An Integrated Perspective of the Operational Forecasting System in Rías Baixas (Galicia, Spain) with Observational Data and End-Users

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Abstract. Rías Baixas is a coastal region located in northwestern Spain (Galicia), between Cape Fisterra and the Portugal-Spain border. Its rich natural resources, which are key for the welfare of the region, are highly vulnerable to natural and anthropogenic stress. In this study, the operational ocean forecasting system developed at the *meteorological agency of the Galician government* (MeteoGalicia) is presented focussing on the Rías Baixas region. This system includes four models providing daily output data: the hydrodynamic models ROMS and MOHID, the atmospheric model WRF and the hydrological model SWAT. Here, MOHID's implementation for the Rías Baixas region is described and the model's performance with respect to observations is shown for those locations where Current-Temperature-Depth (CTD) profiles are obtained weekly by the *Technological Institute for the Monitoring of the Marine Environment* in Galicia (INTECMAR). Although the hydrodynamical conditions of this region are complex, the model skillfully reproduces these CTDs. The model results and derived products are publicly available through MeteoGalicia's web page and data server (www.meteogalicia.gal).

Keywords: Rías Baixas · Modeling · Observational data

1 Introduction

Located in the northwest of the Iberian Peninsula, the region of Galicia is characterised by a singular morphology. Along the coastline, there are deep coastal inlets with SW-NE (southwest-northwest) orientation, called *rías*, which are Pleistocene river valleys flooded by the sea at the end of the Würm Glaciation. They have a typical V form and, as we get closer to the platform, become wider

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and deeper. According to their hydrodynamic and sedimentologic characteristics, the *rías* can be subdivided into distinct zones [14] and in each zone there exists a predominating type of water circulation. The inner zone is influenced by river discharges and tides, the outer zone is dominated by coastal winds that promote water exchange with the open ocean and the middle zone is subject to both influences.

From north to south, four *rías* can be found in the region (see Fig. 1): Muros and Noia, Arousa, Pontevedra and Vigo. All of them have similar characteristics, influenced by tides, winds and river plumes. These estuaries are usually classified as partially mixed during the whole year. In winter, stratification is determined by the river freshwater input, while in summer it is caused by solar heating. The *rías* biodiversity is favoured by the meteorological conditions of the Galician coast. The interaction between the ocean and the atmosphere is affected by the presence of the low-pressure system of the North Atlantic [5]. Namely, the movement associated with the anticyclone of Azores has repercussions in the wind field that interferes with the ocean circulation along the Iberian coast. When the wind blows off the coast, it causes a displacement of the surface waters known as Ekman's transport. Perpendicular to the direction of the wind the transport is directed to the right in the Northern Hemisphere due to Coriolis force. If northerly winds prevail, they drive a surface current directed to the open ocean that is compensated by a current in opposite direction generated in depth. Near the coastline, these cold waters emerge in a process in a process known as "upwelling". On the other hand, "downwelling" occurs when southerly winds drive the warm surface waters towards the coast, where they are forced to sink to the bottom. Upwelling waters are usually rich in nutrients and, in combination with a sufficiently intense solar radiation, promote a rapid growth in phytoplankton populations.

In addition, this area is affected by freshwater plumes originating from the discharges of several rivers, as well as by the Western Iberian Circulation, which both exhibit a strong seasonal cycle. During periods of intense precipitation and associated large river discharges, a buoyant plume may form in the ría and propagate towards the open sea altering key features of the marine ecosystem such stratification, nutrients, turbidity and circulation patterns [15,16]. The complex dynamics of the Rías Baixas ecosystem have been the subject of many previous studies [2,4,7,13,16,19,20].

The Galician coast is part of an important upwelling system extended along the east coast of the North Atlantic from approximately 10°N to 44°N. The high productivity of the *rías* is exploited by a very active mussel farming industry using rafts (*bateas*), as well as by the fishing and aquaculture industry. Moreover, a variety of human activities such as harbours, industrial complexes, buildings, agriculture, sewage emissions, maritime traffic and tourism have direct or indirect effects *rías* and their surroundings. Also, most of the Galicia's population lives in the coastal zone which is subject to a considerable anthropogenic pressure and continuous situations of environmental stress.

