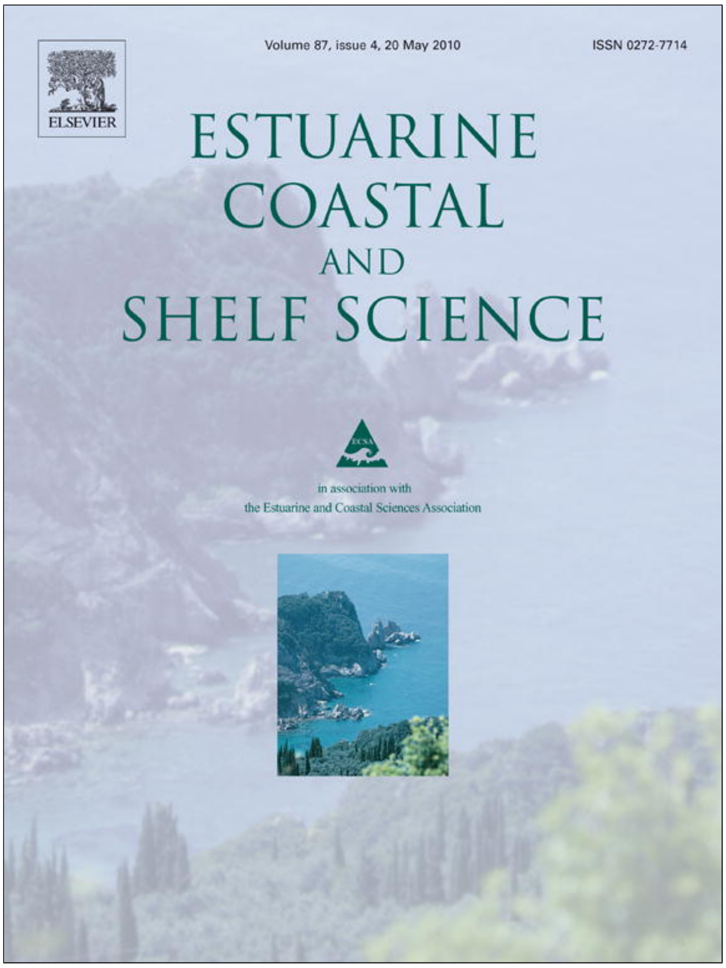
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Poleward intrusion in the northern Galician shelf

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ABSTRACT

The evolution of a warm water mass related to the Iberian Poleward Current (IPC) was characterized along the northern Galician shelf in November 2008 by means of Sea Surface Temperature and wind data. It was observed that under upwelling favorable conditions water temperature decreased along the northern coast and a temperature break appeared between Cape Vilano and Cape Ortegal showing a relaxation of the poleward intrusion. The effect of the IPC was also analyzed inside the Northern Galician Rias taking into account the hydrographical and biogeochemical properties measured on November 18. Water driven by the IPC was observed close to the mouth of the rias, around Cape Estaca de Bares, causing a nutrient salts decrease. Inside the rias a slight biological activity was found near surface resulting from fluvial contributions.

1. Introduction

Several water masses have been identified around the northwestern continental margin of the Iberian Peninsula. From spring to summer, Eastern North Atlantic Central Water (ENACW) is present near the coast (Rios et al., 1992; Prego et al., 1999) while during late autumn and winter the Galician offshore seawaters are under the influence of a northward surface current, which flows over 1500 km along the Iberian margin (Frouin et al., 1990; Haynes and Barton, 1990). This current, known as the Iberian Poleward Current (IPC), is a layer of 25–40 km wide and about 200 m deep.

