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Climatology and reconstruction of runoff time series in northwest Iberia: influence in the shelf buoyancy budget off Ría de Vigo

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SUMMARY: River runoff off northwest Iberia generates a low-density buoyant structure with a strong influence on shelf and coastal circulation. This study estimates the runoff to the shelf of the ten largest rivers in the region based on the furthest downstream gauge records available, and also takes into account the basin area downstream from the station (22% of the basin area for the entire study region). Monthly statistics were computed to obtain mean values for each river to cover the recurrent lack of runoff data in the region. In order to reconstruct gaps in the time series on a daily scale, a method based on the observed discharge of a nearby river basin was used. In addition, the influence of runoff on the shelf was analyzed using monthly CTD data sampled during a 12-year period in the Ría de Vigo and the adjacent shelf. The CTD series shows the existence of a buoyant structure with maximum growth during winter and with large variability of its thermal anomaly. The salinity anomaly correlated significantly with mean winter monthly values of the North Atlantic Oscillation (NAO) index. This atmospheric index integrates both the influence of precipitation —and therefore runoff— and the predominant winds during winter that contribute to the accumulation of fresh water over the shelf.

Keywords: runoff, river plumes, buoyant flux, climatology, Ría de Vigo, Iberia.

RESUMEN: CLIMATOLOGÍA Y RECONSTRUCCIÓN DE SERIES TEMPORALES DE DESCARGA FLUVIAL EN EL NOROESTE DE IBERIA: INFLUENCIA EN EL BALANCE DE DENSIDAD SOBRE LA PLATAFORMA. – La descarga fluvial en el Noroeste de la Península Ibérica genera una estructura de baja densidad con altas implicaciones en la circulación costera y de plataforma. Este estudio estima la descarga fluvial en la plataforma para los 10 ríos más caudalosos en la región, utilizando para ello los registros de caudal disponibles y suplementados para tener en cuenta el área de la cuenca que se encuentra aguas abajo de las estaciones de aforo (~22% del área total de la región de estudio). Se han calculado valores medios mensuales para cada río, que resultan útiles para cubrir la recurrente carencia de datos en la región de estudio. Para reconstruir huecos en las series temporales en una escala diaria, se utiliza un simple método basado en las observaciones realizadas en una cuenca cercana. La influencia de la descarga fluvial sobre la hidrología en la plataforma es analizada mediante datos mensuales de CTD muestreados en la Ría de Vigo y la plataforma adyacente durante los últimos 12 años. Las series temporales de CTD muestran plumas de agua dulce con máximo crecimiento durante el invierno y con gran variabilidad en su estructura térmica. La correlación de la anomalía de densidad con valores medio invernales del índice de la Oscilación del Atlántico Norte (NAO) muestra valores significativos. Este patrón atmosférico es representativo de la influencia de la precipitación —y por tanto, la descarga fluvial— y los vientos predominantes durante el invierno, que contribuyen a la acumulación de agua dulce sobre la plataforma.

Palabras clave: descarga fluvial, plumas de río, flotabilidad, climatología, Ría de Vigo, Iberia.

INTRODUCTION

Fresh water introduced into the coastal region by river discharge creates a budget for both buoyancy and inertia as a consequence of the drainage of a light fluid into a denser environment. The dynamical structure formed can influence sediment transport, biogeochemical processes, larval transport, pollutant patterns and coastal circulation. In the western Iberian region, many rivers contribute to generating river plumes, which have the largest extension during the downwelling season (autumn and winter) when river discharge is high and S-SW winds are predominant. River plumes are known to strongly influence circulation in the area (e.g. Santos *et al*., 2004; Varela *et al*., 2005; Ruiz-Villarreal *et al*., 2006; Álvarez-Salgado *et al*., 2006; Torres and Barton, 2007; Herrera *et al*., 2008; Otero *et al*., 2008). The thickness and the extension of the plume, which has typical values of 10 to 40 m and 15 to 30 km respectively, respond to wind event variability (Otero *et al*., 2008). Typical plume speeds are of around 0.1 to 0.3 m s^{-1}, but can reach values over 1 m s^{-1} in response to extreme meteorological events combined with high river discharge to the shelf (Ruiz-Villarreal *et al*., 2005).

River discharge data or runoff estimations have been used to study processes in Galician rias, including residual circulation (e.g. Otto, 1975; Fraga and Margalef, 1979; Prego *et al*., 1990; Montero *et al*., 1999), seasonal patterns and long-term trends (e.g. Nogueira *et al*., 1997), nutrient salt output by rivers (e.g. Vergara and Prego, 1997), the shelf-rias exchange (e.g. Prego *et al*., 1990; Álvarez-Salgado *et al*., 2000), river plumes over the shelf (e.g. Otero *et al*., 2008) and spatio-temporal variability of organic carbon (e.g. Doval *et al*., 1998). Therefore, the availability of river discharge data is of great interest to oceanography in the area.

Previous contributions have focused on estimating the volume of freshwater input into the Rías Baixas (Otto, 1975; López-Jurado, 1985; Rosón *et al*., 1991; Ríos *et al*., 1992) and not on the overall contribution of fresh water to the continental shelf off northwest Iberia. In contrast with previous local studies, other studies of global coverage have tried to estimate the freshwater discharged into the shelf at the expense of low resolution (e.g. Baumgartner and Reichel, 1975; Fekete *et al*., 2002; Dai and Trenberth, 2002). These global estimations are based on hydrological discharge models which are fed with streamflow data or use daily precipitation and parameterize evaporation to compute runoff. These studies integrate over latitudinal ranges and exclude low-discharge systems. Dai and Trenberth (2002) estimated annual and monthly continental freshwater discharge into the oceans by using the world's largest 150 rivers, but in this estimation only the River Douro appears in the western Iberian region. Currently, the Global Runoff Data Centre (GRDC) —a digital world-wide depository of discharge data and associated metadata under the auspices of the World Meteorological Organization (WMO)— only includes data from the Rivers Miño (from 1982 to 1989) and Douro (1933 to 1991) in northwest Iberia, in its catalogue.

In this contribution, we analyze runoff for the largest rivers between 41ºN (close to the Douro river mouth) and 43ºN (Cape Finisterre). These rivers are strongly regulated by dams and have gauging stations far upstream from the river mouth, and hence do not account for the runoff at the mouth corresponding to the overall basin area. In many cases, stations are non-operational for long periods of time or the recorded data are unavailable. For these reasons, the aim of this study is to gather available data for the region in order to obtain a seasonal climatology useful for many oceanographic studies, particularly for numerical model simulations, and also to reconstruct the time series on a daily scale during periods with no observations. The reconstructed time series allows the study of the interannual variability of river discharge. In addition, we have related runoff to temperature and salinity profiles sampled monthly in Ría de Vigo and the adjacent shelf from 1994 to 2005. River runoff and dominant winds turn out to be the main factors that contribute to the accumulation of fresh water over the shelf.

The paper is organized as follows: In the Material and Methods section we introduce the available streamflow data and we describe the method used for estimating the mean daily discharge for each river. In the Results, we present a climatological estimation of runoff and use a simple method for reconstructing the discharge signal on a daily scale. Temperature and salinity on the shelf are related to runoff, precipitation, the upwelling index and the NAO index. Finally, the Summary and Conclusions are presented.

MATERIALS AND METHODS

Runoff data

Figure 1 shows the ten largest rivers in the study region, which account for more than 96% of the drainage area from Porto to Cape Finisterre as calculated with GIS software. The figure also shows a complete set of gauging stations in the region (height levels and flow meters), including old stations currently not functioning. These stations are maintained by different institutions. Spanish rivers with their basin area entirely within the Galician region (Verdugo-Oitavén, Lérez, Umia, Ulla and Tambre) are administered by the regional government through the organization *Augas de Galicia* (http://augasdegalicia.xunta.es). Spanish rivers with their basins extending over several regions are administered by the national government. The River Miño and its tributary the River Sil and also the catchment area of the River Lima in Spain are administered by the national organization *Confederación Hidrográfica del Miño-Sil* (http://www.chminosil.es). This organization was created in 2008 as a division of the *Confederación Hidrográfica del Norte*, which has administered resources from river basins in the entire northern Spanish region since 1961. Runoff data are available from the previous institutions on request. Finally, Portuguese rivers are administered by the organization *Instituto da Água,* who make the records from their gauging stations available directly through their website (http://snirh.inag.pt). This data set also includes records obtained at the stretch of the River Miño that marks the border between Spain and Portugal.

Estimating mean daily discharge

Neglecting groundwater discharge, gauge records of streamflow are the basic data for estimating continental discharge. The accuracy of river discharge measurements is in the range of 10 to 20%, which is much higher than the precision that can be achieved in measuring precipitation, another variable frequently employed to estimate continental runoff (Hagemann and Dümenil, 1998). Moreover, the most accurate estimation of the freshwater discharge from a river basin is based on streamflow data from a near-coastal gauge, or in its absence, from the station furthest downstream. In spite of the large number of gauging

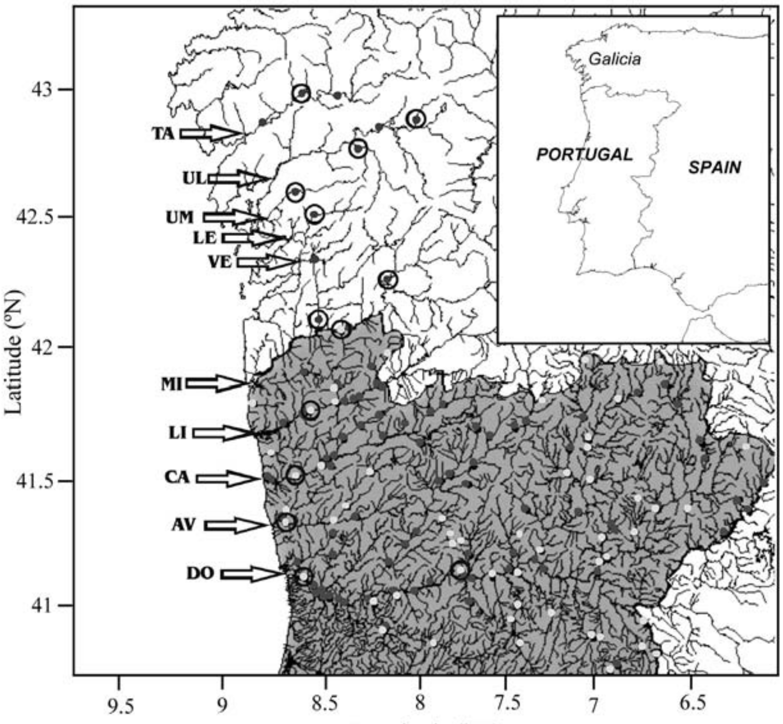

FIG. 1. – Map with all gauging stations in the study region. The gray area is Portugal and the white area is Spain. In the Portuguese region, gray dots indicate conventional recording of data, whereas the white ones indicate automatic recording of data. Black circles show the selected stations in this study. The river mouths are indicated with the first two letters of their names: TA (River Tambre), UL (River Ulla), UM (River Umia), LE (River Lérez), VE (River Verdugo), MI (River Miño), LI (River Lima), CA (River Cávado), AV (River Ave) and DO (River Douro).

TABLE 1. – Gauging stations used in the study. Gauging codes are the same as those available on request to purveyor institutions. The location of the gauge, the maximum instantaneous discharge (MID), mean daily discharge (MDD), the area upstream from the gauging station (SBA) and the total basin area (TBA) are shown. The longest available time series have been employed in the analysis; there may be some gaps in time series.

