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# Hydrography of the Pontevedra Ria: Intra-annual spatial and temporal variability in a Galician coastal system (NW Spain)

Ricardo Prego and Andrew W. Dale
Marine Biogeochemistry Research Group, Instituto de Investigaciones Marinas, CSIC, Vigo, Spain

Maite deCastro and Moncho Gómez-Gesteira
Group of Physical Oceanography, Department of Applied Physics, University of Vigo, Spain

Juan J. Taboada, Pedro Montero, Manuel R. Villareal, and Vicente Pérez-Villar
Group of Non-linear Physics, Faculty of Physics, University of Santiago de Compostela, Spain

**Abstract.** In order to ameliorate the dearth of existing scientific knowledge concerning the hydrography of the Pontevedra Ria, a systematic investigation was carried out between October 1997-98. Salinity variations were closely related to river discharge whereas bottom waters presented oceanic characteristics over the whole year. Current was controlled by tide, river discharge, and wind in the internal ria where the highest velocities were directed along the ria channel with a low transverse component. Favorable atmospheric conditions in spring induced coastal upwelling up the continental shelf. In May the upwelling was sufficiently strong to be detected in the inner ria and intensified in July and August, cooling the ria water to 12°-14°C. Upwelling ceased in September, and from November to March seawater transported by the poleward current (35.9; 15°C) was detected on the shelf. From January until March, unanticipated favorable upwelling conditions provoked an influx of poleward inside the ria. Ria intrusion of poleward water and association with occasional winter upwelling conditions has not been observed previously. Isopycnic three-dimensional (3-D) surface and 2-D isopycnal maps show that with high river runoff or intense upwelling, lower-salinity water leaves the ria near the northern margin in the surface layer. Under negative upwelling conditions, the water is partially dammed inside the ria and exits the ria when the wind speed falls. During upwelling events, ENACW penetrated the ria, especially near the southern shore. Arrival of ENACW at the northern entrance impedes the outward water flow through this mouth.

## 1. Introduction

An assessment of the physico-hydrodynamical characteristics ought to be one of the first steps in any ecosystem analysis. Understanding the hydrographical trends allows for the superimposition and interpretation of biogeochemical parameters, thus leading to practical coastal zone management. In areas where socioeconomic demands are high, this approach becomes all the more important.

The Pontevedra Ria is one such area and is the second largest of four embayments on the northwestern Spanish Galician coast, collectively termed the Rias Bajas (Figure 1 and Table 1). It is within these basins that the principal exchange of terrestrial and marine waters takes place as well as the modification of biogeochemically active elements [e.g., *Prego,* 1993; *Álvarez-Salgado et al.*, 1996]. Aquaculture of the edible mussel *Mytilus edulis* is intense [*Blanton et al.*, 1987], and anthropogenic pressures are similarly high (see the overview by *Ibarra and Prego* [1997]).

Although considerable effort has been devoted to the study of these rias during recent years [*Prego*, 1990; *Fraga*, 1996], the hydrography of the Rias Bajas is only partially understood. Accessible information mainly takes the form of complementary data of more focused studies [*Jimenez et al.*, 1992; *Tilstone et al.*, 1994], and consequently, the sparse details offer little information to fully describe the system hydrography. Despite these shortcomings, some insight can be gained. Fundamentally, evidence suggests that the ria may behave as a partially mixed estuary with residual positive circulation [*Prego and Fraga,* 1992], with a mean tidal excursion in the central part of the ria of approximately 0.8 km [*Ruiz Mateo*, 1984]. Summer thermal stratification and upwelling of nutrient-rich Eastern North Atlantic Central Water (ENACW [*Fiuza et al.*, 1998]) into the rias at the height of the growth season have been documented by *Prego et al.* [1999] and lead to high net community production [*Prego,* 1993]. This water mass may be described as one of two subsurface bodies of water found adjacent to the Galician coast [*Fraga*, 1981], periodically forced into the rias, typically during May to October on a fortnightly basis, by spatial shifts of the Azores anticyclone and offshore Ekman transport [*Wooster et al.*, 1976; *McClain et al.*, 1986]. The anticyclone moves to the south in winter, resulting in prevailing southwesterly winds

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**Table 1.** Ria Dimensions and Mean Annual Contributions of Main Head Rivers

| Ria Baja | Water Content, km$^3$ | Surface Area, km$^2$ | Length, km | Mouth Width,[a] km | Mouth Depth,[a] m | Head River | River Flow, m$^3$ s$^{-1}$ |
|---|---|---|---|---|---|---|---|
| Muros | 2.74 | 125 | 17 | 6.1 | 45 | Tambre[b] | 54.1 |
| Arosa | 4.34 | 230 | 25 | 4.6 (3.7) | 55 (15) | Ulla[b]-Umia | 79.3-16.3 |
| Pontevedra | 3.45 | 141 | 22 | 7.3 (3.6) | 60 (15) | Lérez | 25.6 |
| Vigo | 3.12 | 156 | 31 | 5.1 (2.8) | 45 (25) | Oitaben[b]-Lagares | 17.0-3.4 |
| Total | 13.65 | 652 | - | - | - | | 195.7 |
| Mean | 3.41 | 163 | 24 | 5.8 | 50 | | 48.9 |

[a] Secondary mouth in parentheses.

[b] Estimated flow assuming no modification of river flow by a dam in its course.

on the Rias Bajas and the transportation of humid air from the ocean, which subsequently falls as rain in the ria-river catchment areas. Conversely, high pressures, fine weather, northerly winds, and upwelling characterize spring and summer.

In partially stratified estuaries, mixing between the two layers is mainly by turbulent diffusion, both being spatially and temporally variable [*Dyer*, 1997]. However, vertical mixing may be suppressed by buoyant freshwater inputs driving the horizontal gravitational circulation [*Simpson et al.*, 1990]. In the Pontevedra Ria, lateral circulation may also be important in wider areas [*Bowden*, 1980] such as the outer ria, where numerical models in the Vigo Ria have revealed the presence of a gyre in the surface waters induced by Coriolis effects [*Taboada et al.*, 1998]. The seaward flow presumably increases with mixing of salt across the density gradient while simultaneously provoking an increase in the volume of the