Over the last years, several research institutes and agencies have developed methodologies for monitoring and forecasting aquatic systems in order to mitigate the negative anthropogenic impacts and to promote the benefits arising from the natural resources. These efforts imply the integration of information technologies using numerical models and sensor devices which increasingly contribute to the sustainable management of the water resources. It is a multidisciplinary field covering three main components: measurements, modelling and data dissemination, [1]. Observational data obtained from satellites, buoys and CTDs directly provide ecosystem information and can be used for the calibration and validation of numerical models, making these more accurate to simulate the behaviour of these systems. It is also necessary to have easy access to this information through tools that allow the analysis and visualisation of the data in an effective way. This integrated concept will serve as a decision support tool for offshore operations, navigation, coastal management, tourism activities and the monitoring of marine pollution episodes, as well as other emergency situations. All of these activities critically dependent on precise predictions of the oceanographic and meteorological conditions.

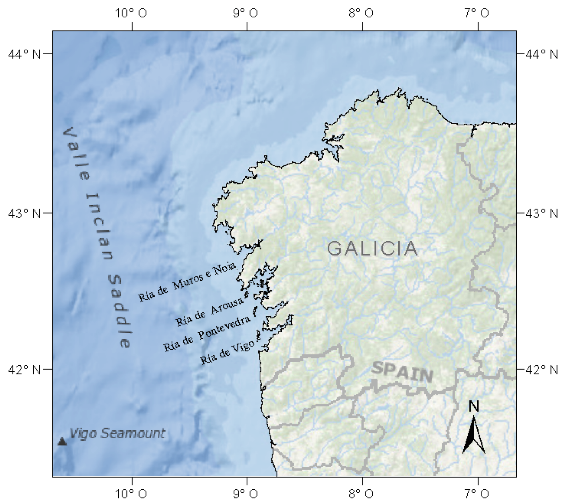

Fig. 1. Geographical overview of the Rías Baixas region, comprising the four coastal inlets/*rías* Muros and Noia, Arousa, Pontevedra and Vigo.

2 Operational Modeling System

At present, the operational scheme involves the coupling of four models, all running daily at MeteoGalicia and each of them covering different scales. At the regional scale, ROMS (Regional Ocean Modeling System) model [17], covers the Northern Iberian Peninsula with a horizontal resolution of 2 km and a vertical discretisation of 41 levels. The model is nested to the MyOcean global model (Copernicus Marine Environment Monitoring Service (CMEMS)) that runs with a horizontal resolution of 1/12° [6]. The numerical output from ROMS provides the initial and boundary conditions for the high resolution near-shore MOHID (Water Modeling System) model developed by MARETEC (Marine and Environmental Technology Research Center) [10,12] that runs at local scale. MOHID is used to simulate the main Galician *rías*: Muros and Noia, Arousa, Pontevedra and Vigo, and runs at a horizontal resolution of 300 m with 29, 34 and 27 vertical levels respectively, (see Fig. 2). The Weather Research and Forecasting Model (WRF), run at 12 and 4 km resolution provides the atmospheric forcing for ROMS and MOHID, respectively. The atmospheric variables ingested by the hydrodynamics models are sea level pressure, winds, surface air temperature, surface specific humidity and radiation on hourly timescale.

To simulate the effect of river discharges, the Soil Water Assessment Tool (SWAT) developed by the Agricultural Research Service and Texas A&M University is applied [18]. This model calculates the daily average flow and temperature of the region's principal rivers and is used to feed both hydrodynamic models.