River	Station	Code	Lat (ºN)	Lon (ºW)	Period	MID($m^3 s^{-1}$)	MDD($m^3 s^{-1}$)	SBA(km^2)	TBA(km^2)
Tambre	Carollo - Sigüeiro	520	42.97	8.39	7/3/2002 - 30/9/2004	27/12/2002 186.65	49.72	561	1526
	Puente de Portomouro	519	42.96	8.64	1/10/1996 - 30/9/2001	5/1/2001 537.14	44.52	1146	
Ulla	Santiso	544	42.84	8.00	1/10/1996 - 30/9/2004	10/4/1998 206.74	14.71	516	2804
	Cira - Deza	552	42.77	8.35	1/10/1994 - 30/9/2004	22/10/2001 350.11	17.66	545	
Umia	Caldas de Reis	564	42.60	8.64	1/10/1997 - 31/7/2001	8/3/1999 81.20	11.77	190	446
Lérez	Cutián	574	42.52	8.53	1/1/1970 - 31/12/1998	-	-	248	450
Verdugo	-	-	42.36	8.54	1/1/2001 - 31/12/2003	22/10/2001 78.43	6.88	136	348
Oitavén	-	-	42.34	8.55	1/1/2001 - 31/12/2003	22/10/2001 60.00	9.52	173	
Miño	Frieiras	Frieiras	42.15	8.19	1/10/2000 - 31/12/2002	16/8/2002 11003.00	245.54	-	16347
	Tea (tributary)	645	42.08	8.52	1/10/1998 - 31/12/2002	21/3/2001 282.17	17.40	287	
	Foz do Mouro	01G/02H	42.07	8.38	1/10/1973 - 30/9/2005	8/12/2000 4680.00	316.42	15407	
Lima	Ponte Lima	03F/02H	41.77	8.58	19/4/1945 - 30/9/1990	24/01/1980 2390.96	67.84	2198	2480
Cávado	Barcelos	04F/02H	41.53	8.62	1/10/1978 - 30/9/1990	21/12/1989 864.66	63.52	1437	1648
Ave	Açude de Tougues	05E/02H	41.37	8.70	1/10/1978 - 30/9/1990	7/2/1979 375.70	25.32	1137	1391
	Ponte Ave	05E/03H	41.35	8.67	1/10/1986 - 30/9/1990	06/02/1988 536.57	30.59	1109	
Douro	Régua	07K/01H	41.15	7.78	1/10/1939 – 30/9/1967	21/1/1941 5520	514	90370	97682
	Rio Mau	07G/03H	41.05	8.38	1/10/1976 – 30/9/1985	15/01/1977 5568	478	95991	

stations in the study region (Fig. 1), the majority of these stations are currently out of order or have recurrent problems in data acquisition (errors during flooding or drought events due to inappropriate location of the station, location not easily accessed on foot, which restricts maintenance, etc.). Consequently, for each

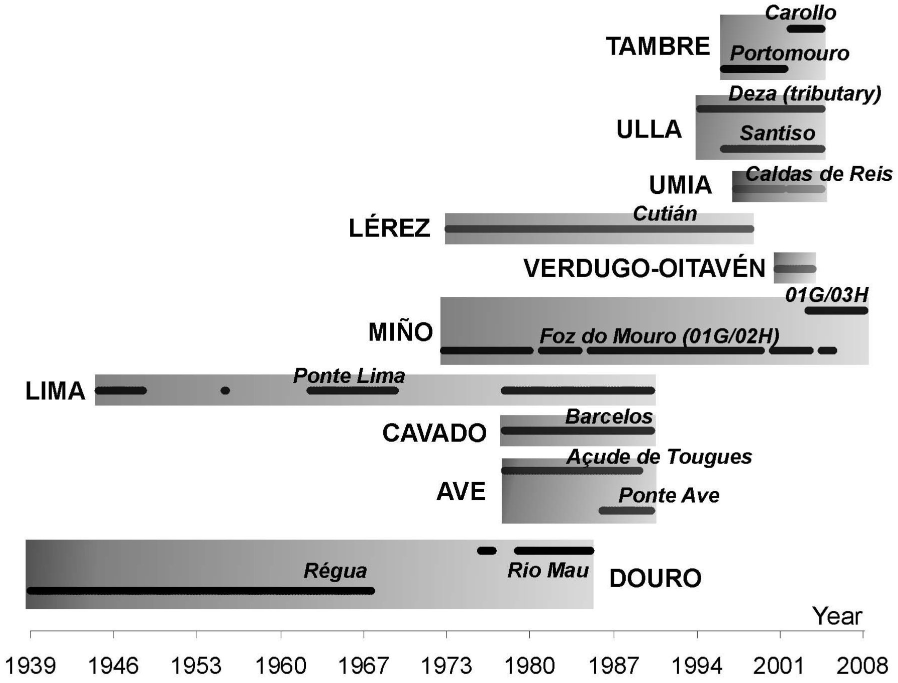

FIG. 2. – Available stream flow data (solid lines) from 1939 to 2008 for all rivers. Shaded regions are periods with runoff estimation in the river basin.

river basin, we have selected the gauging station that is furthest downstream from among the set of available gauges with reliable data (see stations highlighted in Fig. 1). Quality controls were applied to mean daily discharge data during compilation, primarily in order to detect errors and inconsistencies in the time series. Before outliers were rejected and in order not to lose flooding events in the time series, the presence of high values on the same day was checked in the recorded time series of the adjacent river basins. During this process it was necessary to take into consideration the characteristics of the gauging stations and river basins: unmonitored tributaries, relocation of the gauge, conversions from river level to streamflow, presence of dams, etc. (see Appendix for a detailed description). Table 1 summarizes the gauging stations employed and the time series processed (location, monitored area, maximum and mean daily discharge, etc.), and Figure 2 shows the available time series for each river after processing. The Rivers Douro and Miño are the main rivers in the region (see data from Foz do Mouro in the case of the River Miño) and have a mean observed streamflow at the gauge of over 300 m^3 s^{-1}. The observed maximum daily streamflow for these two rivers is 11 to 13 times larger than the mean value. This ratio increases to ~35 in the case of the River Lima.

Many selected stations are located far upstream from the coast and thus streamflow measurements are not representative of the actual outflow into the ocean. The estimation of continental discharge is improved by extrapolating gauge-estimated discharges to the river mouth. This extrapolation is based on the ratio between the total area and the monitored area —upstream the gauging station— of the river basin. Dai and Trenberth (2002), using streamflow records from the world's largest 921 rivers, estimated that the use of outflow at the river mouth increased the global continental discharge by ~19% compared with the use of unadjusted streamflow from the stations furthest downstream. In our study region, this adjustment increases the estimation of the continental discharge by 22% (see areas involved in the estimation in Table 1).

RESULTS

Long-term monthly variability

Long-term monthly means were computed in order to obtain estimates of continental discharge and facilitate the comparison between river basins. Figure 3 shows monthly statistics (mean, median, 5, 25, 75 and 95 percentiles) of runoff estimated at the mouth

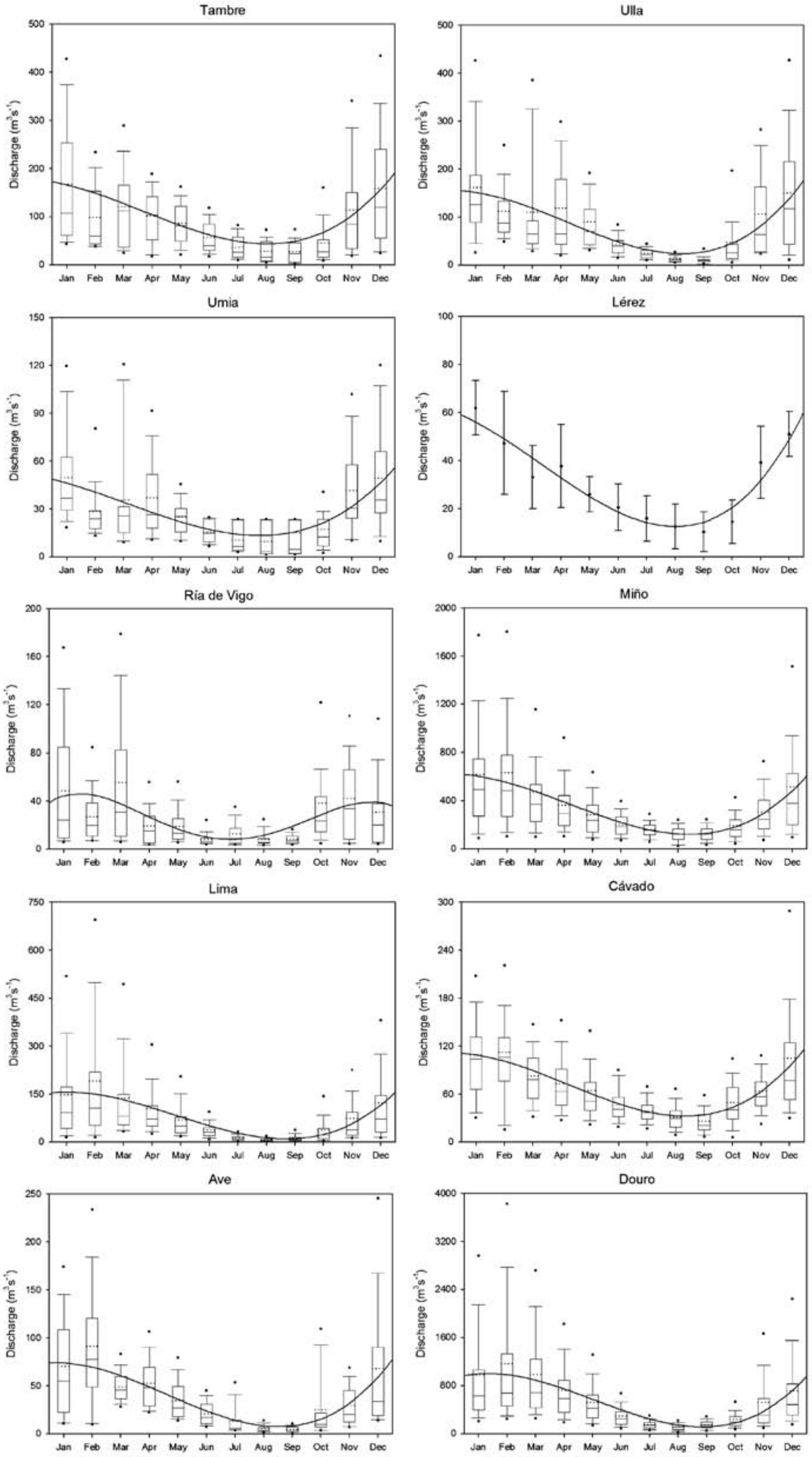

FIG. 3. – Main monthly statistics for the study rivers. The boundary of the box closest to zero indicates the 25th percentile, the solid line within the box marks the median, and the boundary of the box farthest from zero indicates the 75th percentile. Whiskers above and below the box indicate the 95th and 5th percentiles respectively. Dots indicate the minimum and maximum values. In addition, the mean is graphed as a dotted line. In the case of the River Lérez, statistics were computed directly from the few available monthly means and not from estimations of daily discharge data. In this case, only the mean and their associated error bars (±1σ) are plotted. Curves correspond to the polynomial adjustment from monthly means, with an imposed cyclic behavior year-round.