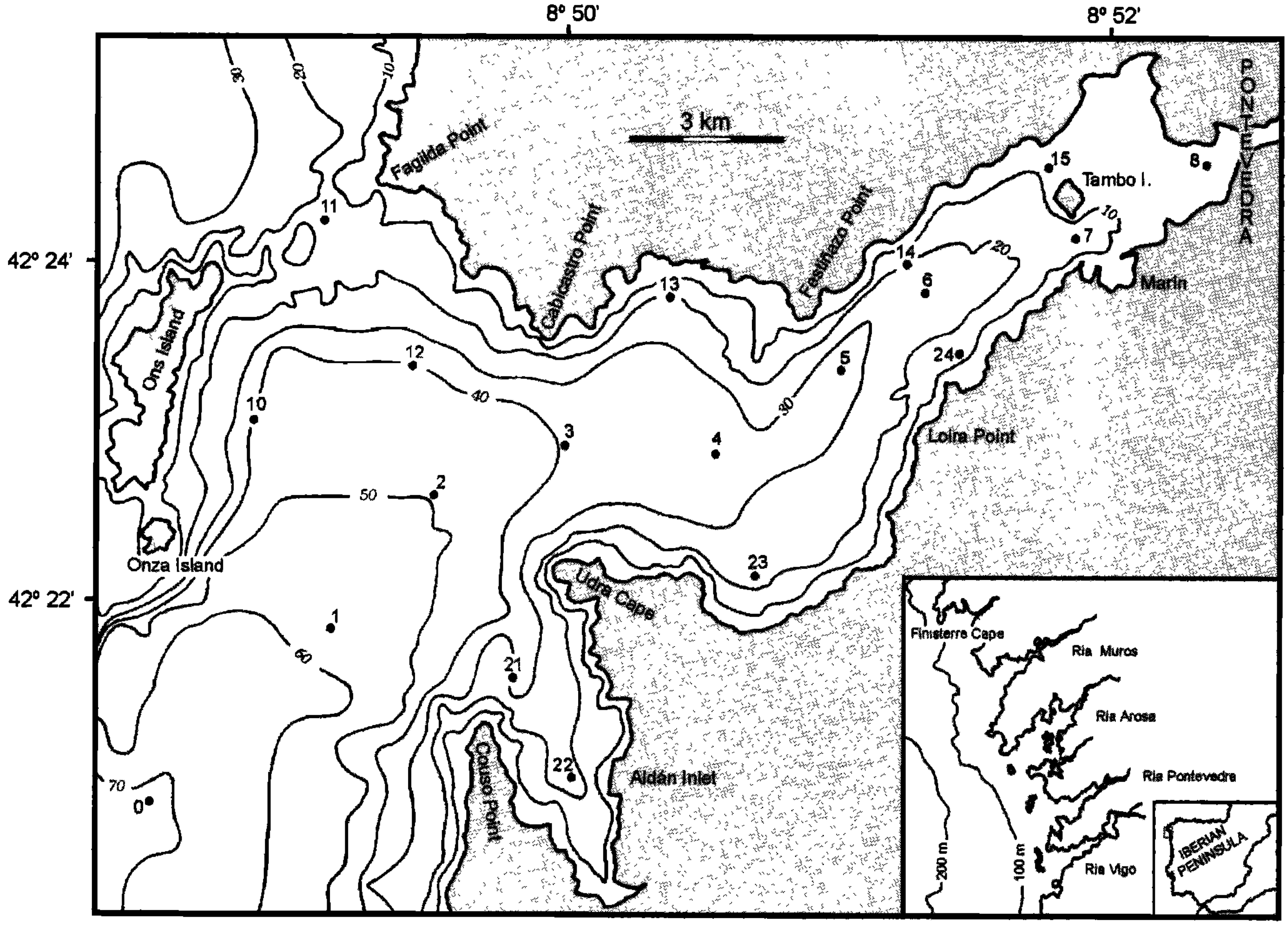

**Figure 1.** Map and bathymetry of the Pontevedra Ria and position of sampling stations. The city of Pontevedra is located at the mouth of the River Lérez in the top left-hand corner.

landward flow. In the inner part of the ria, outgoing flow is enhanced owing to wind forcing and low frictional forces in the surface layer [*deCastro et al.*, 2000], whereas the lower layers show more bias toward tidal-dominated flows. Tidal pumping is a further common feature of partially mixed estuaries and arises when the increase in salinity of the seaward flow leads to seaward pumping of fresh water or, equally, landward pumping of salt [*Uncles et al.*, 1985]. Along with shear dispersion, these processes maintain the ria saline. The fluvial runoff-upwelling interaction in the Rias Bajas, to our knowledge, remains unpublished, although there is some evidence to suggest that elsewhere large seaward freshwater flows have a suppressive effect on coastal upwelling [*Johns et al.*, 1993]. In the Vigo Ria in the absence of upwelling, the seaward flow is certainly the main parameter controlling residual circulation [*Taboada et al.*, 1998]; a finding complemented by previous box model applications by *Prego and Fraga* [1992] and estuarine circulation in general [*Pritchard*, 1989].

Thus it can be summarized that the Pontevedra Ria may not exhibit straightforward estuarine characteristics [*Bowden*, 1980], and consequently, the present understanding requires development. Moreover, the few papers relating to hydrography in the Pontevedra Ria are mainly confined to the gray literature. Therefore the aims of this paper are (1) to define the intra-annual spatial and temporal hydrographical trends inside the ria, (2) to obtain a good understanding of the water exchanges based upon the river-ria-shelf interactions, and finally, (3) to investigate the role of tidal currents in the hydrographic cycle. Accordingly, the discussion is partitioned into several subsections to approach the research objectives: first considering temporal changes, then spatial changes under fluvial- and upwelling-dominated regimes, and finally, the diurnal variability of currents, temperature, and salinity at a fixed station in the inner ria. Additionally, given that the other three Rias Bajas have similar locations and geomorphological characteristics (Table 1), the Pontevedra Ria may be considered as a "template" for the hydrographic study of the neighboring rias and provide a useful background for future projects.

## 2. Ria Topography and Environmental Conditions

The Pontevedra Ria, as with the rest of the Rias Bajas, is V shaped and widens progressively from the Tambo islet toward the mouth (Figure 1), where the ria is connected to the coastal shelf by means of two entrances. The northern entrance (Fagilda Point-Ons Island) is narrow (3.7 km) and shallow (14 m), while the southern entrance (Onza Island–Couso Point) is wide and has a depth of 60 m. The southern mouth, therefore, provides the main channel for water exchange, and the islands Ons and Onza behave as protective barriers against the swell of the open ocean. The ria has an asymmetric form due to the Aldan inlet located at the seaward end of the ria on the southern coast. At the ria head, the River Lérez provides the main freshwater input and generates a sediment accumulation typical of deltaic estuaries [*Vilas et al.*, 1996].

The Pontevedra area is under the influence of North Atlantic weather systems and is considered to have an oceanic climate tending to aridity in summer [*Perez-Alberti*, 1982]. The annual average temperature is 14°-15°C with a thermal amplitude of 10°C oscillating between 9°-10°C in January and 19°-21°C in July. The annual variations between air and sea temperature are small, and relative humidity varies between 70 and 80%.

January and July are the months with the highest and lowest rainfall, respectively, with a mean annual rainfall of 1600 mm. During the campaign period (October 1997-1998), rainfall was 24% higher than the mean annual value with two sharp peaks in November and April and a pronounced minimum in February (Figure 2). The River Lérez discharge (Figure 1) closely follows the rainfall pattern and is generally within 2 and 80 $m^3$ $s^{-1}$ [*Ibarra and Prego*, 1997]. Accordingly, the runoff is highest from December to March with a maximum in February, and lowest from April to October with a minimum in September. In February 1998, the mean river discharge was exceptionally low at 17.8 $m^3$ $s^{-1}$. Nevertheless, the long-term mean annual river discharge of 25.9 $m^3$ $s^{-1}$ compares well with a value of 30.3 $m^3$ $s^{-1}$ for 1998. In contrast to the other Rias Bajas, the Pontevedra Ria may be considered to display a natural hydrographic regime as its head river is not modified by dams. Therefore the need to make corrections to the river flow is negated [*Prego et al.*, 1990; *Rosón et al.*, 1991].

## 3. Materials and Methods

The fieldwork consisted of 23 biweekly cruises from October 1997 to September 1998 on board the R/V *Mytilus*, as part of the PONT97-98 framework: October 15 and 29, November 13 and 26, December 17 and 29 in 1997; and January 13 and 27, February 10-11 and 24-25, March 10-11 and 24-25, April 13-14 and 27-28, May 12-13 and 26-27, June 9-10 and 23-24, July 7-8 and 21, August 3, September 1, and October 7 in 1998. In the text, the cruise dates are designated by the calendar month (October 1997 to September 1998) and letters "a" or "b" refer to the first and second fortnightly cruises, respectively, with the exception of "10c" which corresponds to October 7, 1998.

During each cruise, several hydrographic parameters were measured at 18 stations inside the ria and one station outside (Figure 1). Salinity and temperature vertical profiles were measured with a Seabird 19 conductivity-temperature-depth profiler (CTD), calibrated for salinity by means of an Autosal salinometer. Density was calculated with equations supplied by *UNESCO* [1981]. In addition, salinity, temperature, and current profiles (at depths 1, 5, 9, 13, 17 and 21 m) were recorded every hour over a complete tidal cycle at station 6 with the vessel stabilized with four anchors during sampling. Current speed was measured with a Valeport 808 electromagnetic current meter, accurate to within ±0.001 m $s^{-1}$.

Daily upwelling indices (UI) were calculated by means of the geostrophic wind speed obtained from atmospheric pressure fields at the grid reference 43°N, 11°W [*Lavín et al.*, 1991] following the methods described by *Bakun* [1973]. The upwelling index is the magnitude of offshore or onshore flows of surface water and is equivalent to the Ekman transport derived from surface winds. A positive UI denotes favorable upwelling conditions (northerly winds and southward currents), and a negative UI, the contrary (southerly winds and northward currents). Additionally, daily rainfall, air temperature, and wind data were issued upon request from the Spanish Instituto Nacional de Meteorologia and Marín Harbor Authorities.