The models were calibrated and validated using satellite data, buoy data provided by MeteoGalicia, INTECMAR and Puertos del Estado, and CTDs data collected by INTECMAR. In this paper, we are focusing on the comparison of temperature and salinity obtained from the operational system and the CTD

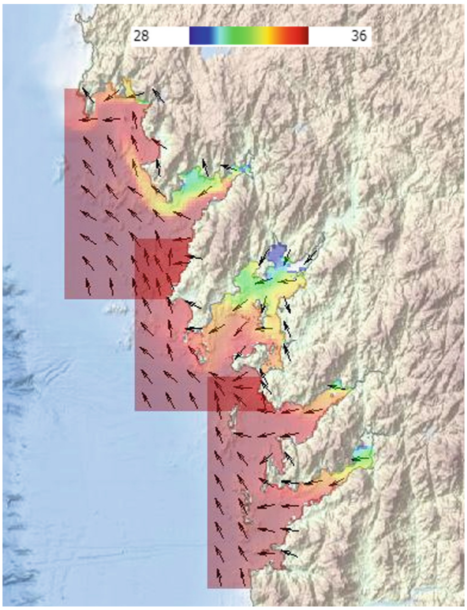

Fig. 2. Salinity and velocity fields from MOHID model for the Rías Baixas (Muros and Noia, Arousa, Pontevedra and Vigo).

profiles. INTECMAR weekly monitors the hydrography of Galician coast since 1992. The current oceanographic network is formed by 43 oceanographic stations distributed along Rías Baixas (Fig. 3) and the Ría de Ares (not shown). All data are downloaded, processed and saved on the INTECMAR data center (and distributed through www.intecmar.gal).

With this operational system, the water level, velocities, temperature, and salinity fields are predicted once a day. The model output is mapped on Meteo-Galicia's official web page and the corresponding files are published on a threads server. The data is publicly available and can be used for both research or commercial purposes. Several protocols for remote access via the threads server have been established and some specific products have been created from this system, such forecast reports for associations and harbours, nautical sports, beach activities as well as mobile applications.

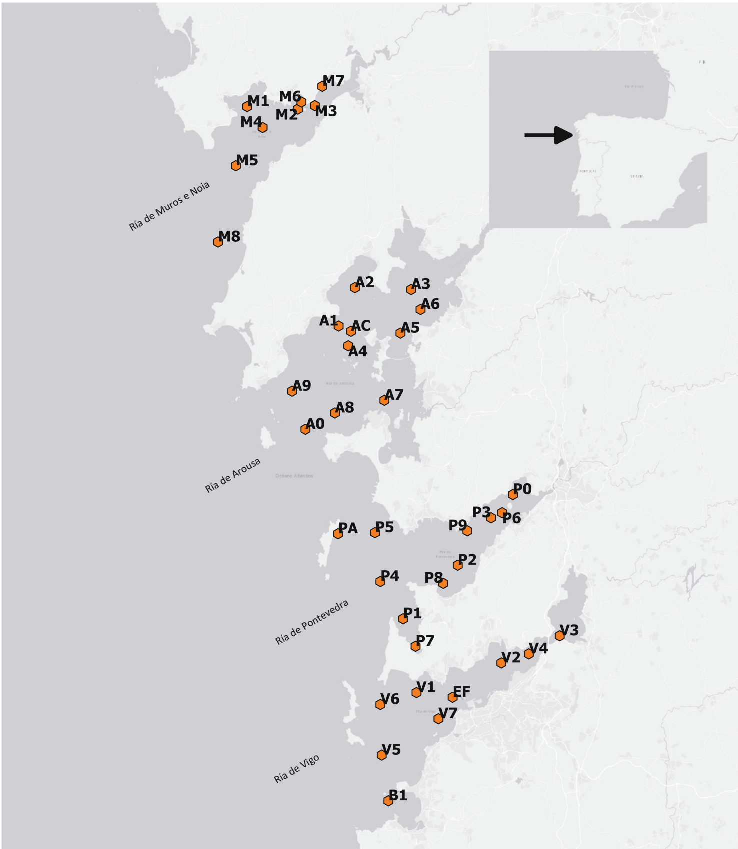

Fig. 3. CTDs stations location map of Rías Baixas (Muros and Noia, Arousa, Pontevedra and Vigo).