TABLE 2. – Coefficients of the weighted polynomial adjustment to monthly means corresponding to the equation $Q = a + bm + cm^2 + dm^3$, where m is the month of the year expressed as $m = 12d/365$, d is the day of the year running from 1 to 365 and Q is the runoff in $m^3\ s^{-1}$. Note that months correspond to *natural years* instead of *hydrologic years* that start in October and end in September. The correlation coefficient r is also shown ($p<0.05$).

River	a	b	c	d	r
Tambre	100.225	30.370	-11.325	0.795	0.93
Ulla	113.606	26.286	-11.549	0.829	0.95
Umia	36.099	4.737	-2.677	0.209	0.93
Lérez	61.220	-4.656	-1.397	0.150	0.97
Verdugo-Oitavén	40.231	-4.324	-0.701	0.092	0.82
Miño	666.168	-53.636	-13.308	1.442	0.98
Lima	193.179	-19.328	-4.523	0.363	0.96
Cávado	102.194	4.035	-4.543	0.363	0.98
Ave	59.100	7.503	-4.418	0.327	0.95
Douro	1398.688	-195.252	-14.793	2.390	0.96

of each river basin. In the figure, a number of low river discharge systems like the River Umia and River Lérez are evident. Their runoff is low around the year with mean monthly discharges below 70 $m^3\ s^{-1}$. Contrastingly, other fluvial systems in the region have large discharges, like the Rivers Miño and Douro, with mean monthly discharges over 110 $m^3\ s^{-1}$.

Seasonal variability is especially strong in the Rivers Ave and Lima, which have low runoff during summer and relatively high discharge during winter. The ratio between mean monthly river discharge in February and August for the River Lima is around 20. Winter is the season with stronger inter-annual variability for all rivers (see observed range between the 25th and 75th percentiles).

A curve fit of mean monthly discharges was performed to obtain a seasonal climatology. We obtained higher χ^2 using a third order polynomial adjustment than using a typical harmonic adjustment. These curves (see Table 2 and Fig. 3) are the best estimation of monthly means that we can obtain with the available data set, and the uncertainties are mainly related to the large standard deviations in runoff values during winter months. The major discrepancies between predicted and observed discharges are found during February. In this month the climatologic value is higher than the mean for rivers flowing into Galician Rías, while it is lower than mean values for those rivers flowing to the south of that region. In the first group of fluvial systems, the mean monthly discharge in February is also lower than that in January and March, with the opposite pattern in the second group.

Figure 4 shows a comparison between this climatology and the estimated discharge at the mouth of the River Miño and River Douro. In the case of the River Douro, only estimations from the most recent available data from the *Rio Mau* station (see Table

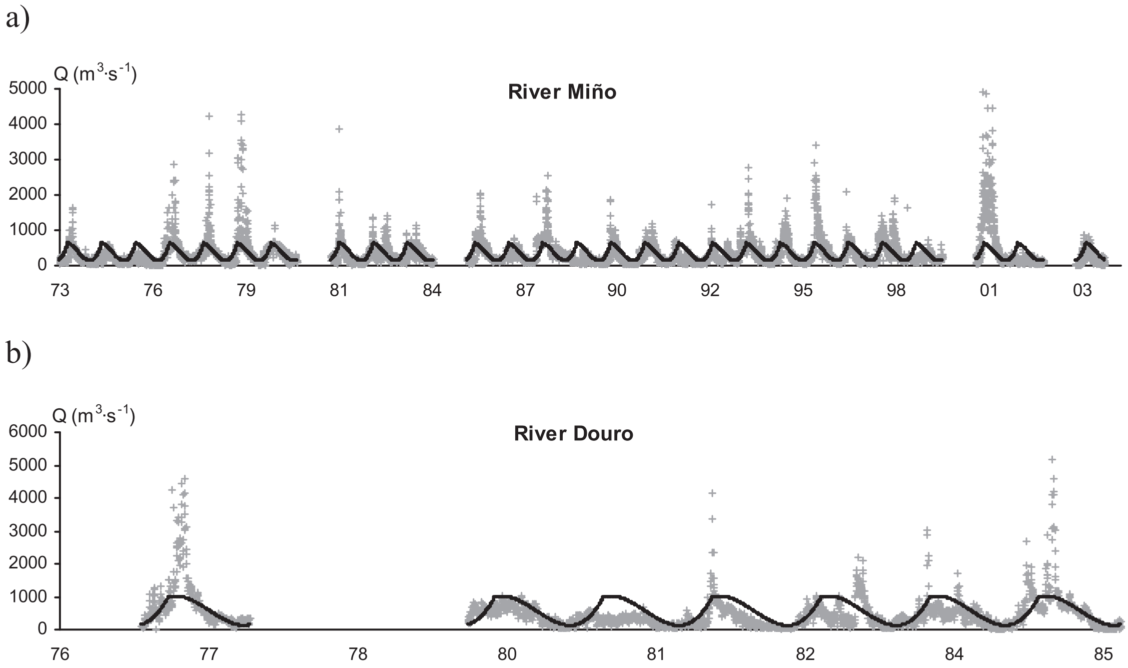

FIG. 4. – Plots showing the high inter-annual river discharge variability and the error-fitting with climatological values. River discharge data corrected as explained in Material and Methods (grey dots) is compared to the estimated climatological value from the Results section (black line). The complete available time series is plotted in the River Miño (a); nevertheless, only data estimated from the Rio Mau station are plotted in the River Douro (b) to avoid a very long time series.

TABLE 3. – Correlation matrixes (r) of runoff estimated at the mouth of river basins (95% significance level). Matrixes are separated into northern (a) and southern rivers (b) due to the higher correlation among rivers flowing into Rías Baixas compared to those flowing into southern regions. The relocation of the gauging station of River Tambre at the end of 2001 resulted in different correlations based on time periods before and after this date.

a)	Tambre	Ulla	Umia	Ría de Vigo	Miño
Tambre	1.00	0.49 / 0.66* / 0.84**	0.37 / 0.48** / 0.57**	0.54	0.01
Ulla	0.49 / 0.66* / 0.84**	1.00	0.58	0.66	0.02
Umia	0.37 / 0.48** / 0.57***	0.58	1.00	0.54	0.01
Ría de Vigo	0.54	0.66	0.54	1.00	0.12
Miño	0.01	0.02	0.01	0.12	1.00

* October 1996 to September 2001; ** March 2002 to September 2004; *** October 1997 to September 2001

b)	Miño	Lima	Cávado	Ave	Douro
Miño	1.00	0.64	0.67	0.77	0.66
Lima	0.64	1.00	0.52	0.74	0.31
Cávado	0.67	0.52	1.00	0.72	0.62
Ave	0.77	0.74	0.72	1.00	-
Douro	0.66	0.31	0.62	-	1.00

1) are plotted. Although the climatological signal is consistent with observations, a high inter-annual variability can be observed in both rivers. Wet winters when discharge was high in both fluvial systems (e.g. 1976/1977 and 1984/1985) contrast with drier winters (e.g. 1979/1980). This variability can be clearly seen during the last years in the River Miño series: while 2001 was a year with heavy rain, 2002 was a dry year and in 2003 the evolution was similar to the climatological cycle. In contrast with winter and early spring, inter-annual differences in rainfall during summer are lower and runoff approximates to the climatological signal. As seen in the figure, during winter the observed daily river discharge can be 5 to 7 times larger than the climatological estimation.

Reconstructed runoff time series

Many studies, like realistic model simulations or biogeochemical budget estimations in estuaries, require the use of real river discharge data instead of climatological values. In northwest Iberia, the lack of river discharge data is a recurrent problem, and for this reason an estimation of the discharge is very useful when a gap in the time series is present.

Estimation based on runoff from a neighboring basin

If the characteristics that affect runoff (precipitation, evaporation, vegetation and water retention of the soil) are similar in two neighboring river basin areas, then we can also expect similarities in runoff. With this simple assumption and knowing the mean daily discharge at the mouth of one river and the relation between the climatological signal in the two basins, we can estimate the unknown runoff in the other river basin. The *similarity degree* between river basins was computed as the correlation coefficient between the observed river runoff at the two rivers (see correlation matrix in Table 3). We are aware that the construction of a dam can have an influence on correlations computed during different periods, but the existence of numerous dams in the region makes further analysis extremely difficult. For rivers flowing into the Rías Baixas, the largest correlation is obtained between the Rivers Tambre and Ulla during the period March 2002 to September 2004 ($r = 0.84$; $p<0.05$), after the relocation of the gauging station (see Appendix for further details). Umia has the lowest correlations with the other fluvial systems. The River Miño has higher similarity with Portuguese rivers than with those flowing into the Rías Baixas. In the southern region, the largest correlation is obtained between the Rivers Miño and Ave ($r = 0.77$; $p<0.05$) and the lowest between Lima and Douro ($r = 0.31$; $p<0.05$).

Figure 5a shows an example of the reconstruction of the River Ulla time series and the comparison with the real signal. In this reconstruction we have used data from the River Tambre, which has the highest correlation with the River Ulla. The reconstructed signal mainly follows the pattern of the real data, although river discharge is overestimated. A good estimation is only obtained during floods, when presumably river dam spill is high in both rivers. Contrastingly, during dry periods, dams retain fresh water. However, Figure 5b shows the reconstruction of

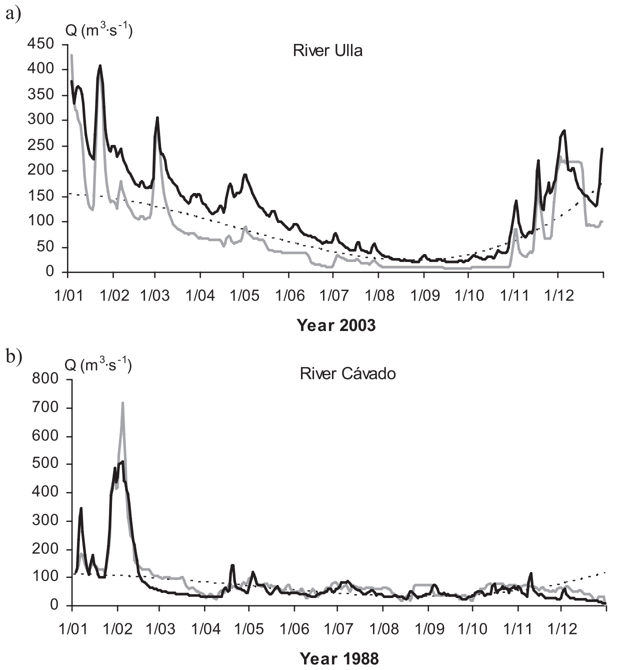

FIG. 5. – Reconstructions of the river discharge signal for the River Ulla (a) and River Cávado (b). The real data (solid gray line) and the climatological signal (dashed black line) are compared to the reconstructed signal (solid black line).

the River Cávado using data from the River Lima. In this case we have used the river with the lowest correlation in Table 3b to show that the estimation is also acceptable, with the exception of the runoff estimated during the winter season. In January, river discharge is overestimated in around 150 m^3 s^{-1} whereas during February the reconstructed signal is around 200 m^3 s^{-1} lower. During March, Cavado river runoff is again underestimated. The actual runoff in the River Lima basin was very high during early January and was lower than expected from mid-February to the end of March. This pattern was reflected in the reconstruction of the Cávado time series.

The method attempts to reconstruct the signal and to estimate the variability of the system on a daily scale and proves to represent individual events. Nevertheless, as we have illustrated, some differences in the actual and predicted series are apparent and we must use these reconstructed series with caution. Similarly to Rosón *et al.* (1991), the estimation improves when the data are smoothed using a running average of 3 to 15 days window size.