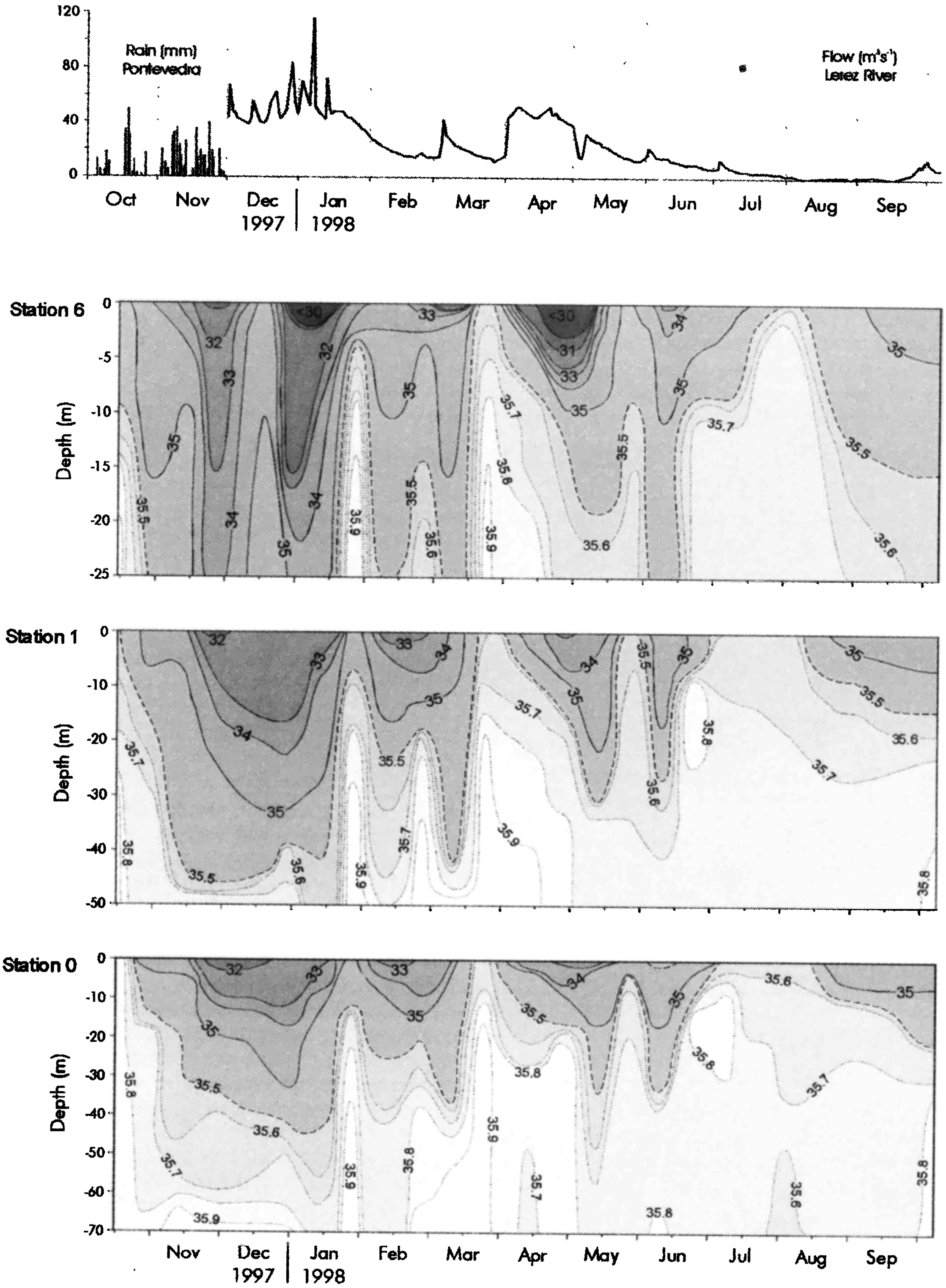

Figure 2. Rainfall (Pontevedra City), River Lérez discharge and water column salinity at station 6 (internal), station 1 (principal mouth), and station 0 (offshore) over the study period (October 1997 to September 1998).

## 4. Results and Discussion

The Galician Rias display hydrographical characteristics dependent on continental river discharge and seasonal oceanic upwelling events. The annual spatial and temporal hydrographical trends in the Pontevedra Ria can therefore be inferred from the salinity, temperature, and current profiles taken throughout the sampling period.

### 4.1. Annual Temporal Changes

Three key stations along the ria axis were chosen for the development of an accurate hydrographical description of the temporal changes in the ria: namely, station 0, located on the adjacent shelf; station 1, located at the main entrance to the ria where the ria exchanges water with the shelf; and station 6, located inside the ria (Figure 1).

Salinity was closely related to the River Lérez discharge, particularly during river floods, and increased progressively seaward from the river mouth (Figure 2). In the wet season (autumn to winter), the ria received on average between 40 and 60 $m^3 s^{-1}$, reflected at station 6 by a salinity decrease affecting the whole water column. Freshwater buoyancy inputs were important during high-runoff events as in January, when river discharges of about 100 $m^3 s^{-1}$ were followed by a notable salinity drop to 30 near the surface (Figure 2) and almost 34 near the bottom, thus evidence of competing buoyancy stratification and downward mixing of fresh water. Mixing in the Pontevedra Ria is a function of continual terrestrial runoff and partial retention of the water inside the ria by winds of a southwesterly component, in other words, unfavorable upwelling conditions (Figure 3). When the winds veered northeasterly toward the second half of January, early February, and March (Figure 3), an intrusion of more saline water occurred and was clearly observed to arrive at station 6 as a series of "pulses" (Figure 2). These additional meteorological conditions are not normally associated with the rainy season in the river catchment, and hence the salinization of the ria is further enhanced. The opposite situation was observed toward the end of April. In this case, the discharge from the River Lérez is high and the mixing layer is far more superficial since fresh water outflow is not hindered by winds, since the UI are negligible (Figure 3). Accordingly, it is possible to detect a salinity of 35 at 10-m depth with fresh water flowing freely out of the ria. This trend is also evident at the ria mouth (station 1, Figure 2) and offshore at station 0 (Figure 2), where the salinity gradient is lower. The isopycnals are more spatially and temporally relaxed in the surface layers at the mouth, indicating longer freshwater mixing times than in the inner ria, whereas in the lower layers water of oceanic salinity (35.5) was always observed at times of offshore water intrusions. Therefore the combined effects of wind (UI) and fluvial flow can be traced with salinity, and it is clear that observed the trends are maintained from the inner to the outer ria to a greater or lesser extent. As far as we are aware, this ria-shelf interaction has not been described previously, and despite the lack of data relative to the other Rias Bajas, it seems reasonable to infer that the haline pattern in the neighboring systems corresponds well to the one described above.

The summer-autumn trends are more adequately described with temperature rather than salinity, since the vertical salinity gradient inside the ria is small (34.0 to 35.7; Figure 2) and minimal outside (35.0 to 35.8). The tendency toward saline homogeneity is due to regular upwelling events of ENACW during the dry season engendered by offshore Ekman transport and northerly winds (Figure 3). The sea level at the mouth of the ria is lowered by the wind-induced flow, setting up a seaward pressure gradient inside the ria which ultimately forces the water seaward above the pycnocline in response to lowered sea level at the mouth [*Blanton et al.*, 1987]. ENACW is subsequently driven into the ria by the outward flow and increases the overall density of the water inside the ria. This pattern can be readily traced with water temperature. The upwelling phenomenon, usually observed from April to October [*Wooster et al.*, 1976; *McClain at al.*, 1986] on the Galician coast [*Fraga*, 1981; *Prego and Bao*, 1997], was identified by the 13°C isotherm on the ria-shelf interface during April and May and from mid-June until the end of August (Figure 3). With a positive UI in spring the upwelled water arrived at the ria mouth but did not, however, penetrate the internal ria. The UI increased in May in both duration and intensity and upwelled water reached station 6, where the temperature fell to 14°C at 7-m depth. This process further intensified in July whereby upwelled water was mixed with existing ria water, and lowered the surface water temperatures at station 6 to 14°C and those at 25-m depth to 12°C, in spite of high air temperatures (35°C maximum) and solar irradiation. Upwelling was especially evident in the Pontevedra Ria since its mouth is the deepest of the Rias Bajas (Table 1) and thus provides relatively unobstructed entry to incoming ENACW. Nevertheless it should be noted that there is considerable interannual variation in upwelling strength on the continental shelf [*Lavín et al.*, 1991].

