flow. However, in the case of the MOHID Land IP scenario, the obtained surface salinity was 26, around 4 units below the other scenarios. The difference in salinity concentrations could influence the extension and vertical distribution of the estuary's plume.

Figure 8 shows the salinity profile of the TagusMouth and PCOMS modelling scenarios and the CMEMS-IBI profile for the same date and time. All the TagusMouth modelling scenarios present higher coefficient of determination than 0.8 and a root mean square error below 1 (Table 1). The Almourol scenario provide the best fit and the smallest error, followed

Table 1 Coefficient of determination (R^2) and Root Mean Square Error (RMSE) between the CTD salinity profile and the salinity profiles obtained for the four PCOMS and TagusMouth modelling scenarios and the CMEMS-IBI model

Model application	Scenario	R^2	RMSE
CMEMS–IBI	–	0.36	1.64
PCOMS	Almourol	0.94	0.87
	Climatology	0.90	1.27
	MOHID Land IP	0.89	2.49
	MOHID Land WI	0.93	1.02
TagusMouth	Almourol	0.86	0.44
	Climatology	0.80	0.56
	MOHID Land IP	0.82	0.93
	MOHID Land WI	0.83	0.49

by the MOHID Land WI scenario. The application forced by the climatology obtained lower correlation though lower error than the MOHID Land IP scenario. As indicated by the validation with the Algés buoy, the MOHID Land IP scenario would be the most adequate forcing for extreme situations which was not the case during this CTD campaign.

In relation with their TagusMouth scenario counterparts, the PCOMS salinity profiles present a slightly higher correlation with the observed data though doubling their RMSE. On the other hand, the CMEMS-IBI model, an application with higher horizontal resolution, but with a different methodology to include the Tagus River, presents the lowest coefficient of determination and an error only surpassed by the MOHID Land IP scenario.

The PCOMS salinity profiles presented slightly lower salinity values than their correspondent profiles for the TagusMouth application (Fig. 8). This numerical effect is due to the horizontal resolution difference between the regional ocean model 0.06° (≈ 5.2 km) and the estuarine model in the coupling area 0.003° (≈ 250 m). The TagusMouth and the PCOMS model applications presented similar surface horizontal distribution in concentration and extension during the CTD monitoring campaign as can be seen, as an example, in Fig. 9 where both models were forced with the Almourol scenario. This image illustrates the Tagus plume heading to the North due to the Coriolis Effect and to the poleward general circulation, typical of the winter circulation regime in this coastal region.

4 Conclusions

By improving the calculation of the fresh water quantity and quality reaching the coastal area, managers and scientists would be able to better reproduce the haline fronts that affect coastal hydrodynamics and the associated ecological processes as the all-year-round low salinity water lens in Northern Portugal, known as Western Iberia Buoyant Plume (WIPB; Peliz et al. 2002). In addition, estimating correctly the land ocean exchange would allow to better understand the nutrient budgets, paths and fate and to evaluate their importance in preserving the ecosystem functions as the fish recruitment variability associated to the river plumes (Santos et al. 2004).

A novel methodology for integrating the water cycle from the rain water to the open ocean by numerical models was set up using an offline coupling technique. The different components of the water continuum, including watersheds, estuaries and regional ocean, were evaluated using the Tagus River, estuary and its associated ROFI as case study. For simplicity, only flow and salinity concentrations were used as quantifiable indicators of the simulations performance for the period between October 2012 and May 2013 when a monitoring buoy was moored at the estuarine mouth and a CTD campaign was performed in the ROFI area.

The watershed applications for the Iberian Peninsula and Western Iberia, described in more detail in Brito et al. (2015), allowed to determine the inland waters contribution to the coastal area, in terms of volume and composition. The main advantages of watershed modelling were to complete the hydrometric monitoring networks providing gapless river flow data and non-monitored variables and to extent their information to non-covered areas. Additionally, watershed numerical modelling allows to forecast river flow and water properties allowing a more efficient management of the modelled systems.