Estimation based on precipitation

The river discharge signal can also be reconstructed based on the precipitation in the river basin following a normalized geometrical progression (Ríos *et al.*, 1992), in a similar way to the runoff estimation to the Ría de Vigo (see Appendix). In this section, we show an example for the River Miño for the period from October 1976 to December 1984. The overall percentage return from gauging stations in this period was 62%. Estimations of mean daily precipitation rate were obtained from the NCEP/NCAR reanalysis data (provided by the NOAA/OAR/ESRL PSD, Boulder, Colorado, USA, from their website at http://www.cdc.noaa.gov/) at a grid point located at the head of the river basin (42.85ºN 7.50ºW). This reanalysis model does not assimilate observations of precipitation and it has low horizontal resolution (1.9º). Nevertheless, it provides a long time series on a daily scale, which makes it suitable for reconstructing gaps in long runoff time series. The method is based on a retention coefficient of the terrain (k) and on the number of previous days to be considered in the estimation (*ndays*). The signal was reconstructed by varying k from 0.01 to 0.99 and *ndays* from 3 to 60 (5742 combinations). The best correlation of the reconstructed signal with real data ($r = 0.54$; $p<0.05$) was achieved with $k = 0.94$ and $ndays = 26$ (the reconstruction with these values is shown in Fig. 6). The reconstructed signal slightly overestimates runoff observations, especially during summer. In the figure we can also observe the reconstruction of the time series using the method based on similarities among river basins. In this case we have used data from the River Douro (at the Rio Mau station), obtaining a significant correlation ($p<0.05$) of $r = 0.66$.

Reconstruction of runoff time series

Following the previous methods, we have reconstructed runoff time series for all rivers (except the

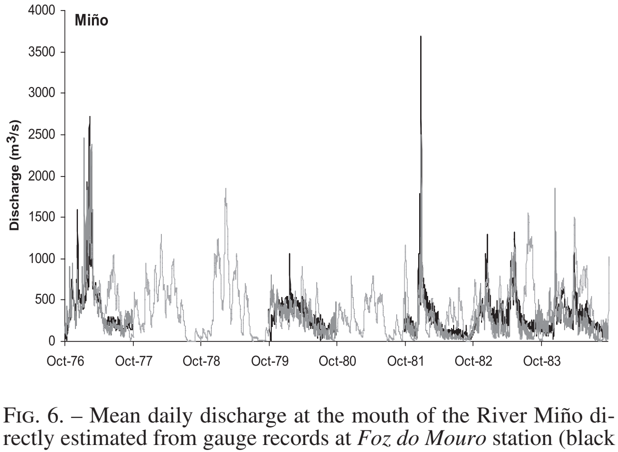

FIG. 6. – Mean daily discharge at the mouth of the River Miño directly estimated from gauge records at *Foz do Mouro* station (black line), estimated from runoff observed in the River Douro (thick gray line) and from precipitation (thin gray line).

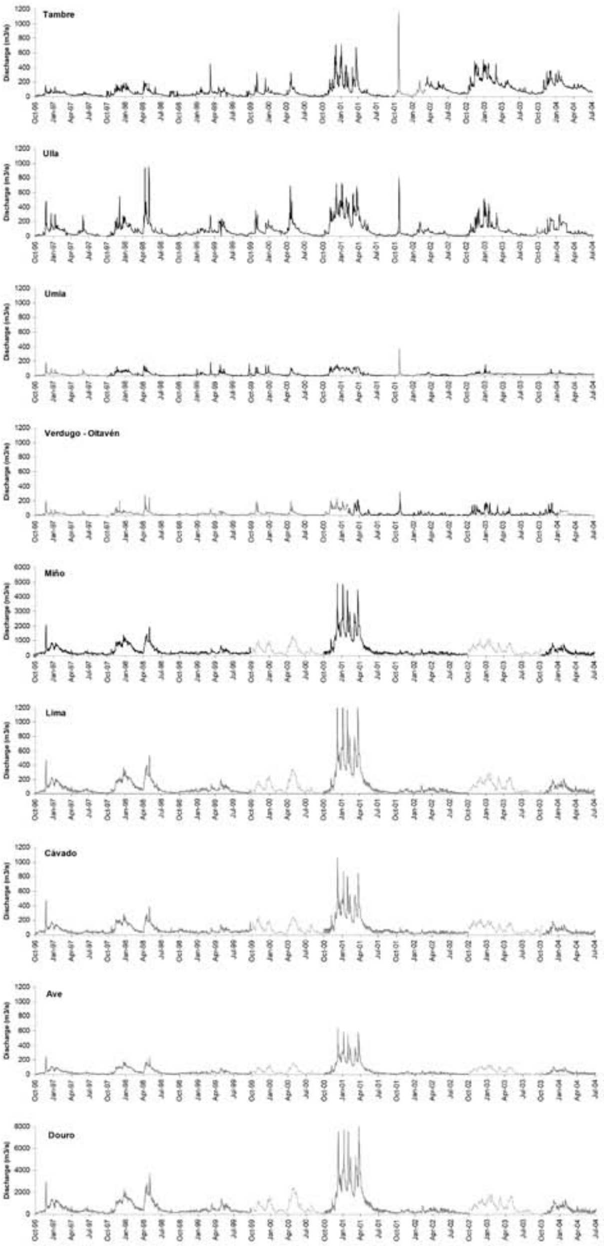

FIG. 7. – Reconstruction of the entire set of rivers based on a high correlated river basin in terms of runoff (thick gray line) and on precipitation rate (thin gray line) from October 1996 to August 2004. Direct estimations of river discharge at the mouth of the rivers from available gauge records (black line) are also shown.

River Lérez due to unavailability of daily records) from October 1996 to September 2004 (Fig. 7). This is the period with more data available for rivers flowing to the Rías Baixas. Rivers flowing to the Rías Baixas were reconstructed based on the known discharge of other river basins, shown in Table 3. The time series of Portuguese rivers were reconstructed using mean daily River Miño discharges estimated from the Foz de Mouro gauging station (see Appendix). This station has the longest time series of Portuguese rivers and the correlation with all Portuguese rivers is acceptable (Table 3). The lack of reliable gauge records at Foz de Mouro during two hydrologic years (1999/2000 and 2002/2003) led us to reconstruct the time series following the method based on the precipitation in the area.

Runoff influence on the shelf buoyancy budget

In the coastal region off northwest Iberia, river discharge creates a buoyancy budget mainly present from autumn to spring (coinciding with maximum river discharge) that strongly influences shelf circulation in the region (Otero *et al*., 2008). The study of short-term river plume dynamics with hydrographical surveys is hampered by the high variability of river plumes in response to wind events, which is of the order of hours. However, although the sampling frequency in the usual surveys is not adequate for resolving the temporal and spatial variability of fresh water, field surveys can be used for assessing the effect of seasonal and interannual scales in river plumes, which result from the cumulative effect of shorter-term wind and runoff variations.

Since 1987, the Instituto Español de Oceanografía (http://www.ieo.es) in the framework of the IEO Radiales program has been performing monthly sampling that constitutes the longest time series of oceanographic conditions that covers both the Ría

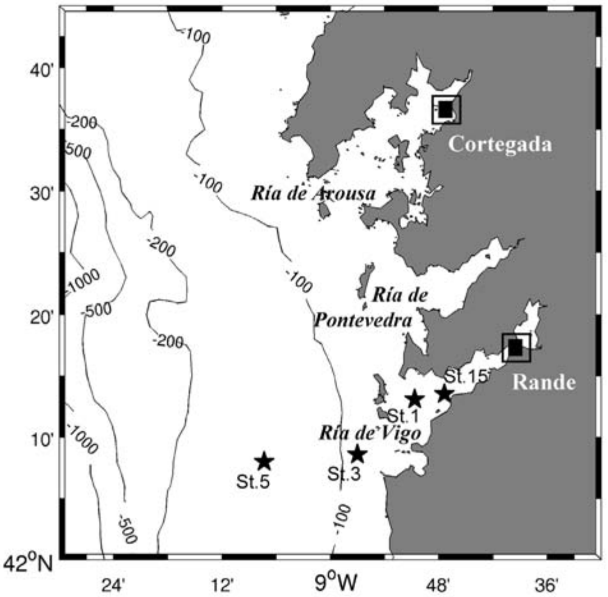

FIG. 8. – Location of the monthly CTD sampling in the Ría de Vigo and adjacent shelf (St.15, St.1, St.3 and St.5) and the oceanographic platforms of Cortegada and Rande. The 100, 200, 5000 and 1000 m isobaths are plotted for reference.

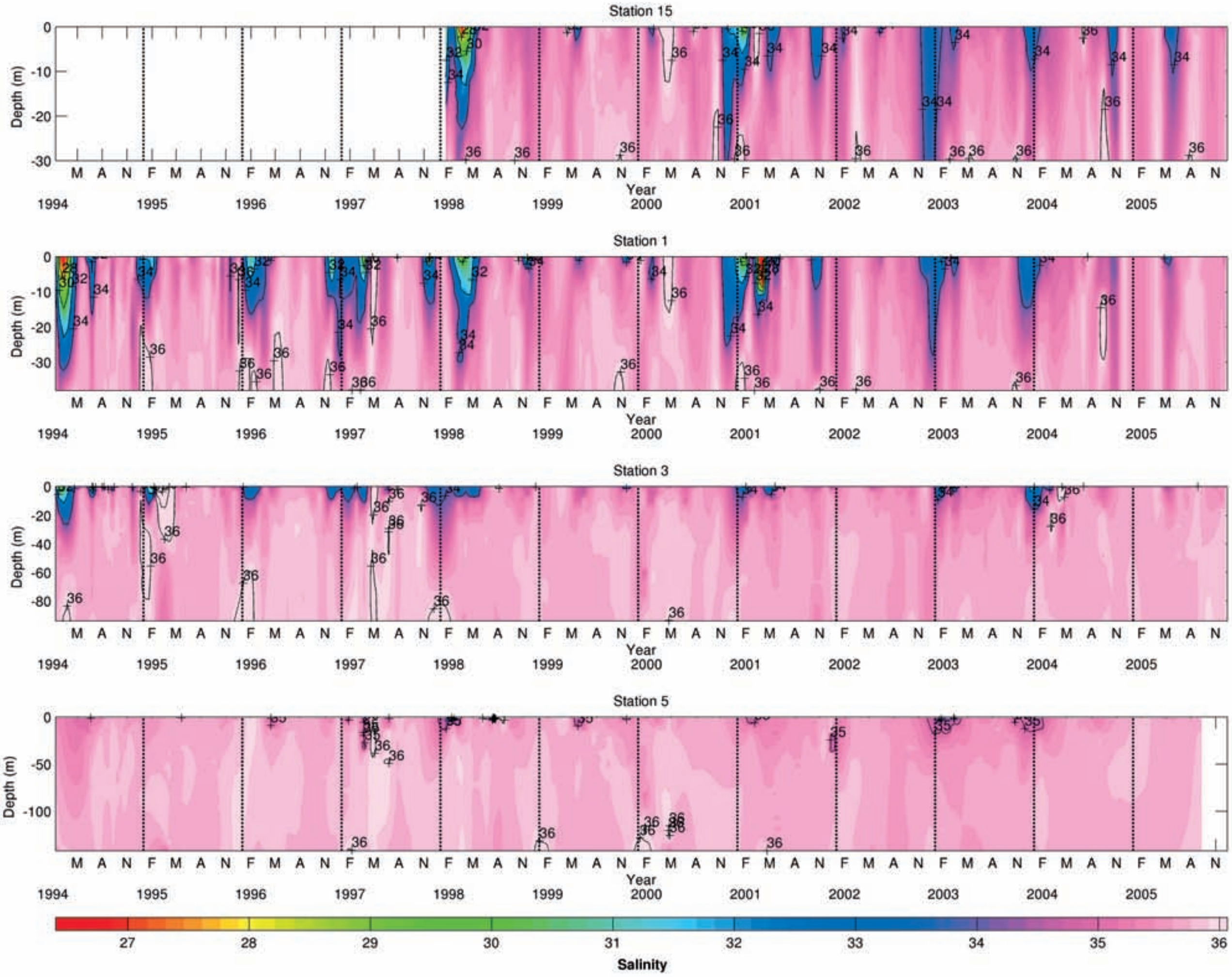

FIG. 9. – Full-depth long-term salinity recorded at the sampling stations from January 1994 to December 2005. Stations are plotted from the inner (top panel; St.15) to the outer (bottom panel; St.5) location with the same color scale. White areas represent a lack of data.