September was characterized by low positive and negative UI (Figure 3). Favorable upwelling conditions ceased, and water temperatures increased despite the decrease in solar irradiation with the close of the dry season. This anomaly presumably results from the absence of upwelling-induced circulation, low river runoff with slight buoyancy forcing, and diminishing, but sustained, solar heating. The combination of the above factors favored thermal stability of the surface layers until autumn mixing, and higher fluvial inputs lowered temperatures until the winter thermal inversion, as seen in the previous winter in 1997 (Figure 3). This phenomenon was believed to be due to atmospheric conditions only, but increasing volumes of cold river discharge also played a key role in this process and produced a longitudinal temperature gradient in the surface layers inside the ria (Figure 3). Accordingly, surface cooling decreased from the ria head to the ria mouth, with a thermal amplitude of the temperature inversion of 3°C at station 6 in comparison with only 1°C at station 0.

### 4.2. Annual Cycle of Water Masses

The interchange between water masses in the ria can be studied more closely by means of a temperature-salinity (T-S) diagram. The subsuperficial inputs of offshore water mainly occur through the deeper southern mouth, and therefore salinity and temperature data measured at 50-m depth at station 1 were used to describe the water exchanges over the sampling period (Figure 4).

From April to September the water mass in the ria was correlated to ENACW of subtropical origin [*Fiuza et al.*, 1998], with salinity values ranging from 35.67 to 35.83 (Figure 2) and temperature ranging from 11.8° to 13.5°C (Figure 3), depending on the upwelling intensity and mixing of existing bottom water in the ria. During spring and summer the upwelling may relax, as in the June cruise 6a in Figure 4. This situation was observed only once during the campaign, although it may be much more frequent depending on atmospheric conditions [*Lavín et al.*, 1991] and the sampling frequency. At the end of the upwelling season, ENACW gave way to a warmer and saltier water mass (cruise 10a). Within less than a fortnight, between cruises 10a and 10b, the abrupt change in thermohaline properties of the water can be attributed to further inputs of warm (15.5° to 17.5°C, Figures 3 and 4) fresher subsuperficial shelf seawater which predominated during the autumn and most of the wet season up to mid-

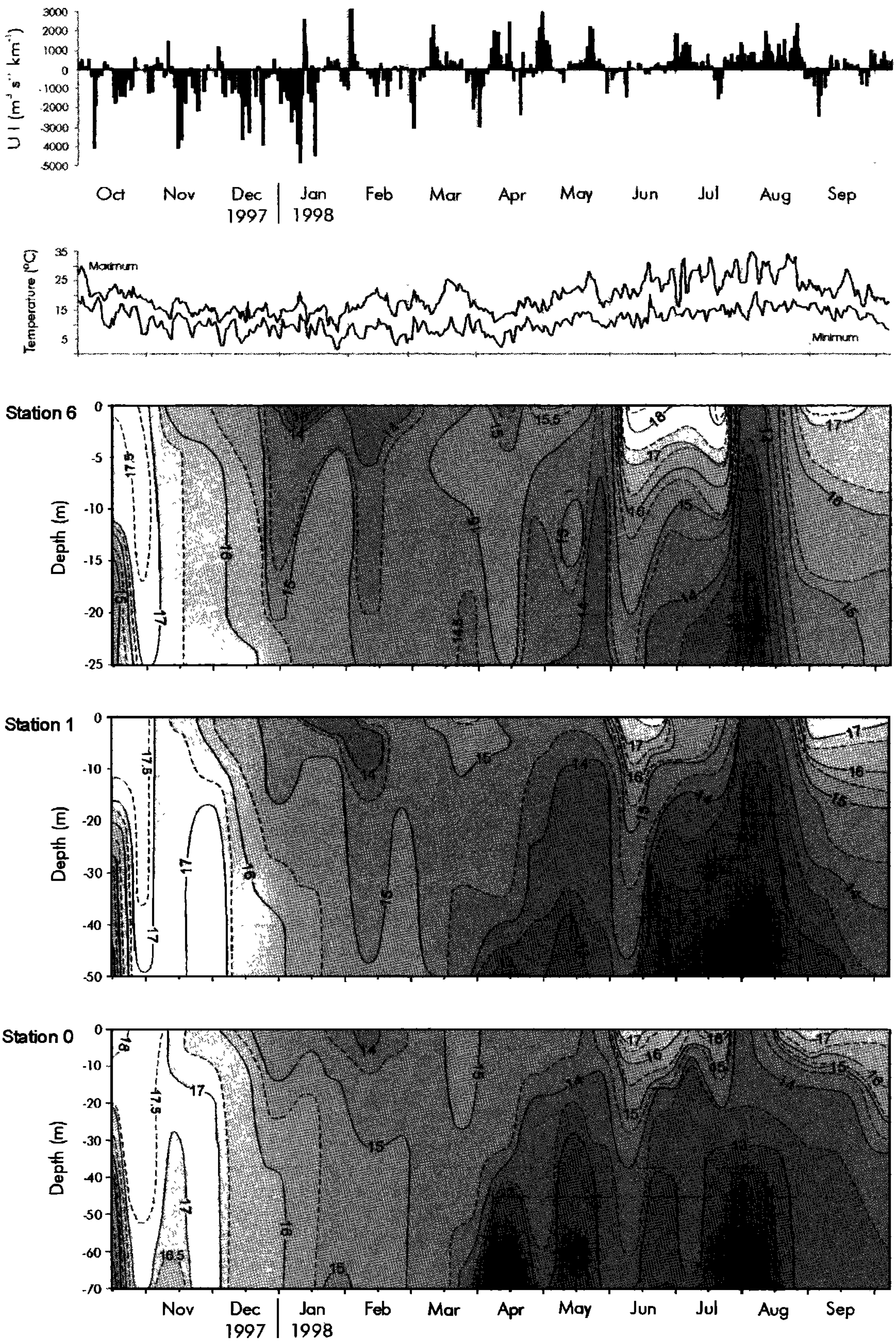

**Figure 3.** Upwelling index (calculated at 43°N, 11°W), air temperature (Pontevedra City), and water column temperature at station 6 (internal), station 1 (principal mouth), and station 0 (offshore) over the study period (October 1997 to September 1998).

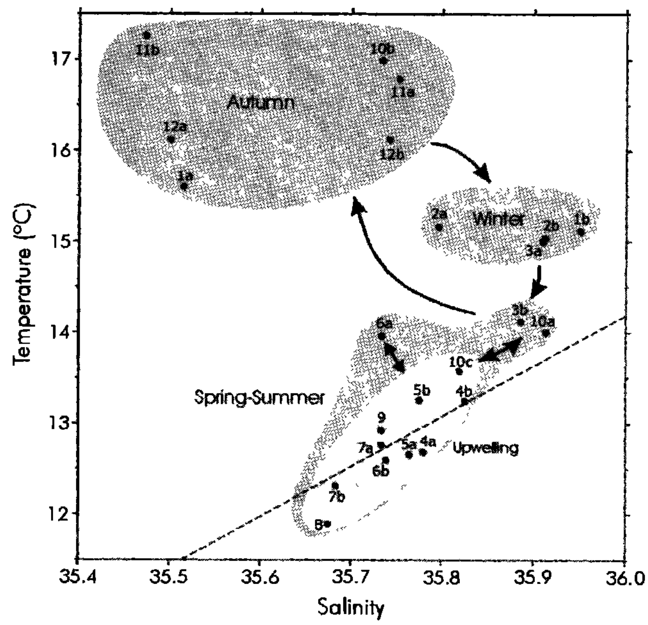

**Figure 4.** Temperature-salinity diagram of incoming seawater at ria station 1 (50-m depth) over an annual cycle. Numbers refer to the calendar month (October 1997 to September 1998), and letters "a" and "b" refer to the first and second fortnightly cruises, respectively, except 10c, which corresponds to the cruise October 7, 1998. The dashed line represents the T-S line for ENACW.

