CIRCULATION PATTERNS IN THE RIA OF PONTEVEDRA UNDER EXTREME FORCING

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ABSTRACT

Two unusual circulation patterns were measured in the Ria of Pontevedra (NW Spain). The first one showed a positive two layered tidal pattern with water leaving the estuary through surface layers and entering it through the bottom ones. This unusual pattern is observed to depend on the particular summer stratification conditions, caused by upwelling events and solar radiation, and on the presence of easterly winds inside the estuary strong enough (~8 m s⁻¹) to move surface water seawards. The second event showed the opposite behavior with a negative two layered tidal pattern with water leaving the estuary through bottom layers and entering it through the surface ones. This pattern is maintained by the existence of two water masses with different densities at intermediate layers.

INTRODUCTION

During the last few years, the hydrographical and hydrodynamical studies of the Ria of Pontevedra have been intensified. From a numerical point of view, the hydrodynamic pattern of this ria was simulated (Prego et al., 2000; Ruiz-Villareal et al., 2002) by means of a 3D hydrodynamic model (MOHID 2000) (Martins et al., 1998; Martins, 1999) adapted to the Galician estuaries. From these simulations it can be observed the tidal circulation along the estuary and the existence of a two layered residual circulation pattern. In Gómez-Gesteira et al. 2003, the residence time at different points of the Ria of Pontevedra was calculated by means of a box model showing to be highly variable depending on fresh water input and sea water inflow. In addition to numeric models, the hydrodynamic behavior has also been studied by means of fieldwork measurements. In deCastro et al. (2000) the hydrodynamical characteristics of the ria was analyzed taking into account wind and tidal effect on water circulation from February to July 1998. They observed that wind direction is strongly dependent on topography in such a way that easterly winds force water to leave the estuary at surface layers and westerly winds force water to enter it. In addition, wind speeds higher than 4 m s⁻¹ are able to dominate the current at surface layers, even against tidal effect. In deCastro et al. (2003) a quasi-permanent...
I. Álvarez, M. Gómez-Gesteira, M. de Castro & R. Prego

Transverse asymmetry was observed in thermohaline properties of the Ria of Pontevedra. In average, the northern coast is less dense than the southern one. This asymmetry is observed to vary seasonally in magnitude depending on external forcing like upwelling indices and river discharge.

On the other hand, the general hydrographic behavior of the Ria of Pontevedra has been analyzed in Prego et al. (2001). In this paper, authors determine that four different water masses pass in front of the Ria of Pontevedra by means of a measurement station placed at the southern mouth of the estuary. The first water mass was observed from April to September and corresponds to Eastern North Atlantic Central Water (ENACW) (Rios et al., 1992; Fiuza et al., 1998). The second water mass was observed when relaxing the upwelling events. The third, which is warmer and slightly more saline than ENACW, was present in the ria from October to December. Finally, the last water mass was observed at the beginning of the year when the pre-existing water mass is replaced by the seawater from the poleward current (Frouin et al., 1990).

Beyond the knowledge of the general hydrodynamical and hydrographical characteristics of the Ria of Pontevedra, to have a good understanding of the estuary behavior, it is important to study particular events which can take place in the estuary under the influence of extreme external forcing like wind, solar radiation, river discharge and upwelling events. In Álvarez et al. (2003) a winter upwelling event was analyzed in terms of thermohaline variables. Distributions of salinity and temperature demonstrate that the water upwelled inside the estuary comes form the poleward current (Frouin et al., 1990), which passes along the Galician coast during winter. At the moment, water coming from the poleward current was never detected inside the estuary.