de Vigo and its adjacent shelf. In this study, we have used the four CTD stations of this sampling (Fig. 8) for the period February 1994 to December 2005 to analyze the impact of the freshwater runoff on the temperature and salinity signal. These stations are coded as St.15 (42º13.3’N, 8º47.7’W), St.1 (42º12.8’N, 8º51.0’W), St.3 (42º8.5’N, 8º57.5W) and St.5 (42º7.8’N, 9º7.5’W). The depths of stations are respectively: 30 m, 38 m, 94 m and 142 m. Data have been interpolated to a 1 m resolution profile from the surface to the bottom. St. 15, the inner station in the Ría de Vigo, started to be sampled in January 1998. Figure 9 shows the full-depth salinity signal from the inner (upper panel in the figure) to the outer station (lower panel). The influence of the freshwater runoff is stronger at the inner stations, which are closer to the river mouth. High inter-annual variability is evident in the time series (Fig. 9). Winter 1994, spring 1998, autumn 2000-spring 2001, and autumn 2003 were periods when water in the sampled water column was fresher. In contrast, salinity during winter 1999, spring 2002 and winter 2005 was closer to typical ocean values in the region. During wet winters, fresh water is observable in the entire sampled water column at stations St.15 and St.1. Surface salinity between stations shows a high correlation (*r*) of 0.82 between the inner stations (St.1 and St.15) and 0.79 between St.1 and St.3 (95% significance level). The correlation decreases to 0.46 if computed between the station on the mid-shelf (St.5) and the station at the southern mouth of the Ría (St.3). Correlations between surface salinity on the mid-shelf and inside the Ría are not significant.

Correlations of the temporal evolution of the salinity profile with river discharge of both the River Miño — the main river in the vicinity of the sampled area — and the runoff estimated for the Ría de Vigo have been performed for each station. We have obtained a correlation of river runoff in the Ría de Vigo with near-surface salinity at the inner stations (St.15 and St.1) of *r* over 0.56; with a 95% significance level. The correlation decreases at the southern mouth and mid-shelf stations. The influence of Ría de Vigo runoff is significant in the first 20 m of the water column ($p<0.05$). The correlation of the salinity profile with the runoff of the River Miño is similar to the correlation with the runoff in the Ría de Vigo, with the exception of the station on the mid-shelf. The lack of correlation at this station is in apparent contradiction with the results of Herrera *et al.* (2006). In their study, the adjacent shelf to the Ría de Vigo was sampled with a weekly frequency from May 2001 to May 2002. They found that at their mid-shelf stations, the salinity signal was significantly correlated with runoff from the River Miño in the first 20 m of the water column ($p<0.05$). If we restrict our data to this period then the correlation of our mid-shelf station with River Miño runoff is significant in the first 14 m of the water column. Consequently, we have to point out that although the River Miño runoff can be associated with low-salinity values in the Ría de Vigo, the correlation is only significant during periods when fresh water from the River Miño plume is present on the shelf off Ría de Vigo.

In their study of the Ría de Arousa, Rosón *et al.* (1991) report a high correlation between the River Umia and Ulla runoff and the surface salinity at the innermost part of the ria, measured during a set of surveys that sampled the ria every 3 to 4 days from May to October 1989. We have shown that the hydrographical sampling in the Ría de Vigo does not resolve the salinity fluctuations associated with river runoff. However, in this respect, it is relevant to point out the recent installation of two oceanographic plat-

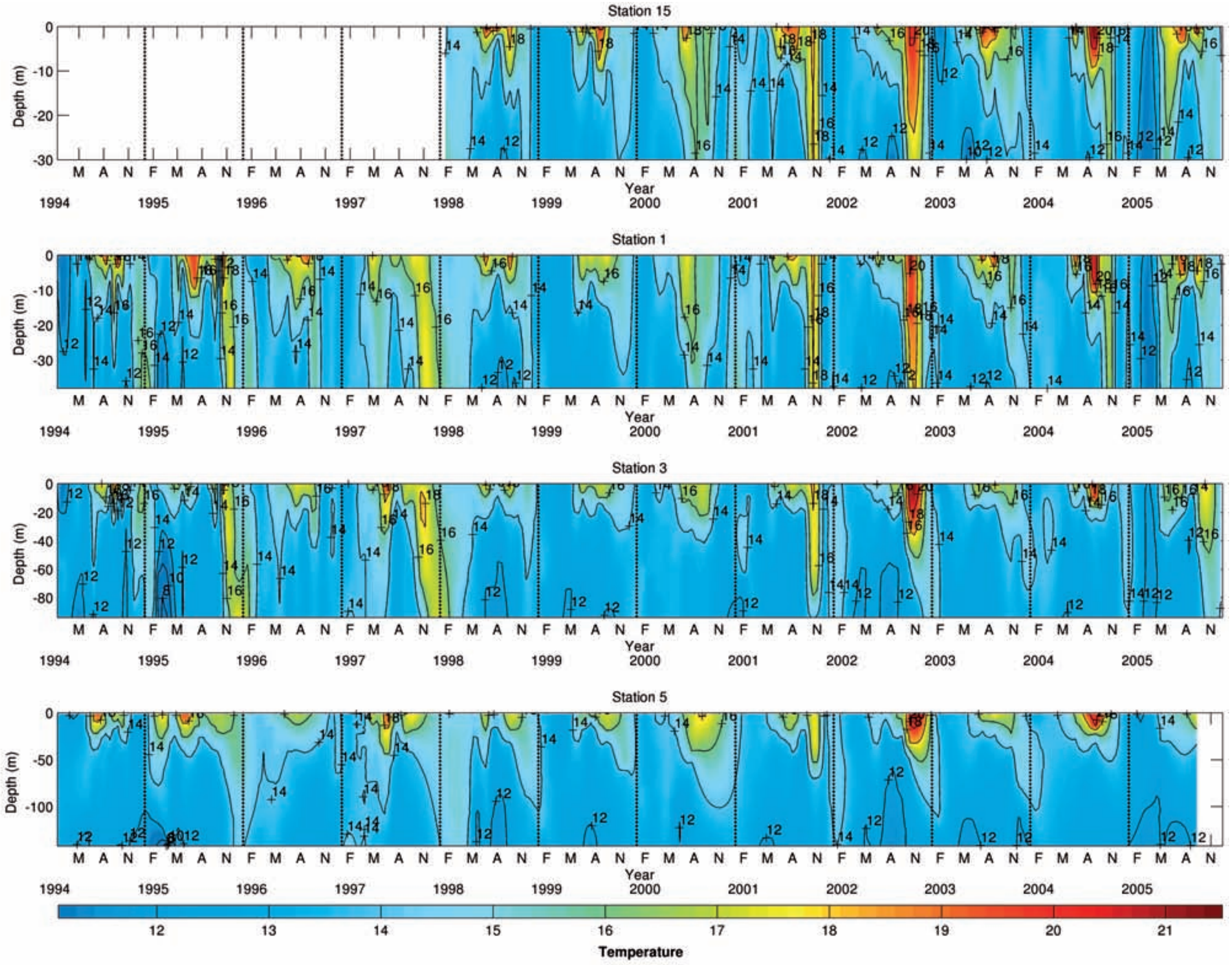

FIG. 10. – Full-depth long-term temperature recorded at the sampling stations from January 1994 to December 2005. Stations are plotted from the inner (top panel; St.15) to the outer (bottom panel; St.5) location with the same color scale. White areas represent a lack of data.

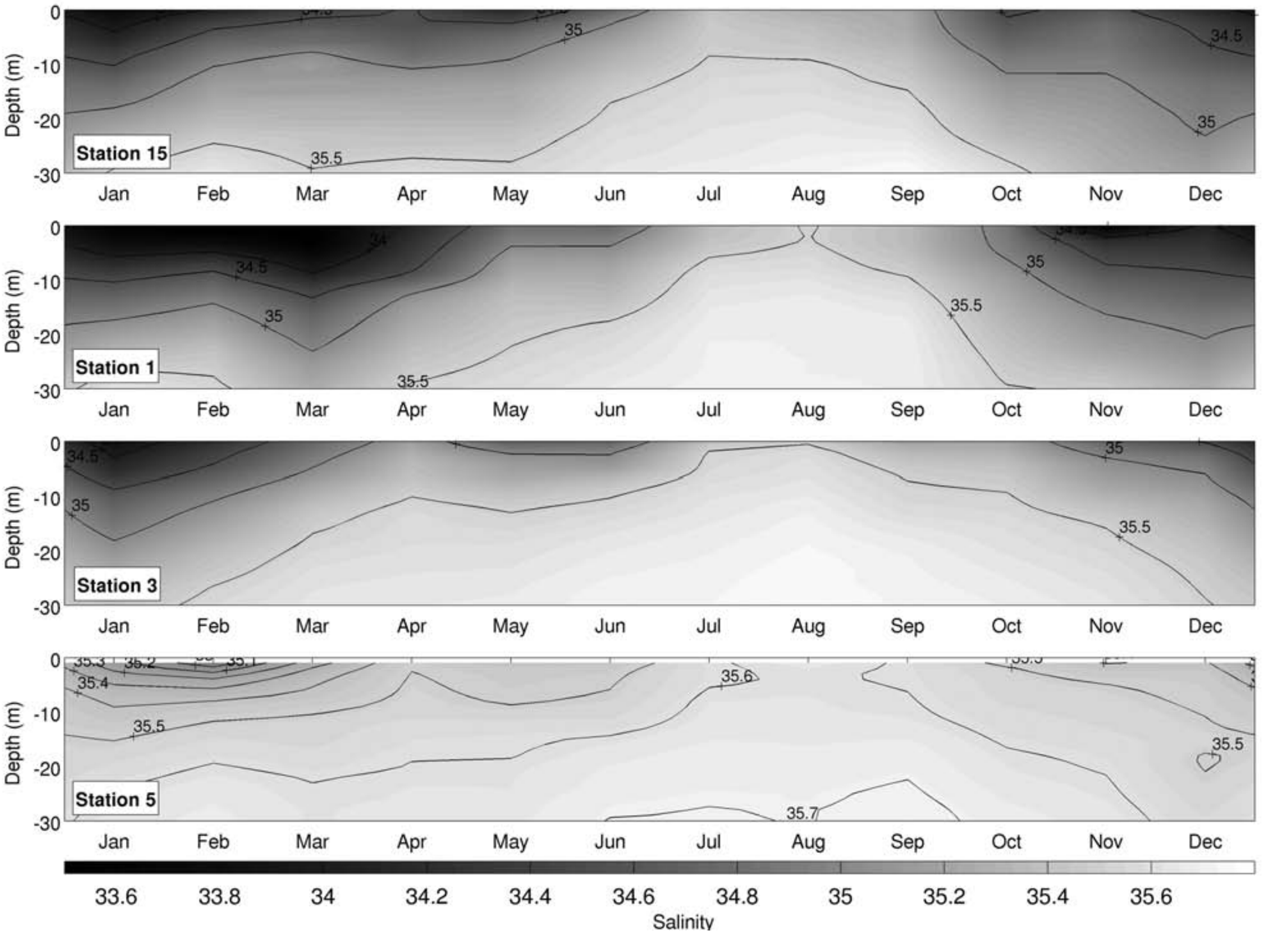

FIG. 11. – Long-term salinity annual cycle computed for the four sampled stations. Data are limited to 30 m depth (the maximum depth of the shallower station) to facilitate the comparison. Cyclic behavior is imposed at the start and end of the year.