January (cruise 1a). Thereafter, the autumnal water mass was replaced by a distinct water body (Figure 4) on a timescale similar to the previous interchange, which persisted from late January to early March (cruises 1b to 3a). In this case, the substitute water mass was transported by the poleward current: a warm (14.5°-16.5°C) and saline (35.9-36.1) wind-induced current flowing poleward at 0.2-0.3 m $s^{-1}$ along the Iberian Peninsula shelf-slope break at a depth and width of 150-200 m and 25-35 km, respectively [*Frouin et al.*, 1990]. Intrusion of the poleward current caused a further widening of the temperature difference of the surface and bottom waters inside the ria from January to March (Figure 3). The same water mass was detected earlier on the shelf (station 0) in November and was correlated to a temperature minimum (16.5°C; Figure 3) and a salinity maximum of 35.9 (Figure 2) in the near-bed water layers but was not of sufficient strength to advect inside the ria. However, in January, along with unanticipated favorable upwelling conditions, this water was observed at the mouth of the ria down to 15 m, as well as inside the ria down to 20 m, and persisted during February and March. The presence of this water body has previously been detected on the continental shelf (R. Prego et al., unpublished data, 1996) but not inside the rias, and consequently, ria intrusion has not been related to winter upwelling conditions. Therefore it appears that there could be two separate upwelling events that share the same mechanism but introduce different water masses inside the ria depending on the season, to wit, intermittent water driven by the poleward current from November to March and ENACW typically from May to September (Figure 5). In view of the fact that the poleward directed water mass is readily upwelled into the rias after discontinuous periods of positive UI (Figure 3), or possibly with relaxation of unfavorable upwelling conditions, it can be surmised that the current lies within close proximity to the ria mouth and is not confined to the upper slope-shelf break as *Frouin et al.* [1990] have postulated. Owing to the paucity of hydrographic studies, for example, measurements of low spatial and temporal resolution (Vigo Ria [*Mouriño et al.*, 1985]), long-term thermohaline studies from a single station (Vigo Ria [*Nogueira et al.*, 1997]), and late spring and summer investigations (Arosa Ria [*Rosón et al.*, 1995]), it is unknown whether this exchange occurs in the neighboring systems of the Pontevedra Ria, although similar topography suggests that the trends reported here are emblematic of all the Rias Bajas.

Consequently, depending on the upwelling stress and relaxation cycle, it is possible to define four different water bodies that penetrate the Pontevedra Ria, each with a different T-S diagram as shown in Figure 5. The profile of the autumnal water (cruise 11b) is consistent with an almost straight line both inside the ria and on the shelf, a pattern typical of mixing fresh water with superficial coastal water. The same is observed in winter (cruise 1b), when mixing with the water transported by the poleward current occurs (salinity 35.97 and

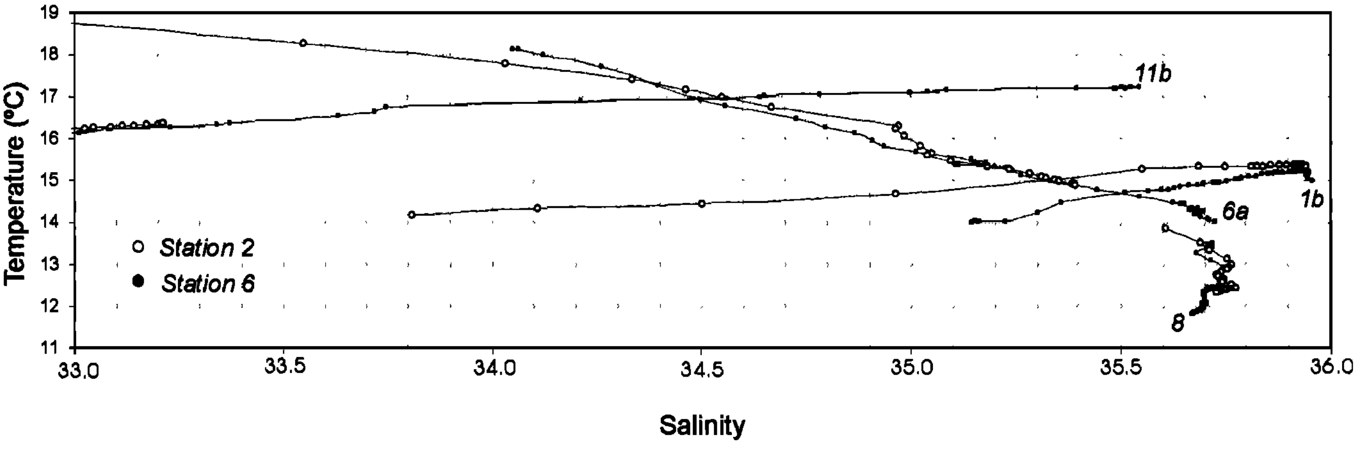

**Figure 5.** T-S diagram corresponding to the four different seawater bodies shown in Figure 4 entering the Pontevedra Ria (stations 2 and 6). Cruise 11b is representative of autumn conditions, 1b of poleward current water, 6a of May to September non-upwelling and cruise 8, of upwelled ENACW water mass.

15.2°C), and in May to September (cruise 6a), when the upwelling relaxes (salinity 35.55 and 12.5°C). The fourth water body is ENACW (cruise 8) whose T-S characteristics are well known [*Fraga*, 1981].

### 4.3. Spatial Changes Inside the Ria

The spatial trends within the ria have been highlighted in Figures 2 and 3, in which two motors clearly drive the residual circulation: the River Lérez and upwelling of water from the continental shelf. In addition, the tidal role should be not be disregarded and will be explored at the end of this section. Figures 2 and 3 further reveal three classic situations which exemplify the fluvial and upwelling patterns in the ria: cruise 11b in winter, when dominant winds are southwesterly i.e. negative UI and high river flows; cruise 4b in spring with light winds and moderate river flow; and cruise 8 in summer characterized by strong upwelling conditions and limited freshwater inputs.

In order to describe the spatiality incurred by the distinct meteorological settings, we focus our argument on water density. Tracking the density elucidates the sinking and rising of seawater at different areas inside the ria and hence aids the qualitative description and importance of each driving force inside the ria. Accordingly, we employ three two-stage diagrams separated into upper and lower parts consisting of the following:

1. Isopycnal contours in the upper part of figures essentially depicting a two-dimensional map of the ria at the depth of separation between the incoming and outgoing layers. Based upon results obtained in the Vigo Ria [*Prego and Fraga*, 1992; *Taboada et al.*, 1998] this depth has been approximated to 10 m.
2. An isopycnic three-dimensional surface diagram is shown in the lower part of the figures, where the density gradients reflect the advection and mixing of the water bodies in the ria. According to mean data in the Rias Bajas [*Prego* 1990; *Fraga*, 1996], a density (gamma-*t*) of 24.0 is assumed to label the influence of fluvial and seawater mixing and 27.0 for the upwelling ENACW water mass. The basis for the data used to construct the figures stems from the observations in Figures 2 and 3.

**4.3.1. Fluvial prevalence.** Toward the end of November 1997 (cruise 11b, Figure 6) when the river runoff was high (60 $m^3 s^{-1}$; Figure 2) and UI negative (Figure 3, -1500 $m^3 s^{-1} km^{-1}$), the longitudinal and horizontal density gradient at 10-m depth was low and varied between 24.0 and 24.2 kg $m^{-3}$ over the whole ria. This corresponds to an almost homogeneous water structure below 10 m. Above this depth, the density is slightly higher near the southern mouth of the ria, and the 24.0 kg $m^{-3}$ isopycnic surface is 4-m below this level in the northern mouth. The isopycnic surface on the lower part of the upper figure is also deeper along the northern coast of the ria indicating a tendency for fresher water to exit via this coast, as expected by the Coriolis effect. Reiterating previous findings, the water is partially retained along the northern coast owing to atmospheric conditions: moderate winds of a westerly component inside the ria and negative upwelling indexes offshore.