It could be also concluded that even in the case of large and complex watersheds, as the Tagus River, numerical modelling is a useful tool for the estimation of the river contributions to the coastal area. Modelling results have shown that during average conditions the WI modelling domain was able to provide a good estimate of the river flow while during strong

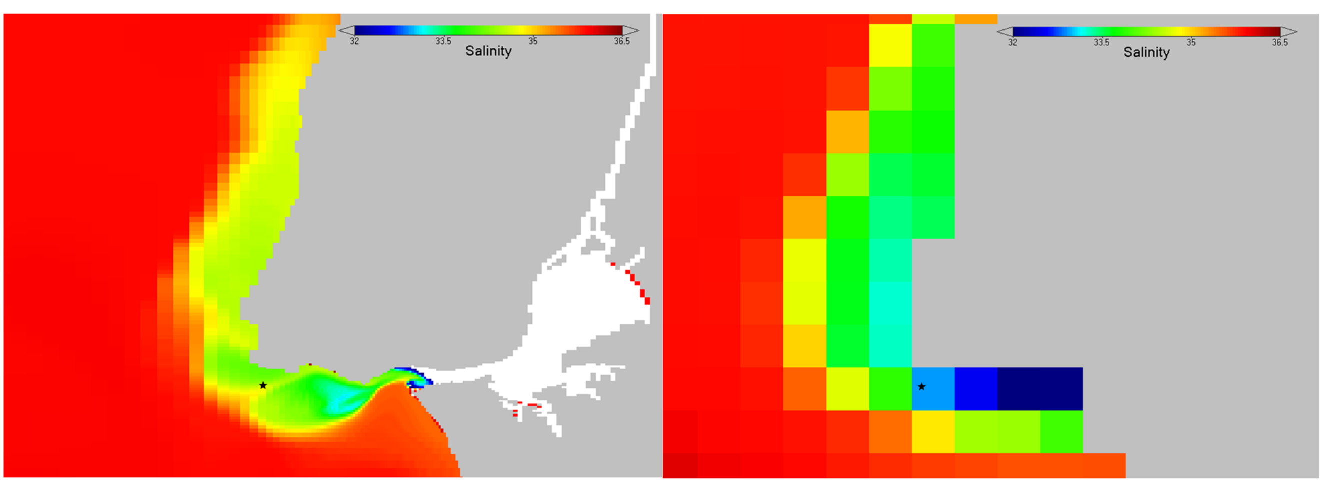

Fig. 9 Surface salinity for the TagusMouth (*left*) and PCOMS (*right*) domains during the coastal campaign on 11 December 2012 at 12 h for the Almourol modelling scenario. Salinity values below 32 are represented in white. The CTD location is also depicted in both images by a star

events the complete catchment fits better the observations. Future work should be done in order to combine both domains to provide the most probable flow, perhaps through the use of artificial neural networks. In any case, the watershed model approach has shown to produce a more realistic land boundary condition than using river climatologies.

At the estuary level, the MOHID Land scenarios performed better than the climatological values when implemented as land boundary conditions and could be regarded as suitable river forcing for areas without hydrometric monitoring stations or to complete time gaps. From the operational point of view, estuarine applications require larger computational time due to the finer horizontal resolution that implies a shorter model time step. By using multiple regular grids and avoiding the inclusion of those high resolution areas embedded in a single ocean regional model, this methodology allows to reduce the regional ocean model computational time and to include several estuaries with adapted horizontal resolutions specific for each estuary, thus, not being limited by the design of an irregular and complex single grid.

The estuarine fluxes from the four modelling scenarios were inserted in the PCOMS ocean regional model using a novel offline methodology that proved to recreate adequately a salinity profile observed during the simulation period. However, due to the large differences in horizontal resolutions between the estuarine and the regional ocean model and the location of the estuarine mouth, confined in a semi-enclosed coastal bay, the salinity dispersion is slightly different in both modelling domains. Improving the regional ocean model horizontal resolution would influence positively the capacity to replicate plume dynamics and concentrations, as was also observed by Herzfeld (2015).

The approach followed in this methodology allows to continuously improve the solution by substituting direct discharges by estuarine fluxes, if an estuarine application becomes available or if a new river monitoring station is installed. However, the time step of the offline estuarine fluxes would be limited by the stored modelling results time step. That limitation should be taken into consideration when running estuarine models in order to include the tidal signal with enough detail.

The main objectives of the present study were to introduce the use of large multi-watershed model applications as land boundary conditions for estuarine models and to evaluate the use of those estuarine model applications to include the fresh water influence into regional ocean models using a novel methodology. Each component of the system—watershed, estuarine and regional ocean model applications—will be further evaluated and validated in future works as, due to the complexity of the system, it could not be covered in a single research paper.

The developed methodology is generic and has already been applied to several estuaries in the Portuguese coast favouring the achievement of more precise coastal circulation and to study their influence in the creation of salinity and temperature fronts and the nutrient coastal input. When combined through this methodology, this set of operational models are able to provide gapless data of fresh water for large regional areas and to improve the reproduction of coastal hydrodynamics. The operational version of the models described in this work is accessible at http://forecast.maretec.org/.

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