forms in the inner part of the Ría de Vigo (Station of Rande, 42.29ºN 8.66ºW) and the Ría de Arousa (Station of Cortegada, 42.63ºN 8.78ºW). These stations have been operating since November and August 2007 respectively (Fig. 8). The University of Vigo supports these stations in collaboration with MeteoGalicia (http://meteogalicia.es) and INTECMAR (http://www.intecmar.org) and data are freely available through their websites. These stations provide high frequency sampling (10 min) in near-real time. The salinity data at these stations is likely to improve estimations of runoff at the mouth of the rias at high temporal resolution. At the time of writing this manuscript, river gauge data for rivers Verdugo-Oitaben (Ría de Vigo) and Umia and Ulla (Ría de Arousa) were not available to the authors. Therefore, we have estimated runoff to Ría de Vigo and Arousa based on precipitation measured at nearby meteorological stations [Fornelos de Montes (42.32ºN 8.40ºW) and Sergude (42.82ºN 8.46ºW) respectively], following a normalized geometric progression (see reconstruction of runoff time series). Mean daily surface salinity observed at Rande significantly correlates ($p<0.01$) with the estimated runoff in Ría de Vigo ($r = -0.42$; $n = 356$) and the surface salinity in Cortegada with the runoff estimated in Ría de Arousa ($r = -0.41$; $n = 479$). Near the bottom (~18 m in Rande and ~8 m in Cortegada), correlation is slightly stronger: -0.55 and -0.43 respectively. The existence of stratification together with the presence of lateral flows therefore complicate the estimation of runoff, which illustrates the necessity for further studies to exploit the correlations of river gauge measurements with salinity and currents at these stations.

Figure 10 shows the temporal evolution of the temperature from the IEO Radiales CTD time series. Intense upwelling summer events are distinguishable as cold features that influence bottom layers from the outer to the inner stations (e.g. summer 1998). The presence of fresh water associated with river plumes is observed at St.5 from autumn to spring with a high inter-annual variability. The plume shows low temperatures during winter 1994 (T<12ºC) and autumn 2000 (T<14ºC), whereas temperature is relatively high during autumn 2001 and 2002 (T>18ºC on early autumn). During autumn and winter, river plumes are usually observable as cold anomalies in Sea Surface Temperature (SST) maps processed from satellite imagery (e.g. Ribeiro *et al*., 2005, Ruiz-Villarreal *et al*., 2006). The thermal signature of the plume contrasts with the warmer ocean waters, and thermal fronts can be easily detected using classical image processing techniques. During other periods, the river plume is characterized by a warm anomaly (e.g. autumn 2001) or by a temperature similar to that of the ocean water beneath it (e.g. winter 1997). During these events, it becomes difficult to detect the associated thermal front. This phenomenon is associated with the rapid heating of the very shallow and stable surface water of the plume during an upwelling event in autumn or winter (e.g. Ribeiro *et al*., 2005).

To compare CTD time series data with climatological values of river discharge, we calculated monthly averages of the temperature and salinity data for the sampled period (Figs. 11 and 12). Lower salinity values are found at all depths from January to March (Fig. 11), when the accumulated fresh water on the shelf is high. The presence of river plumes is reduced from July to September. The station on the mid-shelf shows a minimum salinity in February, which coincides with the maximum annual discharge of the River Miño (see Fig. 3), whereas the inner station has a salinity minimum in January that coincides with one of the peak discharges of runoff to the Ría de Vigo. St.1 and St. 3 show the strong influence of both rivers. Mean monthly temperature (Fig. 12) follows a similar pattern to mean monthly salinity. High seasonal variability is evident at inner stations, with the SST lower than 13ºC in January and higher than 18ºC in August. Contrastingly, the SST difference between winter and summer is only ~3ºC at the station on the mid-shelf. During November, December and January, the mean temperature is relatively low, although high values during these months can be observed

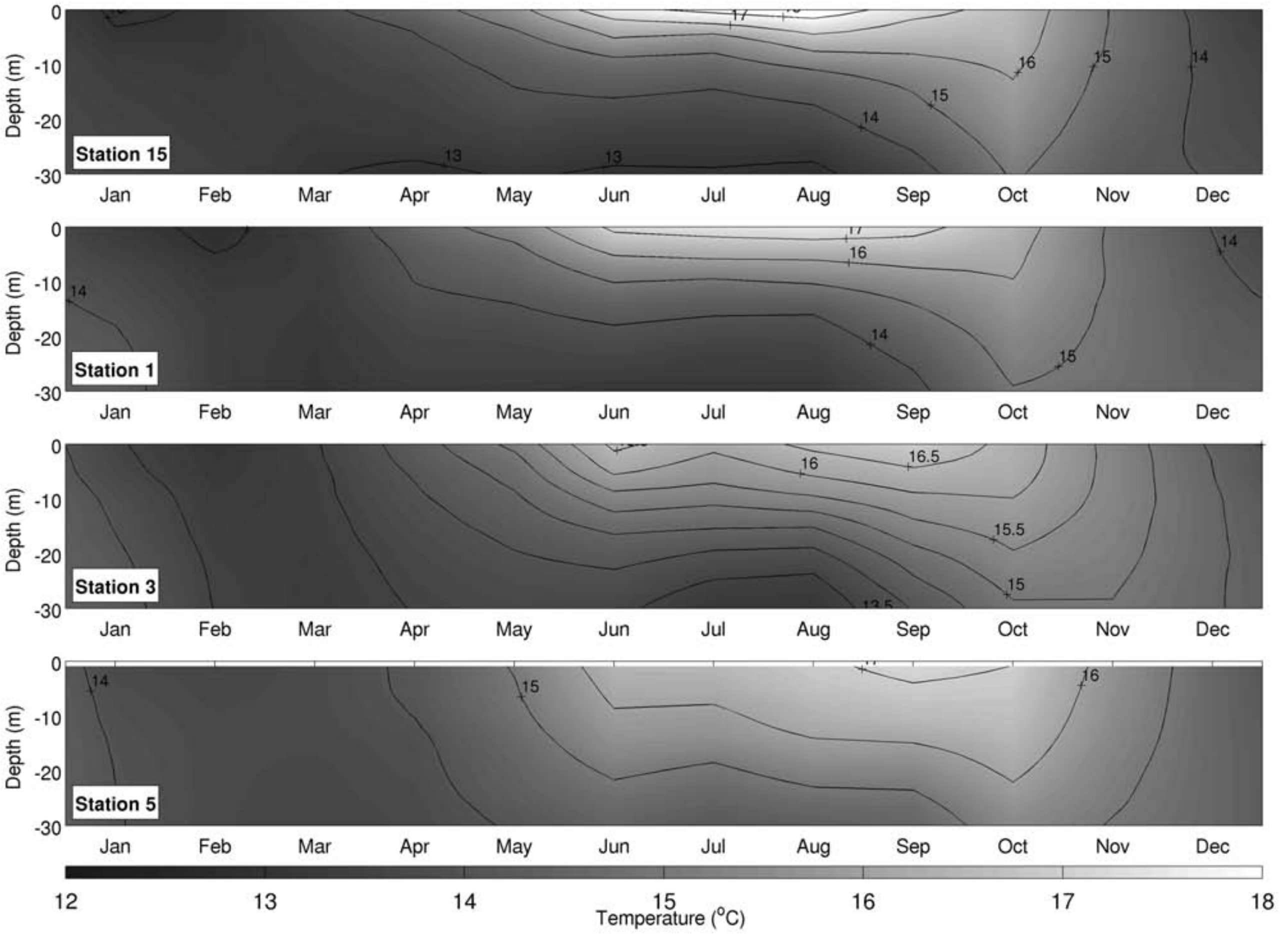

Fig. 12. – Long-term temperature annual cycle computed for the four sampled stations. Data are limited to 30 m depth (the maximum depth of the shallower station) to facilitate the comparison. Cyclic behavior is imposed at the start and end of the year.

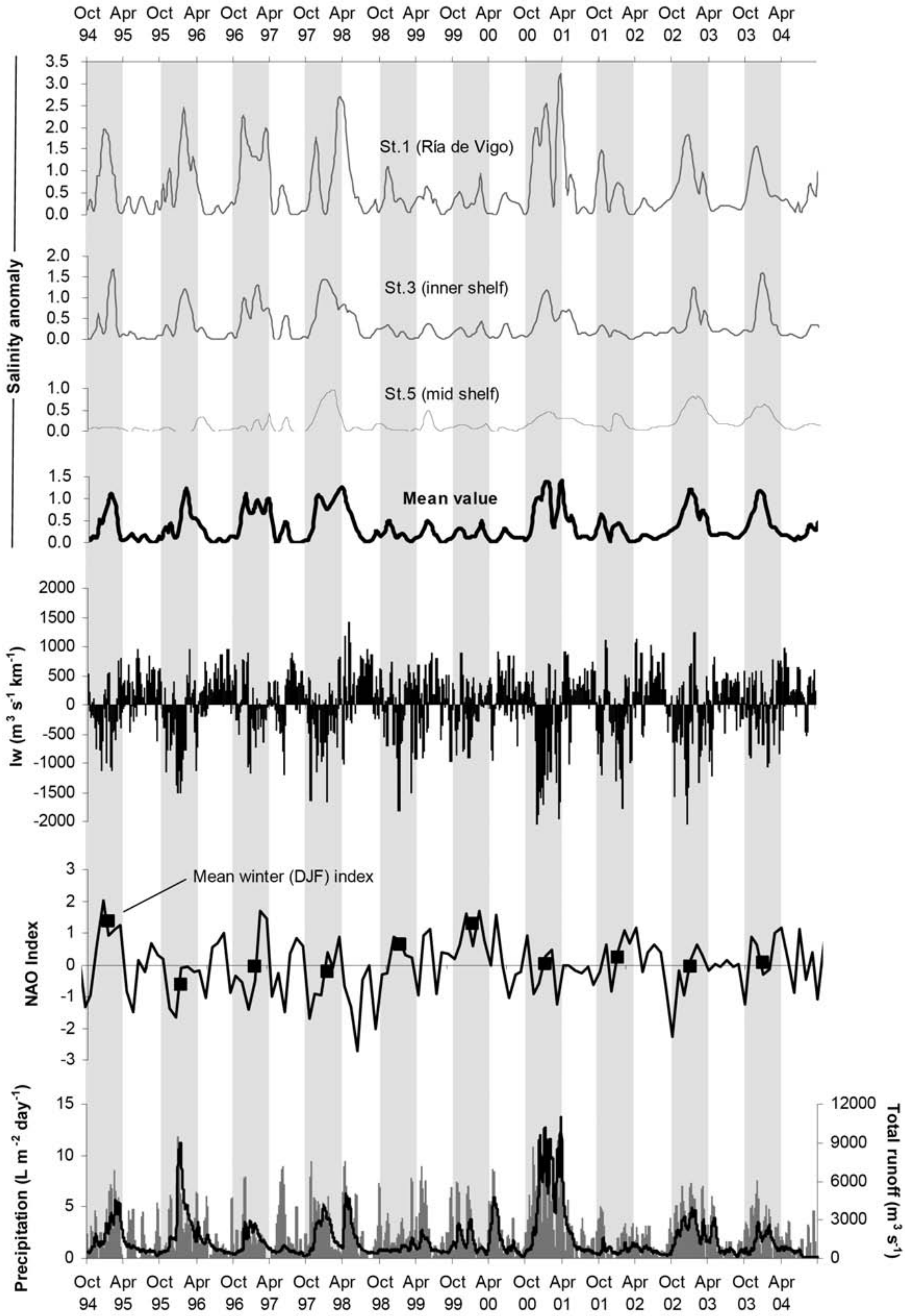

FIG. 13. – Integrated vertical salinity anomaly relative to 35.7 for stations 1, 3 and 5. An averaged value for these three stations is also plotted. The upwelling index (*Iw*; positive upwelling favorable), mean daily precipitation (gray bars) and the total mean daily river discharge estimated for the study region (solid line) are shown. Monthly values of the NAO index (solid line) are shown together with mean winter monthly values, which are the monthly mean of December, January and February (squares). Shaded regions separate the upwelling season (October to March) from the downwelling season (April to September).