The aim of this paper is to describe two unusual circulation patterns characterized by a positive and negative two layered tidal circulation. The first circulation pattern shows water leaving the estuary continuously through surface layers and entering it through the bottom ones. The second event shows the opposite behavior with water leaving the estuary through bottom layers and entering it through the surface ones. These two circulation patterns will be analyzed in terms of external forcing.
AREA UNDER STUDY

The Ria of Pontevedra belongs to the group of Rias Baixas, located at the west coast of Galicia (NW of Spain), between Cape Finisterre and Portugal (Figure 1). This ria, as the rest of the Rias Baixas, is V-shaped and widens progressively from the ria head towards the ria mouth. It is situated between 42°15' and 42°25'N and 8°35' and 8°58'W with a surface of 141 km², a mean depth of 31 m and a volume of 3.47 km³. This ria is oriented in the SW-NE direction with the Lérez river in the innermost part of the ria and the Onza and Ons islands in the outer part of the estuary. Both islands behave as protector boundaries to the open sea swell. The ria of Pontevedra communicates with the coastal shelf by means of two entrances. The northern entrance (Cape Fagilda -Ons island), is narrow (3.7 km) and shallow (14 m) while, the southern one (between Onza island and Cape Couso) is wide with a depth of 60 m. The main channel of this ria is in the southern entrance. At the ria head, the River Lerez is the main freshwater runoff which flows into the estuary. The monthly average discharge of this river oscillates between 2 and 80 m³ s⁻¹ following a similar pattern to the rainfall one. In this way, the level of the discharge is high from December to March with a maximum in February and a minimum in September.

As the rest of the Rias Baixas, the Ria of Pontevedra, behaves as a partially mixed estuary (Dyer, 1997). This partial stratification is maintained by the river discharge in winter and by solar heating in summer. In addition, the Ria of Pontevedra behaves as an estuary with positive residual circulation with surface water leaving the ria and bottom water entering it (Otto, 1975; Prego & Fraga, 1992). This positive estuarine circulation is enhanced in summer by coastal upwelling, which last from April to October (Blanton et al., 1987; McClain et al., 1986; Tilstone et al., 1994). This upwelling is commonly attributed to the action of northerly winds along the shelf producing, by Coriolis effect, an Ekman transport offshore, which displaces surface water seaward. This displaced surface water is replaced by a colder nutrient-rich deeper water known as Eastern North Atlantic Central Water (ENACW) (Wooster et al., 1976; Fiuza et al., 1998). The Rias Baixas are characterized by a mesotidal and a semidiurnal tide, which is the principal factor of their dynamics. Typical tidal amplitudes of 2 and 4 m were measured during neap and spring tides, respectively. As well as tide, different factors like the freshwater contribution, the wind regime inside the estuaries and upwelling events, control the water exchange between the ria and the shelf.

Figure 2.
Current pattern (m s⁻¹) corresponding to 7-8 July recorded at different depths every hour over a complete tidal cycle at the anchored station.
MATERIALS AND METHODS

The fieldwork was carried out within the framework of the PONT97-98 program. The measurements of several hydrographic parameters were taken bi-weekly from October 1997 to October 1998 on board the R. V. Mytilus at nineteen stations (Figure 1). An anchored station (st 6) was located in the main channel of the estuary in its inner-middle part. Temperature and salinity vertical profiles were measured with a CTD profiler (Seabird 19) calibrated for salinity by means of an Autosal salinometer. Density was calculated with equations supplied by UNESCO. Current samples were taken at station 6 every hour over a complete tidal cycle by means of an Electromagnetic Current Meter (Valeport Model 808).

The upwelling indices were calculated by means of the geostrophic wind speed obtained from atmospheric pressure fields at point 43º N and 11º W (Lavin et al., 1991, 2000) following the method described by Bakun (1973) and averaged for 7 days before each cruise.

The river discharge was measured daily at a station located beyond the limit of tidal influence. In addition, the river discharge considered for each cruise is the result of averaging the river runoff from the previous 7 days to the day of hydrographic sampling.

Additionally, the wind pattern along the main axis of the ria and the air temperature were measured in situ on top of the main mast on board the RV Mytilus.