3 Results and Discussion

In Figs. 4, 5, 6 and 7, a comparison between the model (dashed lines) results and CTD data (continuous lines), collected at the locations shown in Fig. 3, is provided for the *rías* of Muros and Noia, Arousa, Pontevedra and Vigo, respectively. The chosen days represent known patterns of the vertical profiles, that commonly occur during the winter (blue lines) and summer (red lines) seasons. Temperature profiles are presented in the first column and salinity profiles in the second. The distinct panels in each column represent distinct locations, moving towards the open sea from top to bottom.

In the CTD data, the typical two-layer estuarine circulation of this *rías* appears. During winter events, and particularly at those sites located near the river mouths, the salinity of the surface layers is strongly influenced by freshwater input from river discharges whereas the salinity of the deeper layers is similar to ocean water. The temperature profiles of these sites are characterised by a week gradient in surface layers and by an almost homogeneous water column in the deeper layers. During summer, a strong temperature stratification is found near the surface at all stations. The salinity stratification is weak and virtually disappears when moving towards the open sea.

The most important model results are an underestimation of the temperature values in summer whereas salinity is overestimated in winter. The best model results are obtained for wintertime temperature in the Ría of Muros and Noia and summertime temperature in the Ría of Vigo, whereas the worst results are obtained for summertime temperature in the Ría of Muros and Noia and for salinity during both seasons in the Ría of Pontevedra.

The Figs. 8, 9 and 10 only comprise the Ría de Vigo. They show the simulated and observed vertical profiles throughout the year 2017 at three different locations. Looking at the spatial distribution, the stations present different patterns depending on their location. Station V3 (see Fig. 8), located in the innermost part of the ría, is mainly influenced by river discharge. Station V5 (see Fig. 10), located at the mouth of the ría is subject to the conditions of the adjacent platform. The station EF (see Fig. 9), in the middle of the channel, suffers both effects. Consequently, considering their locations, during the rainy months of winter and spring, a strong haline stratification of the water column is seen in observations, mainly at V3 station. At the other two locations, this stratification is also visible, but clearly less pronounced. During the summer months, a thermal stratification is generally observed at all locations. However, the vertical profile at location V3 is more homogeneous while at the V5 and EF stations the temperature gradient is restricted to the first meters. Regarding all stations, in September, a salinity increase and a temperature decrease indicate an upwelling event. In summary, the model performs better for temperature than for salinity profiles.

Albeit MOHID correctly reproduces the main features of the vertical profiles, predictions are not perfect and the modelling system is subject to continuous improvement. One promising approach is to enhance the performance of the auxiliary models ROMS, WRF and SWAT, providing boundary conditions

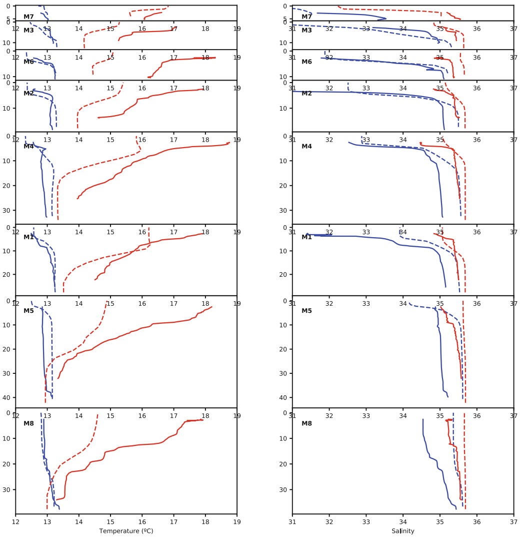

Fig. 4. Vertical profiles for temperature (left panel) and salinity (right panel) at the Ría de Muros and Noia CTDs stations, for the days 2018/01/15 and 2018/07/10 corresponding to a winter and summer situation (blue and red lines, respectively). CTD profile (continuous line) and MOHID model profile (dash line). (Color figure online)