(see autumn 1997, 2001 and 2002 in Fig. 10). During summer, upwelling raises colder waters and enhances the stratification into the rias. Warming (cooling) in spring (autumn) is observed earlier at inner stations (St.15 and St.1) than at outer stations (St.3 and St.5). This behavior suggests that the response of the rias to seasonal variations is faster than the response observed on the shelf.

Figure 13 shows a 10 year time series, from October 1994 to 2004, of the salinity anomaly relative to 35.7 computed at stations St.1, St.3 and St.5 (the inner station St.15 was sampled from 1998 and is not included in this analysis) and integrated in the first 38 m of the water column (the shallowest depth among these stations). The number of observations during the analyzed period (n) is 118. Positive anomalies correspond to lower salinities. These salinity anomalies are subsequently integrated in a single value. This mean value is compared with the mean daily precipitation rate and the estimated mean daily discharge. The precipitation rate directly influences the total runoff, which increases the salinity anomaly. The lagged correlation between the salinity anomaly and the total runoff is maximum with a 6 day lag (r = 0.63; hereafter, significance level of 95%); correlation between the salinity anomaly and the precipitation rate is lower (r<0.58) with the same lag. The salinity anomaly is also compared with the upwelling index (Bakun, 1973), which was computed using mean daily winds from NCEP reanalysis output interpolated to the location of the Silleiro buoy (42º06'N 9º23'W). Along-shore winds were rotated 15º in order to account for the orientation of the west coast (positive upwelling favorable). The upwelling index is negatively correlated with the salinity anomaly; the strongest correlation is obtained by averaging upwelling index data from the 55 days previous to the sampling (r = -0.46). Along-shore winds induce the export of the river plume offshore during upwelling events —the plume spreads and shallows, consequently reducing the value of the vertically averaged salinity anomaly— and induce confinement during downwelling events —the plume stretches and deepens, increasing the anomaly. Hence, the salinity anomaly on the shelf is influenced by both river discharge and dominant winds in the shelf. Downwelling favorable wind events and high river discharge are observed in winter 1996, autumn 1997 and 2000. During these periods the mean salinity anomaly experiences a strong increase. High river discharge was observed in spring 2000, although upwelling conditions contributed to exporting the river plume, which decreased the salinity anomaly. It is important to note that the strong confinement of the plume under the action of downwelling favorable winds can induce a relatively low salinity anomaly at the outermost station, although the salinity anomaly remains high at inner stations (e.g. winter 1996). During long dry periods, the salinity anomaly remains low on the entire shelf (e.g. spring 1997, spring 2002, autumn 2001).

The North Atlantic Oscillation (NAO) index has been recognized during decades as one of the major patterns of atmospheric variability in the Northern Hemisphere. The NAO index represents the frequency and strength of winter storms crossing the Atlantic Ocean. During negative phases, storms generally take a west-east track, causing warm and wet winters in the Iberian region and colder and drier winters in Northern Europe. A negative phase is therefore related to increased precipitation and runoff in northwest Iberia (negative correlation). We have correlated winter (DJF; December, January and February) monthly values of the NAO index (n = 10; available at the Climate Prediction Center, NOAA-CPC, USA) with the mean winter (DJF) precipitation (r = -0.30) and runoff (r = -0.37). Many authors have previously pointed out the low correlation between NAO and precipitation, and consequently river discharge, in northwest Iberia (e.g. Zorita *et al.*, 1992; Esteban-Parra *et al.*, 1998; Rodríguez-Puebla *et al.*, 2001), largely due to complex climate variations in both spatial and temporal dimensions (Esteban-Parra *et al.*, 1998; Serrano *et al.*, 1999; Trigo and DaCamara, 2000; Lorenzo and Taboada, 2005). However, storms in the study region are also associated with the predominant downwelling favorable winds. The DJF NAO index shows a correlation with the DJF upwelling index (r = 0.53), which influences the accumulation of fresh water on the shelf. The correlation between DJF NAO and the mean DJF salinity anomaly on the shelf is -0.54. Higher correlations are obtained when the DJF salinity anomaly is compared with the DJF upwelling index (r = -0.65), precipitation (r = 0.69) and runoff (r = 0.71) in the region.

CONCLUSIONS

The best estimation of the freshwater discharge to the coastal region is obtained with data from the furthest downstream river flow gauging station available, supplemented with estimates of discharge of the unmonitored area from the gauging station to the river mouth. In northwest Iberia, taking into account unmonitored areas increases the freshwater discharge estimation by 22%. Unfortunately, the lack of reliable and available river gauge records is a recurrent problem in the study region. In these cases, the estimation of an acceptable value becomes crucial to cover these gaps in the time series. With this aim, we have computed a climatological seasonal cycle of river discharge based on monthly statistics for the main rivers in the region. The relation between year-round climatological cycles of neighboring river basins is used to reconstruct gaps in the time series on a daily scale. With this simple although rough technique, we have reconstructed the time series of runoff for the main rivers for the period 1996 to 2004, obtaining better estimations than when mean daily precipitation from NCEP reanalysis is used. However, given the sparseness of the data set and the strong influence of dams on river discharge, improvements in the reconstruction of runoff from adjacent river basin data will require the use of an improved data set, preferably together with the use of hydrological models.

River discharge estimations have been compared to salinity and temperature CTD data in the Ría de Vigo and the adjacent shelf sampled monthly. Correlations between the salinity anomaly and the estimated runoff to the Ría de Vigo and River Miño were high ($p<0.05$), showing the main influence of both freshwater sources. However, the analysis of the temperature signal of the buoyant plume reveals its high inter-annual thermal variability. During autumn and winter, the buoyant structure is not always present as a cold anomaly when compared with ocean waters. Comparison between stations shows higher seasonal variability and a stronger response to the upwelling regime at inner zones, although the sampled time series is still too short to extract further conclusions.

Our results show that the temporal evolution of the salinity anomaly on the shelf is correlated with precipitation and runoff in the region and also with the dominant winds in the region, summarized in the upwelling index. Along-shore wind exports (upwelling favorable) or confines (downwelling favorable) the buoyant structure. If the confinement is strong enough, the influence of fresh water on the mid-shelf is occasionally present, in spite of the high river discharge in the region; under these conditions fresh water is confined to the inner coastal regions. Mean winter values of the NAO index represent the frequency and strength of storms crossing the Atlantic Ocean, and therefore the precipitation (which influences runoff) and predominant winds in the area. Consequently, the winter NAO index is correlated with the freshwater balance over the shelf.

Currently, authorities have plans to extend the network of gauging stations near the mouth of the rivers and are investing in making their databases available. This study is a complement, which is useful for reconstructing historical river discharge and estimating the historical freshwater budget on the shelf. Further studies should be made using the River Transport Model (RTM) in order to take into account rainfall and the particular characteristics of the individual river basins.

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REFERENCES

Álvarez-Salgado, X.A., J. Gago, B.M. Míguez, M. Gilcoto and F.F. Pérez. – 2000. Surface waters of the NW Iberian margin: Upwelling on the shelf versus outwelling of upwelled waters from the ‘Rías Baixas’. *Est. Coast. Shelf Sci.* 51(6): 821-837.

Álvarez-Salgado, X.A., J.L. Herrera, J. Gago, P. Otero, J.A. Soriano, C.G. Pola, C. García-Soto. – 2006. Influence of the oceanographic conditions during spring 2003 on the transport of the Prestige tanker fuel oil to the Galician coast. *Mar. Pollut. Bull., Prestige Special Issue*, 53(5-7): 239-249.

Baumgartner, A. and E. Reichel. – 1975. The world water balance: mean annual global, continental and maritime precipitation, evaporation and run-off. 179 pp. Elsevier. Amsterdam.

Bakun, A. – 1973. Coastal upwelling indices, west coast of North America, 1946-71. U.S. Dept. of Commerce NOAA Technical Report NMFS Special Scientific Report, Fisheries #671: 1-103.

Dai, A.G. and K.E. Trenberth. – 2002. Estimates of freshwater discharge from continents: latitudinal and seasonal variations. *J. Hydrometeo.*, 3(6): 660-687.

Doval, M.D., E. Nogueira and F.F. Pérez. – 1998. Spatio-temporal variability of the thermohaline and biogeochemical properties and dissolved organic carbon in a coastal embayment affected by upwelling: the Ría de Vigo (NW Spain). *J. Mar. Syst.*, 14(1-2): 135-150.

Esteban-Parra, M.J., F.S. Rodrigo and Y. Castro-Diez. – 1998. Spatial and temporal patterns of precipitation in Spain for the period 1880-1992. *Int. J. Climatol.,* 18(14): 1557-1574.

Fekete, B.M., C.J. Vörösmarty and W. Grabs. – 2002. High-resolution fields of global runoff combining observed river discharge and simulated water balances. *Global Biogeochem. Cycles*, 16(3): 1042, doi: 10.1029/1999GB001254

Fraga, F. and R. Margalef. – 1979. Las Rías gallegas. In: *Estudio y explotación del mar en Galicia*, pp. 101-121. Secretariado de Publicaciones de la Universidad (Santiago de Compostela).

Hagemann, S. and L. Dümenil. – 1998. A parameterization of the lateral waterflow for the global scale. *Clim. Dyn.*, 14(1): 17-31.

Herrera, J.L., R.A. Varela, G. Rosón and S. Piedracoba. – 2006. Variability of the western Iberian buoyant plume over the Galician shelf: wind forcing and runoff variability. In: I. Álvarez, M. de Castro, M. Gómez-Gesteria, M.N. Lorenzo and R. Prego (eds.), *Oceanography of the Bay of Biscay,* pp. 281-284.

Herrera, J.L., G. Rosón, R.A. Varela and S. Piedracoba. – 2008. Variability of the western Galician upwelling system (NW Spain) during an intensively sampled annual cycle. An EOF analysis approach. *J. Mar. Sys.,* 72(1-4): 200-217.