During cruise 4b in April 1998 a river runoff of 46 $m^3 s^{-1}$ (Figure 2) and UI close to zero (Figure 3) forced the water to leave the ria via both the northern and southern mouth (Figure 6, bottom). The quasi-planar isopycnic surface in spring illustrates the contrast to winter conditions, and the higher density of 26.0 kg $m^{-3}$ is indicative of reduced freshwater retention. Unhindered passage of freshwater flow out of the ria has been mentioned previously and is mainly due to switching meteorological conditions, as the UI suggest, and emphasizes the important role of winds in water circulation both inside the ria and on the adjacent shelf. The hydrographic differences between periods of negative UI and negligible UI are elucidated in more detail on cruises 11b and 4b. When onshore Ekman transport is strong (cruise 11b), there is a deepening of the pycnocline as water piles up at the ria mouth, thus confirming the hypothesis put forward by *Blanton et al.* [1987]. Conversely, in the absence of onshore winds, the pycnocline becomes shallower with unopposed density-driven circulation. A total retention of ria water, similar to the one reported for Vigo Ria by *Prego* [1992] and for Pontevedra by *Fraga and Prego* [1989], was not observed owing to the high river discharge, which favored the water to exit mainly via the northern mouth.

Two further consequences can be inferred from the isopycnals. The first is the low-density water observed close to Ons Island on cruise 4b (25.8 kg $m^{-3}$). This may be interpreted as water exiting the ria via both the north and the south mouth, with relatively less dense water trapped against Ons Island. This phenomenon presumably plays a dominant role in the interchange of waters between the continental shelf and the ria and in the accumulation of muds in this area, as shown by sediment maps [*Vilas et al.*, 1996]. The second inference is that the Aldan hydrography (Figure 1) is dominated by the ocean and partially isolated from the rest of the ria, as has been previously predicted with a three-dimensional model [*Taboada et al.*, 2000]. In addition, taking into account the low freshwater input at Aldan, it would be more acceptable to consider this region as an inlet rather than a small ria, as is commonly believed.

**4.3.2. Upwelling prevalence.** In accordance with the data in Figure 3, the temperature minimum in August 1998 is a good indictor of summer upwelling conditions, which in this investigation was more intense than previous upwelling events in the neighboring rias [*Prego and Fraga*, 1992; *Rosón et al.*, 1995]. The upwelled water was ENACW, as reflected by the T-S diagram (Figure 5), and it affects the entire ria and shelf (Figure 3 and 27.1 kg $m^{-3}$ isopycnal in Figure 7) cooling the water inside (Figure 3). The isopycnal corresponding to 27.0 kg $m^{-3}$ (Figure 7, bottom), characteristic of ENACW, shows that the water mass had a higher density than ria water and thus penetrated the ria above the seabed at the southern mouth as a deep flow rising up to 16 m below the surface as a result of the upwelling strength. The low river flow of 2 $m^3 s^{-1}$ further aided ENACW intrusion, which may otherwise impede landward advection [*Johns et al.*, 1993]. Furthermore, the 27.0 kg $m^{-3}$ surface shows that in cases of intense upwelling, the exit of seaward flowing ria water by the northern mouth was impeded by the presence of ENACW upwelling over the shallow sill (Figure 7, top). Coupled with the topographic effects of the adjacent coastal margin, this is a region of notable upwelling, and consequently, upwelling is most intense near the northern mouth and water only leaves via the southern exit, the opposite of the given examples of fluvial dominance (Figure 6). The coastal upwelling effect can also be readily observed inside the ria on the southern margin where the isopycnal surface rises (Figure 7, bottom). It can therefore be assumed that oceanic shelf water always tends to

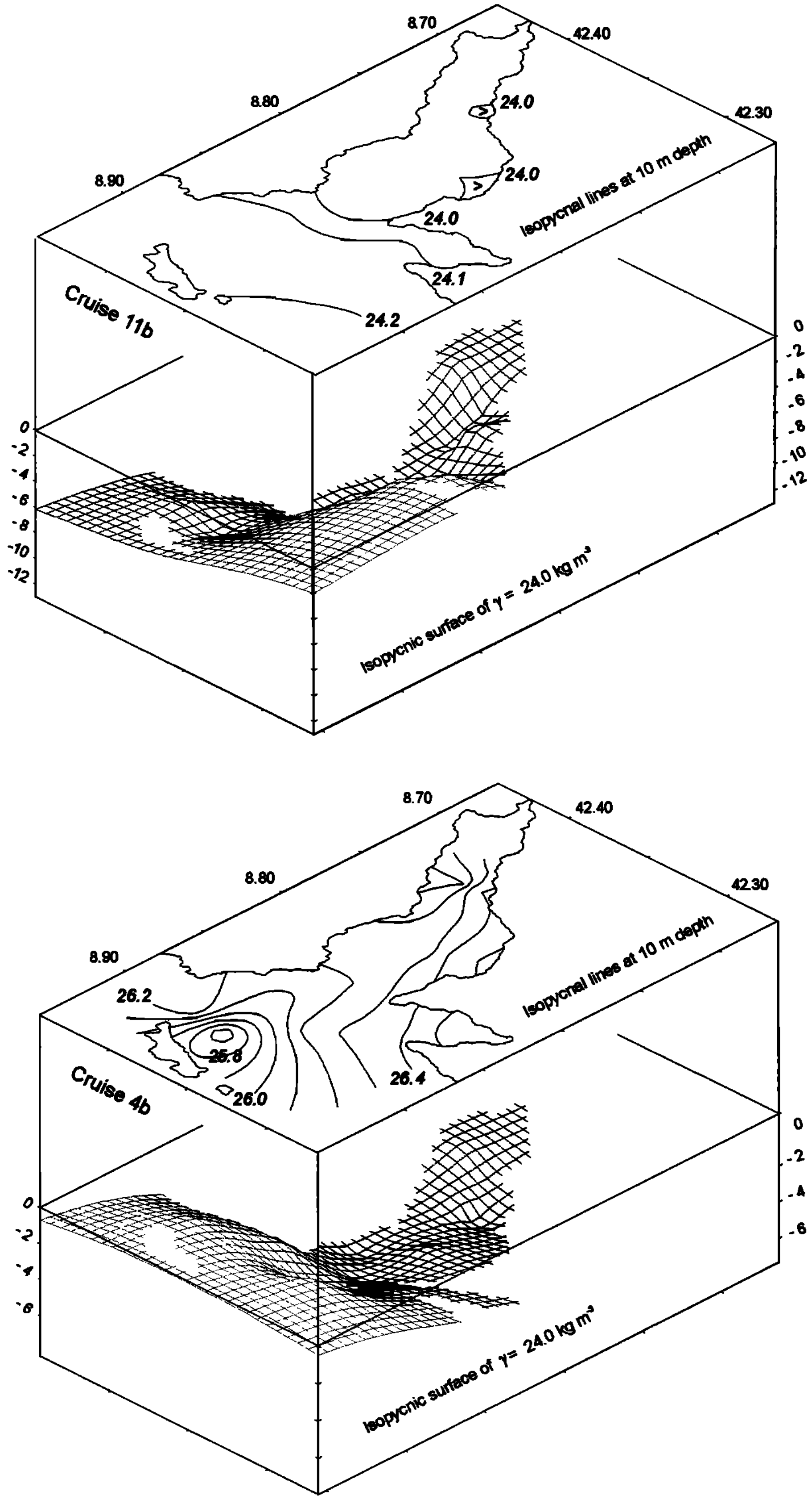

**Figure 6.** Two-dimensional isopycnal contour plot of density (gamma-*t*) in the Pontevedra Ria at 10-m depth (upper part of figures) and three-dimensional isopycnic surface (lower figures) in two opposite cases under fluvial prevalence: negative UI (cruise 11b) and slight UI (cruise 4b).