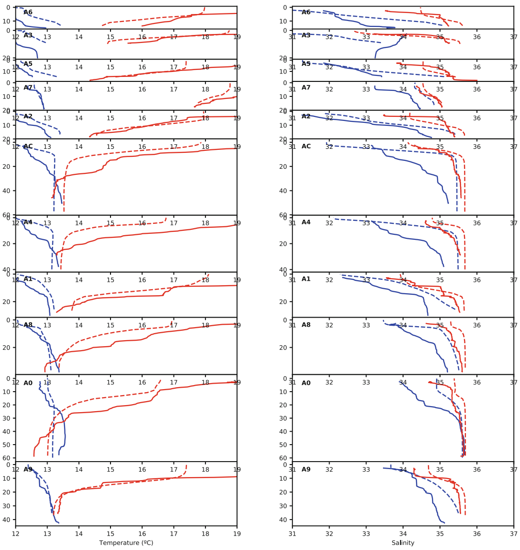

Fig. 5. Vertical profiles for temperature (left panel) and salinity (right panel) at the Ría de Arousa CTDs stations, for the days 2018/01/21 and 2018/07/10 corresponding to a winter and summer situation (blue and red lines, respectively). CTD profile (continuous line) and MOHID model profile (dash line). (Color figure online)

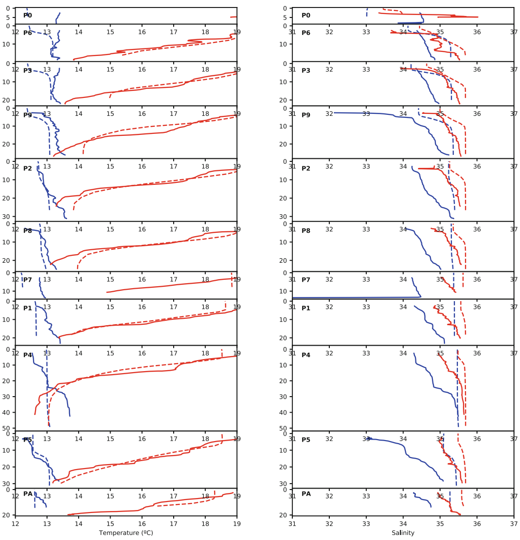

Fig. 6. Vertical profiles for temperature (left panel) and salinity (right panel) at the Ría de Pontevedra CTDs stations, for the days 2018/01/15 and 2018/07/10 corresponding to a winter and summer situation (blue and red lines, respectively). CTD profile (continuous line) and MOHID model profile (dash line). (Color figure online)

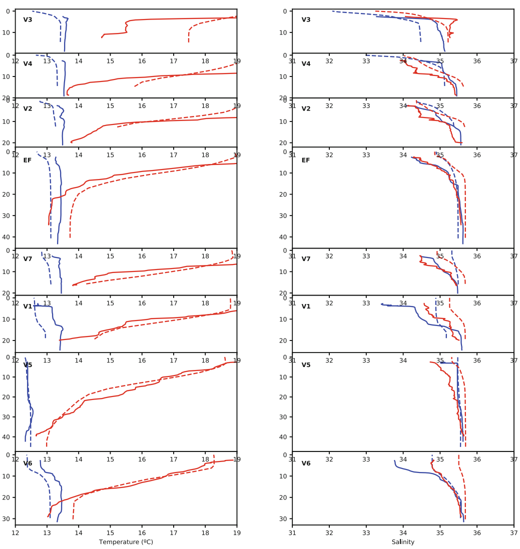

Fig. 7. Vertical profiles for temperature (left panel) and salinity (right panel) at the Ría de Vigo CTDs stations, for the days 2018/01/31 and 2018/07/10 corresponding to a winter and summer situation (blue and red lines, respectively). CTD profile (continuous line) and MOHID model profile (dash line). (Color figure online)

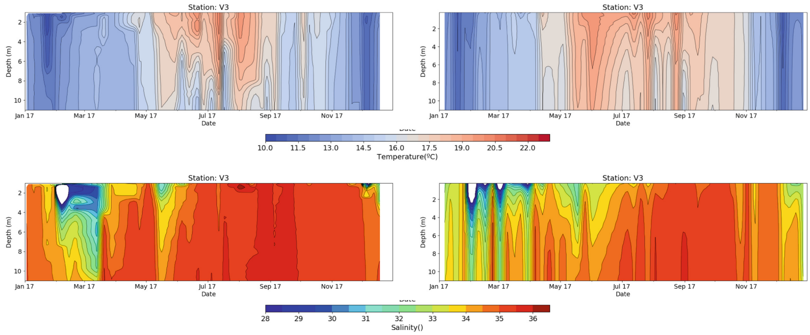

Fig. 8. Vertical profiles at V3 station along the year 2017. Weekly monitoring campaigns. CTD (left), MOHID model (right). Temperature (up), Salinity (down).