RESULTS AND DISCUSSION

Positive circulation

During cruise carried out on 7th - 8th July a persistent singular current pattern was observed at the anchored station (Figure 2). A two layered tidal circulation pattern can be clearly observed. During the whole night water is leaving the estuary through surface layers and entering it through the bottom ones. The zero level layer is observed to rise during flood and to sink during ebb. The maximum current values are 0.16 ms⁻¹ at surface layers and 0.08 ms⁻¹ at the bottom ones. A similar pattern had not been previously observed in these estuaries.
station, ST plots were represented both at an external station (st. 2) (Figure 5(a)) and at the anchored one (Figure 5(b)) at a depth of 50 and 20 m respectively. These plots were represented for three cruises, a cruise under intense upwelling conditions (3rd-4th August), another one under strong river discharge (24th-25th February) and the cruise under scope (7th-8th July). At the external station and at the anchored one a typical upwelling water (ENACW) (Fraga, 1981; Fiuza et al., 1998, Rios et al., 1992) was detected at bottom layers during the cruises carried out in July and August. It is also possible to see how at the external station the water observed in July is closer to ENACW than at the anchored one.

As it was commented in area under study, the stratification of the Ria of Pontevedra is maintained, in summer, by solar heating. So, in addition to the ST plots, the temperature vertical profile was represented for the three cruises in Figure 6. The cruise carried out in August showed an almost homogeneous vertical profile, while in February it can be observed a strong stratification but only at surface layers. The situation on 7th-8th July shows an important temperature stratification through the water column. This temperature attains 17º at surface layers, 14.5º at intermediate layers (at a depth of 14 m) and 13.2º at bottom layers (at a depth of 23 m).

To better characterize the stratification and therefore the water column stability, the Brunt-Väisälä frequency was calculated for the previous three cruises. The Brunt-Väisälä frequency, $N$, is given by:

$$N = \left(\frac{g}{\rho} \frac{\Delta \sigma_l}{\Delta z}\right)^{1/2}$$

where $\rho$ is the density, $\sigma_l$ is the density at atmospheric pressure - 1000 kg m$^{-3}$ and $z$ is the depth measured from surface. High values of $N$ indicate that the water column is stable. This stability inhibits vertical mixing producing a stratified water column. Low values of $N$ indicate an unstable column which favors the vertical mixing producing an homogeneous water column. The Brunt-Väisälä frequency for the three cruises is represented in Figure 7. In August $N$ have lower values throughout the entire water column. This indicates that, at this date, the ria is vertically homogeneous.
Figure 6.
Temperature vertical profile corresponding to the anchored station for the three cruises carried on 24-25 February (triangles), 7-8 July (circles) and 3-4 August (crosses).

Figure 7.
Brunt-Väisälä frequency calculated for the three cruises under study. Black line represents 24-25 February; dark gray line corresponds to 7-8 July and light gray line corresponds to 3-4 August.

Figure 8.
Current pattern (m s⁻¹) corresponding to 13 May recorded at different depths every hour over a complete tidal cycle at the anchored station.
showing the presence of ENACW which even reaches the surface layers. On February N takes high values at surface layers and low values at the bottom ones showing that the water column is stratified at surface layers and homogeneous at the bottom ones. This stratification at surface layers is due to the river discharge, which corresponds to a winter situation. The situation on July is quite different since the N values show stratification along all water column. It is also possible to see how this stratification is higher at surface and intermediate layers (above 10 m) than at the bottom ones showing the effect of the solar heating at surface and the entrance of ENACW through bottom layers.

Taking into account previously variables analyzed we can observe how the two layered tidal current shown in Figure 2 is due to two main factors, the wind force and a strong vertical stratification in the estuary.

**Negative circulation**

During cruise carried out on 13th May 1998 an unusual circulation pattern characterized by a negative estuarine circulation was observed at station 6. This circulation pattern is depicted in Figure 8, showing water entering the estuary through surface layers and leaving it through the bottom ones. The zero level layer shows the opposite behavior to the previous situation sinking during flood and rising during ebb. Maximum velocities of 0.12 m s⁻¹ were measured at surface layers during the flood tide. As in previous case no similar pattern was previously observed in the Rias Baixas.