The spatial importance and variability of intrusions of ENACW along the Galician shelf has been extensively studied (Wooster et al., 1976; Rios et al., 1992; Alvarez et al., 2005) especially at the western Galician Rias Baixas and its neighboring sea area due to the regular occurrence of upwelling events. The different orientations of the Galician coastline influence upwelling frequency and intensity and as result, upwelling favorable conditions are prevalent in spring-summer along the western Galician coast but not along the northern one (Gomez-Gesteira et al., 2006; Alvarez et al., 2009). Therefore, upwelling research has been mainly focused south of Cape Finisterre and it has been considered a typical spring–summer process driving ENACW into the estuaries (Prego et al., 1999; Alvarez et al., 2005). However, this phenomenon can also be observed in fall-winter under northerly winds blowing at the shelf. These winter upwelling events can pump inside the estuaries seawater associated with ENACW (deCastro et al., 2006, 2008) or driven by the IPC (Alvarez et al., 2003; Prego et al., 2007). Because of the occurrence and intensity of the IPC varies between years (Pingree and LeCann, 1990; Garcia-Soto et al., 2002) the intrusion of this water mass inside the estuaries is not a well studied phenomenon. Thus, the influence of the IPC has been investigated mainly along the Galician shelf in relation to plankton distribution (Fernandez et al., 1993; Huskin et al., 2003; Cabal et al., 2008).

From Cape Finisterre to Cape Ortegal (Fig. 1) upwelling events associated with the presence of ENACW have been also observed in summer at the Artabro Gulf (Prego and Varela, 1998) although these events are less common than along the western Galician coast and generally restricted to a band near the edge of the continental shelf (Prego and Bao, 1997; Varela et al., 2005). Eastward of Cape Ortegal there is not information about wind induced events except a recent characterization of a winter (February 2008) upwelling event which introduced shelf bottom seawater inside the Northern Galician Rias (Alvarez et al., 2009).

The present study aims to contribute to the knowledge of the processes which affect the northern Galician coast in terms of water masses and wind induced phenomena. On the one hand, the presence of a warm water mass related to the IPC at the northern

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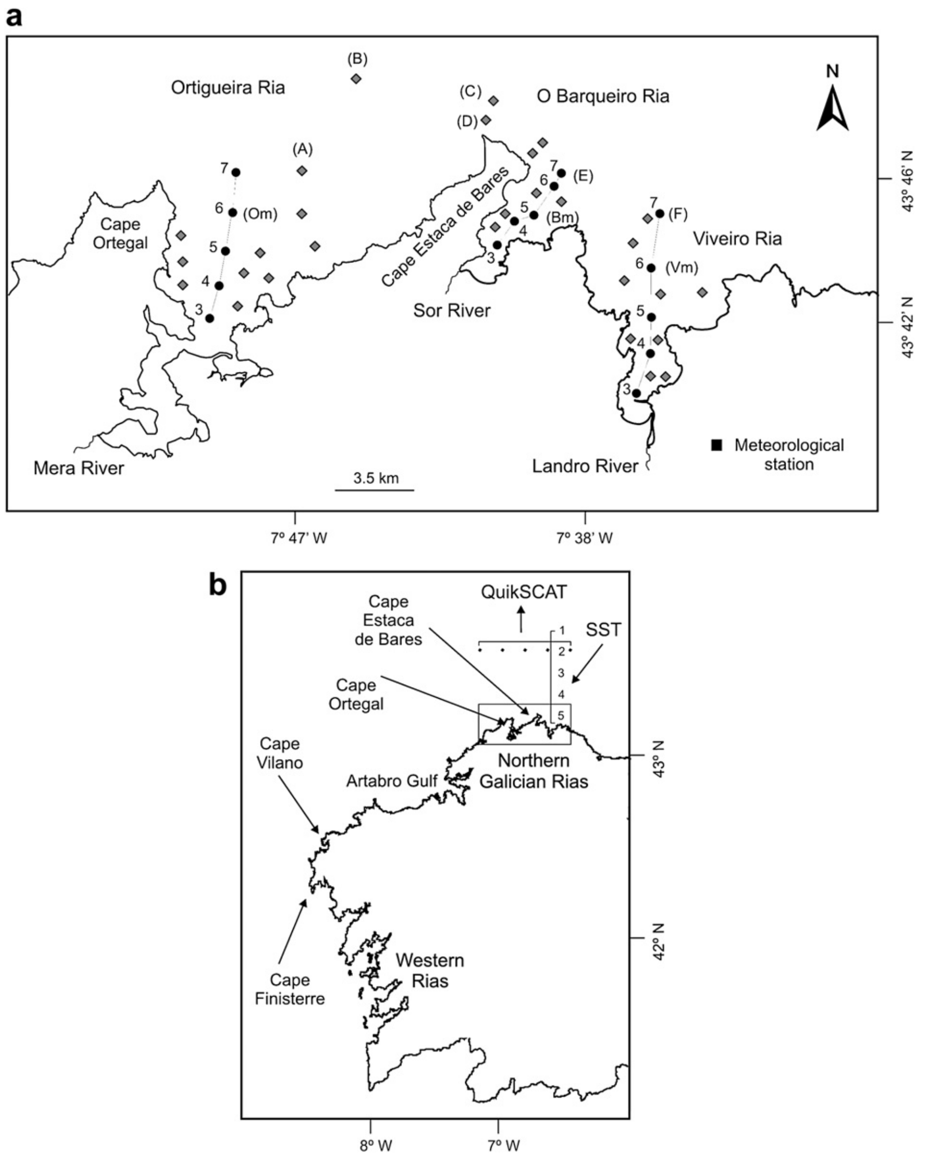