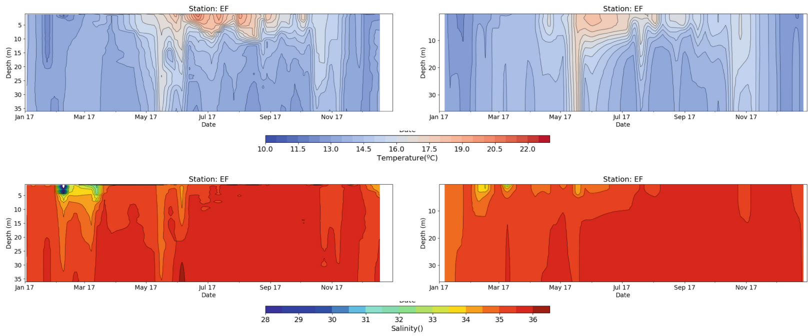

Fig. 9. Vertical profiles at EF station along the year 2017. Weekly monitoring campaigns. CTD (left), MOHID model (right). Temperature (up), Salinity (down).

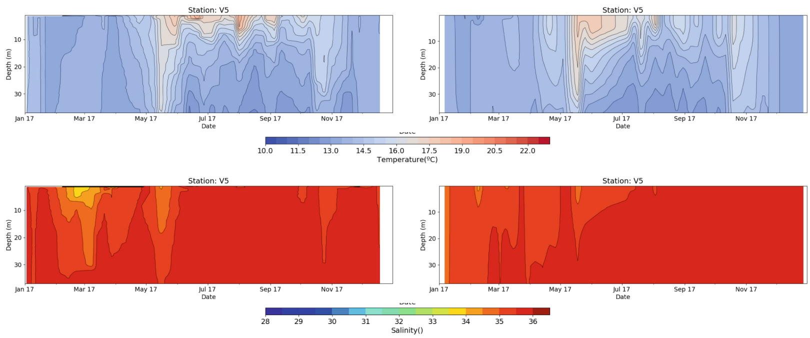

Fig. 10. Vertical profiles at V5 station along the year 2017. Weekly monitoring campaigns. CTD (left), MOHID model (right). Temperature (up), Salinity (down).

to MOHID. One of the explanations of the lack of freshwater in the MOHID domains is SWAT model tends to underestimate peak flows although it reproduces acceptably the variability of dry and wet seasons. Currently, an effort is being spent on a correction of freshwater discharges in SWAT and on an increase in model resolution for WRF.

4 Conclusions

For now more than a decade, MeteoGalicia has been employing an open-access operational forecasting system for the Rías Baixas region, providing a sufficiently accurate forecast to support decision making for many economic and societal activities. This ocean modelling system has been subject to continuous development and improvement, and agile validation tools have been built to visualise the system's behaviour. The main focus of the current efforts is to increase the integration between the operational prediction systems and ocean observation data, with the aim to develop sophisticated management tools.

In general, the model results for the Rías Baixas region show a good agreement with measured data. However in some particular areas of the *rías* the model still has difficulties to reproduce the observed profiles. Also, the results presented here should be re-confirmed by an analysis of a longer time series.

A significant part of these efforts has been funded by the European projects EASY/EASY-CO, RAIA/RAIA-CO/RAIA-TEC. The objective of those projects was the development of a trans-boundary observation and prediction infrastructure based on numerical models and an extensive network of ocean observations. In this context, an ocean observatory for the western Iberian coast was created (www.marnaraia.org), providing reliable information to the general public.

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