To explain this circulation pattern, the external forcing like river discharge and upwelling index were also analyzed. Figure 9 shows the daily Lerez river discharge and the upwelling indices from April 1 to May 15 1998. The river discharge values were not the highest ones, which took place during winter (Prego et al., 2001), but they were considerably high compared to the summer ones with values under 10 m³ s⁻¹. The upwelling index was calculated averaging during the seven previous days to the cruise. It is possible to see how on May 13, the upwelling index was negative with a value of -284 m³ km⁻¹ s⁻¹. The periods of negative upwelling indices, associated with southerly winds at the shelf, ranged from May 10 to May 15. In addition, just before the period of negative upwelling indices, a period of positive ones took place (from April 30 to May 9). Note that during this upwelling event, the river discharge decreased from 48 to 25 m³ s⁻¹.

As in the previous situation (positive circulation) thermohaline variables were also analyzed. The vertical profile of density (γt) for a middle station (st. 2, Figure 1) and an inner one (st. 6, Figure 1) was represented in Figure 10. In this case, no pycnocline was observed and the inner station is denser than the one located in the middle part. The maximum density difference between stations is close to 1 at a depth of 15 m.
In addition to this plot, the density contour plot of the main channel of the estuary on May 13 is represented in Figure 11. In this figure an upward tilt (toward the head) of the 26.0, 26.5 and 27.0 isopycnals can be observed from station 2 to station 7. This shows the presence of denser water at the inner stations than at the middle ones at intermediate depths (between 10 and 30 m). Thus, the negative estuarine circulation shown in Figure 9 can be interpreted in terms of the thermohaline patterns due to the existence of denser water in the inner part of the estuary than in the middle one (at certain depths), which is able to generate the observed unusual circulation.

CONCLUSION

The Rias Baixas in general, and the Ria of Pontevedra in particular are characterized by a two-layer residual circulation pattern with surface water leaving the estuary and bottom water entering it. This behavior can change under strong external forcing factors and a two-layer tidal circulation can be obtained. This phenomenon was observed in the Ria of Pontevedra twice in 1998. The first one (7th-8th July) corresponds to a positive two-layered tidal pattern and the second one (13th May) corresponds to a negative two-layered tidal pattern. Both patterns never observed at the moment in the Rias Baixas.

On 7th-8th July the circulation pattern showed water leaving the estuary through the surface layers and entering it through the bottom ones. Averaging during a tidal cycle the outward current was \(-5\text{ cms}^{-1}\) and the inward one was \(4.9\text{ cms}^{-1}\). In that case, the unusual two-layer circulation pattern, is due to the combination of several factors which can be summarized in two, presence of easterly winds inside the estuary and a vertical estuary stratification. The easterly winds are strong enough (around \(8\text{ ms}^{-1}\)) to force the surface water to move seaward (DeCastro et al., 2000) even against tide. On the other hand, solar heating and favorable upwelling conditions on the adjacent shelf generated the vertical stratification.

The opposite behavior, a negative two-layer tidal circulation, was observed on 13 May. In this case, water is observed to move inward at surface layers and outward at bottom ones during a tidal cycle. The observed velocities along the whole estuary were averaged during a tidal cycle, obtaining a negative residual velocity of \(6.2\text{ cm s}^{-1}\) for the surface layers and \(-5.8\text{ cm s}^{-1}\) for the bottom ones. The origin of this negative two-layer circulation can be explained by means of upwelling events and river discharge. During the period of time ranging from April 30 to May 9 (before the cruise under scope) an upwelling event, which introduces ENACW inside the estuary, took

![Figure 11. Density ($\gamma$) vertical transect of the main channel of the estuary on May 13 1998. Numbers represent the location of the stations in the main channel and black points represent the measurement depths.](image-url)
place under prevalence of northerly winds at the adjacent shelf. During this upwelling event, the river discharge showed an important decrease. In addition, after this period of time southerly winds blew on the shelf from May 9, which tend to stop the estuarine circulation. This situation generated two different water masses at intermediate layers (from 10 m to 30 m depth). In the inner part of the estuary, the water was a mixture of estuarine water and ENACW and in the middle part of the estuary, the water mass was also a mixture, but of estuarine water and fresh water coming from the river discharge. This water mass distribution gave rise to the existence of denser water in the inner part of the estuary than in the middle one. As denser water tends to occupy the bottom layers and the lighter one tends to occupy the surface ones, a negative estuarine circulation pattern was generated in the estuary.

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