Fig. 1. (a) Map of Northern Galician Rias showing the sampling hydrographic stations (black circles and gray polygons). Letters refer to the selected stations to analyze the TS diagram of the water column (Fig. 3). (b) Black dots represent the 5 control points considered to analyze wind data provided by the QuikSCAT. Numbers represent the 5 control points located in front of the Northern Galician Rias to analyze the SST data.

Galician shelf in November 2008 will be characterized by means of Sea Surface Temperature and wind data. On the other hand, the influence of this water mass on the chemical and biological patterns will be analyzed inside the Northern Galician Rias.

2. Material and methods

2.1. Area under study

The Northern Galician Rias of Ortigueira (38 km^2 of surface), O Barqueiro (10 km^2) and Viveiro (27 km^2) are located along the northern Galician coast (Fig. 1), eastward of 8°W (Cape Ortegal). They are dominated by marine processes except at the inner estuarine (mesotidal) zone which is partially enclosed with well-developed beach barriers (see Alvarez et al., 2009 for a complete description). At the innermost area, these rias receive the fluvial discharges of the Mera (Ortigueira Ria), Sor (O Barqueiro Ria) and Landro (Viveiro Ria) Rivers, whose annual average volume of water is 4.2, 6.0 and 7.1 m^3 s^{-1}, respectively. The annual average air temperature is 14 °C with a thermal fluctuation of 10 °C and rainfall varies between 1100 and 1800 mm yr^{-1}. The wind regime is characterized by westerly winds in autumn–winter, while in spring and summer easterly winds prevail. Nevertheless, easterly winds can be also observed in autumn–winter (Gomez-Gesteira et al., 2006; Alvarez et al., 2009).

2.2. Atmospheric variables

Surface wind fields during November 2008 were provided by the QuikSCAT satellite (http://podaac.jpl.nasa.gov/DATA_CATALOG/quikscatinfo.html). The data set consists of global grid values of meridional and zonal components of wind measured twice daily on an approximately 0.25 × 0.25° grid. An average between both measurements was considered. Wind speed measurements range from 3 to 20 m s^{-1} (accuracy: 2 m s^{-1} and 20° in direction) and the reference height of wind data is 10 m. In addition, wind data close to the coast (~25 km) are not available due to the existence of a small coast mask. However, previous studies have shown that

QuikSCAT data are comparable to modeled data in this area (Gomez-Gesteira et al., 2006).

Ekman transport was calculated using wind data and analyzed along the whole Galician coast and at five control points considered along the northern coast at the latitude 44.25°N (black dots, Fig. 1(b)). The obtained discrete series covers from 8.25°W to 7.25°W. Data was averaged for the two previous days to each date under study. This average was considered because of atmosphere–ocean interactions take place on a wide range of spatial and temporal scales and the effect of the wind pushing on the ocean surface has not an immediate response.