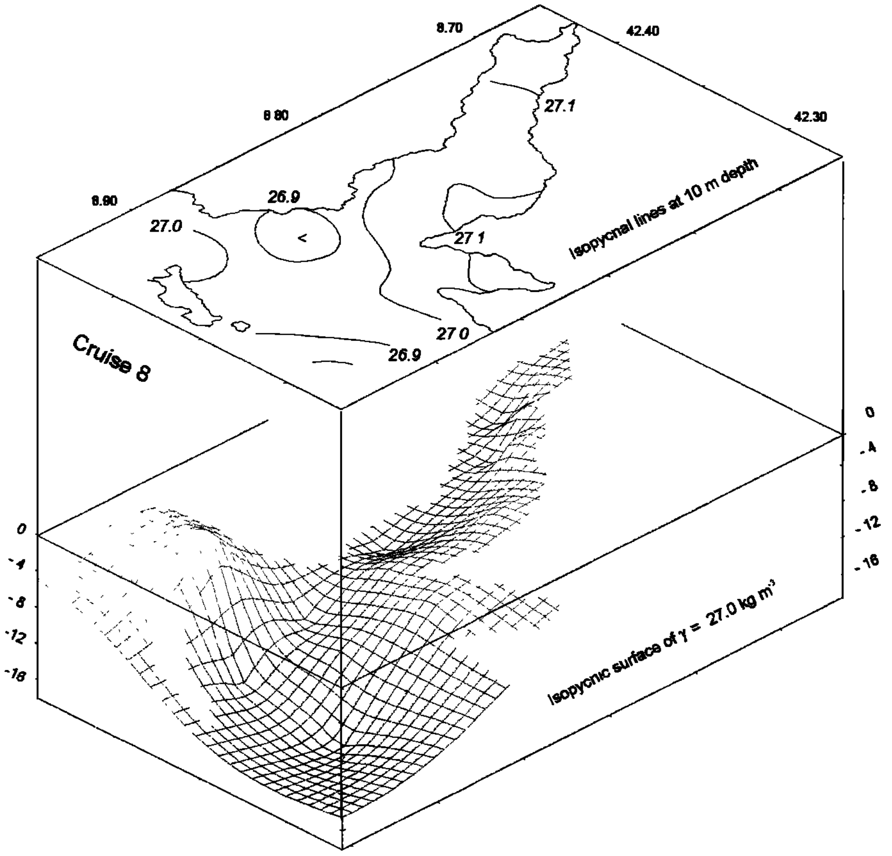

**Figure 7.** Two-dimensional isopycnal contour plot of density (gamma-*t*) in the Pontevedra Ria at 10-m depth (upper part) and three-dimensional isopycnic surface (lower part) under upwelling conditions (positive UI) on cruise 8.

penetrate the ria via this margin, given that the same upwelling trends occur under fluvial prevalence. This hypothesis can thus be extended to the Vigo and Arosa Rias, which also have islands situated in the ria mouth.

The primary advantage of isopycnal surfaces is their usefulness as "hydrodynamic tracers," which is not possible with salinity or temperature data alone. Representations of the type presented here are clearly useful tools when visualizations of the combined effects of water advection and mixing of distinct water masses are required. This approach to hydrographic analysis of the Galician Rias Bajas is proposed here for the first time, although we believe that it has application to coastal systems worldwide.

**4.3.3. Tidal influence.** The Rias Bajas are mesotidal with short tidal excursions. The tidal excursion calculated for station 3, using the methodology of *Head* [1985] and current measurements according to *Ruiz Mateo* [1984], works out to be less than 0.8 km. However, despite this seemingly small tidal influence, measurements were made at the anchored station 6 (Figure 1) situated in the inner part of the ria over 11 separate tidal cycles in order to qualitatively determine the tidal role with more accuracy. Station 6 is under the greatest influence of river discharge and tidal effects and therefore provides a suitable reference point for the study of the main currents in the ria and the hydrographic response of the system to changes in external factors, such as wind, tide, and river discharge. We acknowledge that both the speed and direction residual flows and tidal pumping of salt are influenced by channel topography [*Uncles et al.*, 1985], and therefore we restrict our argument to the deeper part of the section.

An overall analysis of the data at the semidiurnal station has shown that maximum currents correspond to the upper 5 m of the surface layer during February to July 1998, when highest surface velocities oscillated around 22 cm $s^{-1}$ and around 14 cm $s^{-1}$ below 5 m, with a tidal range of 3.2 m. Therefore the Pontevedra Ria may be compared with hypersynchronous-type estuaries [*Dyer*, 1997], where convergence exceeds friction and tidal currents increase toward the head of the estuary. Accordingly, it is postulated that tidal forcing in the Pontevedra Ria is only important in the innermost part of the ria landward of station 6, since seaward of the mid-ria channel the ria widens and both gravitational circulation and tidal currents are presumably reduced, increasing the importance of transverse shear dispersion of salt [*Uncles et al.*, 1985].

Current velocities over a typical tidal cycle (i.e., negligible wind influence) are exemplified by those obtained in cruise 5b (Figure 8), when winds measured on board the boat were of an east-southeasterly component with an average velocity of 1 to 3.5 m $s^{-1}$. Both at the surface and bottom the water leaves the ria on the ebb and enters on the flood whereby the whole water column shifts back and forth on the same timescale. At high and low tide, the velocities at all levels are practically zero. Maximum velocities (0.12 m $s^{-1}$) were measured at approximately 6-m depth on the incoming flow, and near the bottom, velocities decreased owing to bed friction. Con-

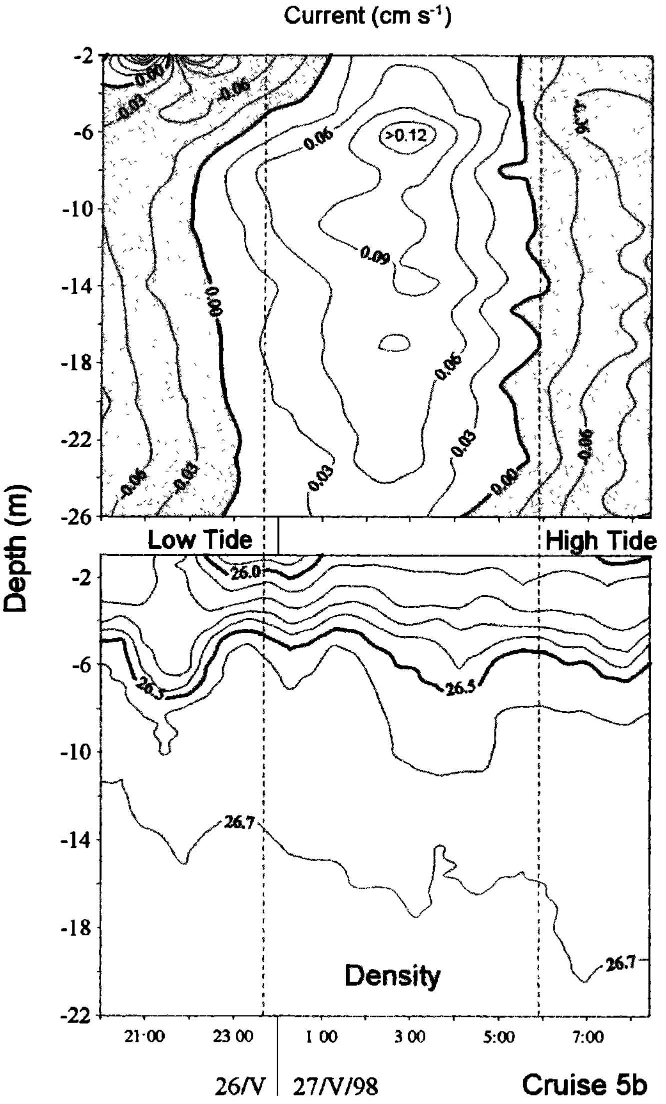

**Figure 8.** Current and density (gamma-*t*) contour plots in the inner zone of the Pontevedra Ria without wind influence (cruise 5b). The data were collected over a tidal cycle at station 6 (anchored) with a tidal range of 3.2 m on May 26-27, 1998.

siderable vertical shear dispersion was observed in the water column around low tide, where the surface layers continued to ebb for up to 2 hours while the lower layers were on the flood. At high tide the effect was less important. This inertia of the water column is similar to what is commonly known as tidal straining [*Simpson et al.*, 1990], which describes the inertia of the surface layers to move with the bottom layers at the start of the ebb. In view of the fact that the transverse component of the current is practically negligible in comparison with the longitudinal flow, the currents in Figure 8 only depict the latter.