López-Jurado, J.L.M. – 1985. Notas climatológicas e hidrológicas de las Rías Bajas. *Inf. Téc. IEO*, 23: 1-13.

Lorenzo, M.N. and J.J. Taboada. – 2005. Influences of atmospheric variability on freshwater input in Galician Rías in winter. *J. Atmos. Ocean Sci.*, 10(4): 377-387.

Montero, P., M. Gómez-Gesteira, J.J. Taboada, M. Ruiz-Villarreal, A.P. Santos, R.R. Neves, R. Prego and V. Pérez-Villar. – 1999. On residual circulation of the Ría de Vigo, using a 3-D baroclinic model. *Bol. Inst. Español Oceanogr.*, 15(1-4): 31-38.

Nogueira, E., F.F. Perez and A.F. Rios. – 1997. Seasonal patterns and long-term trends in an estuarine upwelling ecosystem (Ría de Vigo, NW Spain). *Est. Coast. Shelf Sci.*, 44(3): 285-300.

Otero, P., M. Ruiz-Villarreal and A. Peliz. – 2008. Variability of river plumes off Northwest Iberia in response to wind events. *J. Mar. Syst.*, 72(1-4): 238-255

Otto, L. – 1975. Oceanography of the ría de Arosa (NW Spain). *Konink Meteor. Int. Medelingen* en Verhandelingen, 96: 1-210.

Piedracoba, S., X.A. Álvarez-Salgado, G. Rosón and J.L. Herrera. – 2005. Short-time scale thermohaline variability and residual circulation in the central segment of the coastal upwelling system of the Ría de Vigo (northwest Spain) during four contrasting periods. *J. Geophys. Res.,* 110, C03018.

Prego, R., F. Fraga and A.F. Ríos. – 1990. Water interchange between the Ría de Vigo and the coastal shelf. *Sci. Mar.*, 54(1): 95-100.

Ribeiro, A.C., A. Peliz and A.M.P. Santos, 2005. A study of the response of the chlorophyll-a biomass to a winter upwelling event off Western Iberia using SeaWiFS and in situ data. *J. Mar. Sys.*, 53(1-4): 87-107.

Ríos, A.F., M.A. Nombela, F.F. Pérez, G. Rosón and F. Fraga. – 1992. Calculation of runoff to an estuary. Ría de Vigo. *Sci. Mar.*, 56(1): 29-33.

Rodríguez-Puebla, C., A.H. Encinas and J. Sáenz. – 2001. Winter precipitation over the Iberian Península and its relationship to circulation indices. *Hydrol. Earth Syst. Sci.,* 5(2): 233-244.

Rosón, G., F.F. Pérez, X.A. Álvarez-Salgado and A.F. Ríos. – 1991. Flujos y características químicas de los aportes de agua continental a la Ría de Arosa. *Sci. Mar.,* 55(4): 583-589.

Ruiz-Villarreal, M., K. Bolding, H. Burchard and E. Demirov. – 2005. Coupling of the GOTM turbulence model to some three-dimensional ocean models. In: H.Z. Baumert, J.H. Simpson and J. Sundermann (eds.), *Marine Turbulence: Theories, Observations and Models*, pp. 225-237. Cambridge Univ. Press.

Ruiz-Villarreal, M., C. González-Pola, G. Díaz del Río, A. Lavín, P. Otero, S. Piedracoba and J.M. Cabanas. – 2006. Oceanographic conditions in North and Nortwest Iberia and their influence on the Prestige oil spill. *Mar. Pollut. Bull.* 53(5-7): 220-238.

Santos, A.M.P., Á. Peliz, J. Dubert, P.B. Oliveira, M.M. Angélico and P. Ré. – 2004. Impact of a winter upwelling event on the distribution and transport of sardine (*Sardina pilchardus*) eggs and larvae off western Iberia: a retention mechanism. *Cont. Shelf Res.,* 24 (2): 149-165.

Serrano, A., A.J. García, V.L. Mateos, M.L. Cancillo and J. Garrido. – 1999. Monthly modes of variation of precipitation over the Iberian Peninsula. *J. Clim.*, 12(9): 2894-2919

Torres, R. and E.D. Barton. – 2007. Onset of the Iberian upwelling along the Galician coast. *Cont. Shelf Res.*, 27(13): 1759-1778.

Trigo, R.M. and C.C. DaCamara. – 2000. Circulation weather types and their impact on the precipitation regime in Portugal. *Int. J. Climatol.*, 20(13): 1559-1581.

Varela, R.A., G. Rosón, J.L. Herrera, S. Torres-López and A. Fernández-Romero. – 2005. A general view of the hydrographic and dynamical patterns of the Rías Baixas adjacent area. *J. Mar. Sys.*, 54(1-4): 97-113.

Vergara, J. and R. Prego. – 1997. Estimación de los aportes fluviales de nitrato, fosfato y silicato hacia las Rías Gallegas. Procesos biogeoquímicos en sistemas costeros hispano-lusos: VIII Seminario Ibérico de Química Marina: 33-40, ISBN 84-89690-27-8.

Zorita, E., V. Kharin and H. von Storch. – 1992. The atmospheric circulation and sea surface temperature in the North Atlantic area in winter: their interaction and relevance for Iberian precipitation. *Int. J. Climatol.,* 5(10): 1097-1108

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APPENDIX

In this appendix, we describe the main characteristics of the river basins involved in this study. We present specific details needed to estimate river discharge at the mouth of the estuary. In the following equations, Q is the river discharge (m^3 s^{-1}), A the drainage area (km^2) and h the measured level of the river (m) at the gauging station. The height level depends on the station and on the sampling period. See Table 1 for values of the drainage area.

River Tambre

The furthest downstream gauging station available is Portomouros (St. 519) which is missing data for high discharges due to the difficulties in reading the level during flooding events. Height level data are converted into streamflow data using adjustment functions provided with the data on request. The station is located upstream of the Barrié de la Maza reservoir and hence important differences between estimations and the actual discharge flowing into the estuary are expected. This station was relocated upstream at the end of 2001; the new station is Carollo-Sigüeiro (St. 520).

River Ulla

The River Ulla is regulated by the Portodemouros dam. The only gauging station with available data is *Santiso* (St. 544), which unfortunately is located upstream of the reservoir. The River Deza, the main tributary of the River Ulla, flows into the main river downstream from the dam. This tributary is monitored by the *Cira* gauging station (St. 552) at a location near its confluence. Time series records for the two stations are available for the same period. The total runoff estimation for the River Ulla is:

$$Q_{UL} = \frac{(A_{UL} - A_{DE})}{A_{544}} \cdot Q_{544} + \frac{A_{DE}}{A_{552}} \cdot Q_{552} \qquad \text{[A1]}$$

Note that in the equation above, the area of the tributary is subtracted from the area of the main river. Data from these stations show important problems. Homogeneity in the measurements at St. 544 was lost after the a bridge was built which modified the flow at this location. The accuracy of the measurements of stream flow at St. 552 for low river discharge conditions is low.

River Umia

This river has a large dam (A Baxe) which was built from 1998 to 2001, breaking the natural behavior of this river basin. The only gauging station with available data valid for our estimations is *Caldas* (St. 564), located downstream from the reservoir. This station was removed from its original location to dredge the channel at the end of July 2001 and was replaced in early February 2002.

River Lérez

This river has no important dams or reservoirs. Mean monthly values – and not mean daily discharge – were collected from 1970 to 1998 at the *Cutián* gauging station (St. 574). After 1998, data were not recovered due to the impossibility of reaching the station by foot.

Rivers Verdugo and Oitavén

The main rivers flowing to the Ría de Vigo are Verdugo and Oitavén, which converge in their last stretch near the coast. The River Verdugo has no important reservoirs, whereas the Oitavén is strongly regulated by the Eiras dam. In this study, we have used an overall estimation of runoff to the inner part of the Ría de Vigo, based on the work of Ríos *et al.* (1992). The estimation is a function of the rainfall in the drainage basin and of the retention coefficient of water by the terrain, following a normalized geometrical progression. We have used the following equation, which integrates precipitation in the previous month (see Piedracoba *et al.*, 2005):

$$D = \frac{1-k}{k-k^{30+1}} \cdot \sum_{n=1}^{30} P_n k^n \qquad \text{[A2]}$$

where D is the drainage expressed as l m^2 d^{-1}, $k = 0.75$ is the retention coefficient which accounts for the proportion of water not discharged into the river compared to the rainfall during the previous day in the drainage area, and P is the rainfall collected during day n, expressed in l m^{-2}.

River Miño

The River Miño is the largest river in the Galician region and is strongly regulated by the reservoir of Frieiras. The absence of natural behavior is noticeable in the available time series. The best estimation of river discharge is obtained with data from the gauging station of *Foz do Mouro* (St. 01G/02), located downstream of the reservoir, and adding the contribution of the Tea tributary on the Spanish side, which also flows downstream of the dam:

$$Q_{MI} = \frac{A_{01G/02}}{(A_{MI} - A_{645})} Q_{01G/02} + Q_{645} \qquad [A3]$$

The gauging station of the Tea tributary is located near the confluence of the two rivers, and therefore the estimation based on the ratio of the total basin area and the monitored area is not applied to this tributary. Note that we must extract the basin area of Tea from the total basin area in the equation above. Measurements of river discharge at the locations of the reservoir are also available (St. Frieiras). The River Miño runoff at these locations is computed by adding the free spill and the harnessed flow. Nevertheless, comparisons between the run-off time series estimated from *Foz do Mouro* data and from Frieiras reservoir data showed large differences. Consequently, we have not used Frieiras data.

River Lima

River Lima is regulated by dams like Touvedo or Lindoso. The gauging station with the longest available time series is *Ponte de Lima* (St. 03F/02H), downstream of all dams, with streamflow time series data from 1945 to the end of 1990. Although height level data is available for later dates at the same location, either the adjustment equation from height level to streamflow data is not provided or data are not available via the web.

River Cávado

River discharge of the River Cávado is regulated by the dams of Penida, Vilarinho das Furnas, Gerês and Alto Rebagão. The gauging station with the longest available time series is *Barcelos* (St. 04F/02H) near the mouth of the river and hence downstream of all the reservoirs. This station was installed in 1935 and is currently recording data, although recent dates are not available, which shortens the usable time series.

River Ave

The River Ave is a short river without important reservoirs or dams along its course. Two gauging station located at *Açude de Tougues* (St. 05E/02H) and *Ponte Ave* (St. 05E/03H) are used in the estimation.

River Douro

The River Douro has several dams along its course, especially in the region where it constitutes the border between Spain and Portugal (e.g. Saucelhe, Aldeiadavila, Bemposta, Picota). Many stations have been measuring height level and streamflow data in this river basin at different locations and different periods, but records either are not always clearly available (e.g. stations of *Arnelas, Atães, Crestuma, Entre os rios, Freixo* and *Tapada do Outeiro*) or the adjustment equations to streamflow data are not provided (e.g. *Cais dos Banhos,* located at the mouth of the river and with records sent by telemetry from 1997). For these reasons, we have employed data from *Rio Mau* (St. 07G/03H), located downstream from the confluence with its main tributary the River Támega, which has data available from 1976 to 1985. The closest dam to the Rio Mau station is *Carrapatelo,* located upstream of the confluence of the River Douro with the River Támega. This tributary has the Torrão dam near its mouth. These time series have been complemented for periods before 1967 with records from the upstream station of *Regua* (St. 07K/01H), located upstream of the Carrapatelo dam.