The circulation pattern described above may be altered when winds in the ria are greater than 4 m $s^{-1}$, which appears to be the velocity threshold for wind-induced circulation in the surface layers [*deCastro et al.*, 2000]. This is the case in February (cruise 2b; Figure 9), when the wind measured on the boat was of an easterly component with a velocity of 5 to 7 m $s^{-1}$. The asymmetry of the tidal cycle in both time and space is clearly visible in the water column. Essentially, there was a weak gravitational circulation on approach to high tide with the incoming tidal flow tending to circulate below the surface layer with a velocity of no greater than 8 cm $s^{-1}$, while the seaward flow simultaneously passes overhead for most of the tidal cycle with velocities reaching 15 cm $s^{-1}$. Therefore the flow at depth may move in the contrary direction to the wind as a result of the barotropic pressure gradient established by the wind. The water flows out of the ria regardless of the tidal state and results in an ebb of 4 hours and a longer flood of 8 hours to compensate for the indirect wind influence on the bottom waters.

Density did not present any large intratidal cycle contrasts, although it did show vertical oscillations of the isopycnals at tidal frequencies (Figures 8 and 9). The lowest density on cruise 5b was recorded on the ebb (25.9 kg $m^{-3}$) when a pocket of lower-density water passed the boat. The internal

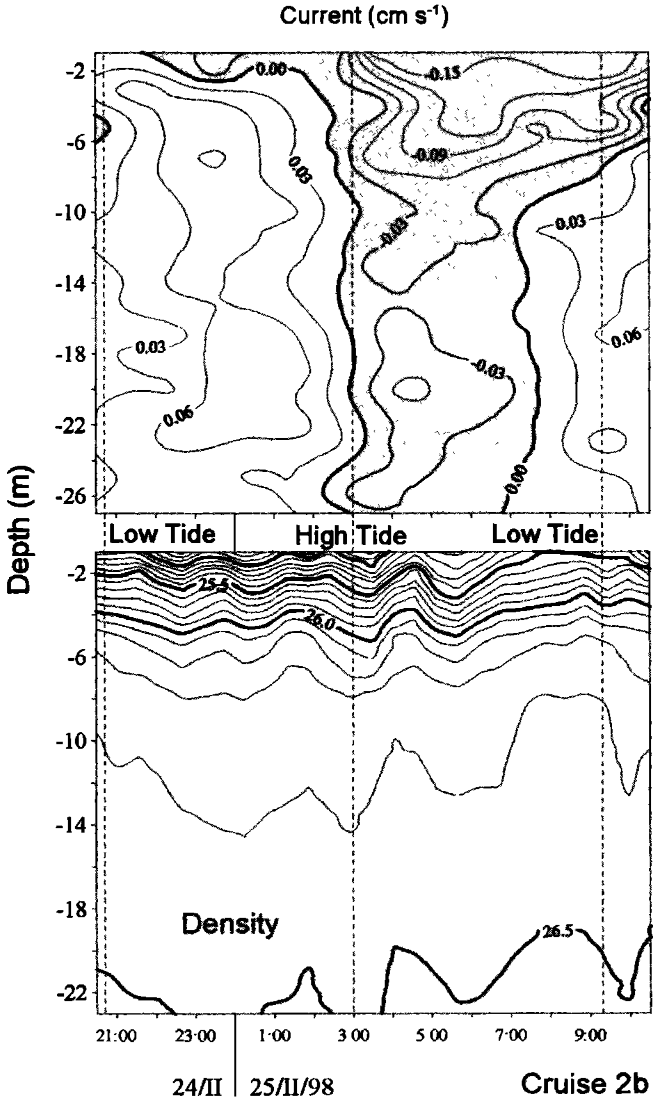

**Figure 9.** Current and density (gamma-*t*) contour plots in the inner zone of the Pontevedra Ria under wind influence (cruise 2b). The data were collected over a tidal cycle at station 6 (anchored) with a tidal range of 3.0 m on February 24-25, 1998.

waves on both cruises are in phase throughout the water column with greater amplitude in the bottom layers than at the surface. An interestingly feature between these structures is the higher wave height in the upper water column on cruise 5b under low wind influence, which is suppressed on cruise 2b. The marked superficial stratification in both figures reflects the thermal gradient characteristic of May and modification by river discharge and tide at the surface layers (uppermost 7 m).

In February, freshwater buoyancy effects mainly control water column stratification and density ranges from 24.4 kg $m^{-3}$ in the surface layers up to 26.2 kg $m^{-3}$ at 5-m depth over a complete tidal cycle. Contrary to what might be expected from the typical setting, there is a surface density minimum during the flood. The rationale could lie with the continual decreasing May fluvial runoff (Figure 2) or, as is more likely, a freshwater discharge near station 7 from a paper pulp factory before high tide. Aside from the paper factory, effluents from a wastewater treatment plant for the city and Marín Harbor are focused in the inner ria in the zone of Marín (Figure 1). The upshot of the contamination has been studied previously on various occasions [*Figueiras et al.*, 1985; *Mora et al.*, 1989], observing wind-influenced isolated pockets of low-salinity water at low tide. Presumably, therefore, the water in this area is advected in line with the circulation pattern previously described.

In contrast to estuaries [*Dyer*, 1997], tides in the Pontevedra Ria only play a significant role in the innermost part of the ria. Given the similar physical and topographical features of the Rias Bajas (Table 1), this finding further clarifies the complex hydrodynamics in this part of the ria and highlights the physical contrast between general estuarine systems and the Galician Rias Bajas.

## 5. Conclusions

A 12-month campaign in the Pontevedra Ria has provided the first insight into the physical processes controlling the hydrography. The hydrodynamics are largely dependent on freshwater inputs inasmuch as the wind regime of the North Atlantic high-pressure cell, the latter determining the extent of oceanic water penetration. Local winds are capable of modifying tidal currents in the inner ria. Upwelling and runoff are the driving forces behind the residual circulation, although by the nature of their origin they are not superimposed, but rather occur separately during the dry and wet seasons, respectively. Occasionally, however, they may be interlinked when favorable upwelling conditions occur in February and rains in June. Fundamentally, it is the large-scale weather patterns which control the hydrography in the Pontevedra Ria.

Facilitated by the wide deep connection to the continental shelf, four distinct water bodies penetrate inside the ria during the course of a year: (1) an autumnal shelf water, (2) seawater showing characteristics of the poleward current in winter, (3) subsurface shelf seawater in May to September when the upwelling relaxes, and finally, (4) the ENACW water mass, whose regular upwelling into the ria in summer is well recognized. The succession of these changes from one water mass to another is rapid and is certainly faster than the 2-week resolution of the sampling frequency.

Oceanic water always enters the ria along the southern coastline, independent of fluvial or upwelling dominance in the ria. Conversely, water tends to leave the ria via the northern coast, except in the case of strong upwelling when water only exits through the southern mouth. This phenomenon is favored by the presence of the islands in the mouth. The rhythmic exchanges of ria and shelf water are superimposed on the spring neap tidal regime. Tidal forcing, however, appears to be a minor factor in the exchange and mixing of water with the ria, although can be important locally on short timescales where it has strongest influence in the innermost part of the ria.

An important conclusion to this work has been to highlight the extendibility of our results to the other Rias Bajas, while simultaneously drawing comparisons to classical estuaries of which rias are commonly classified. Furthermore, we emphasize that similar behavior is probable in other temperate systems dominated by dynamic climate regimes, above all those on eastern seaboards where upwelling is common.

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A. W. Dale and R. Prego, Marine Biogeochemistry Research Group, Instituto de Investigaciones Marinas, CSIC, 36208 Vigo, Spain (awdale@iim.csic.es; prego@iim.csic.es)

M. deCastro, M. Gómez-Gesteira, Group of Physical Oceanography, Department of Applied Physics, University of Vigo, 32004 Ourense, Spain. (mdecastro@uvigo.es; mggesteira@uvigo.es)

P. Montero, V. Pérez-Villar, J. J. Taboada, and M. R. Villareal, Group of Non-linear Physics. Faculty of Physics, University of Santiago de Compostela, 15706 Santiago de Compostela, Spain. (uscfmpmv@cesga.es; uscfmjth@cesga.es; uscmrv@cesga.es)

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