Sea Surface Temperature (SST) data were obtained from the National Centre for Ocean Forecasting (NCOF) (http://www.ncof.co.uk/) by means of the Operational Sea Surface Temperature and Sea Ice Analysis (OSTIA) system. OSTIA uses satellite data provided by the GHRSST project (http://ghrsst.jpl.nasa.gov/), together with in-situ observations to determine the sea surface temperature for the global ocean with a resolution of approximately 5 km. SST images were analyzed around the Galician coast. In addition, five control points were considered in front of the Northern Galician Rias in a perpendicular section at approximately 7.7°W (numbers, Fig. 1(b)).

2.3. Hydrographical and hydrochemical measurements

A cruise was carried out at the Northern Galician Rias onboard the R/V *Mitylus* in November 18, 2008. Vertical profiles of salinity, temperature and chlorophyll-a were measured with a CTD sounder Sea-Bird 25 in several stations placed inside Ortigueira, Barqueiro and Viveiro Rias and their adjacent shelf (gray polygons in Fig. 1(a)). Moreover, one section with five stations located along the main channel of each ria was considered (St.3 to 7, black dots in Fig. 1(a)). The water column was sampled at 0, 5, 10, 20, 30, 40, 50 m depth using General Oceanic 10 L bottles by means of a General Oceanic Rosette. Dissolved oxygen, nutrient salts and chlorophyll-a subsamples were taken for analysis.

Daily river flows of the main rivers running into the three northern rias during November 2008 were supplied by the 'Aguas de Galicia' company. Moreover, a telescopic pole with a bottle holder was used to collect water samples in these three rivers at the fluvial end-limit of estuaries in November 17, 2008. Salinity and temperature were measured using WTW Multiline P4 sounder and dissolved oxygen, nutrient salts and chlorophyll-a sub-samples were taken for analysis.

Daily air temperature was supplied by the Regional Weather Forecast Agency (METEOGALICIA). Data were measured at the meteorological station located 43.66°N and 7.56°W (black square in Fig. 1(a)).

Next day to sampling, dissolved oxygen was analyzed in the water samples following the Winkler method (Grasshoff et al., 1999) making use of a 702-MS Titrino (Metrohm). Then oxygen saturation percentages were calculated from the dissolved oxygen concentration, salinity and temperature data of the sample. Nutrient salts were analyzed (Grasshoff et al., 1999) in an Integral Futura (Alliance Instruments) autoanalyzer system with separate lines to nitrate, nitrite, ammonium, phosphate and silicate determinations. Chlorophyll-a concentration, after sample filtration through Whatman GF/F filters and extraction with 90% acetone (Unesco, 1994), was determined by spectrofluorimetry. From the chlorophyll-a result along the sections, CTD fluorometer was calibrated.

3. Results and discussion

3.1. Sea surface temperature conditions and Ekman transport patterns

SST images were considered around the Galician coast during the previous days of the cruise carried out on November 18 (color maps in Fig. 2) to analyze the intrusion process of warm seawater at the northern Galician shelf and rias. SST image corresponding to November 14 showed the presence of warm superficial water mass near the Galician coast with temperatures around 14.8–15.5 °C in front of the Northern Galician Rias (Fig. 2(a)) and around 16 °C near the continental slope of the western Galician shore. This water mass can be associated with the IPC, which runs from the south of Portugal to the north of the Bay of Biscay (Frouin et al., 1990; Haynes and Barton, 1990) and can be identified by a signal warmer than the surrounding ones (Garcia-Soto et al., 2002) as shown in Fig. 2. IPC presence was discontinuous along the Galician coast showing a break between Cape Vilano and Cape Ortegal with temperature values around 14.5–15.0 °C. On November 15 (Fig. 2(b)), this gap almost disappeared and temperature increased to 15.5–16.0 °C. During the next few days (Fig. 2(c–f)) the break was re-established and the gap between offshore areas of the western and Northern Galician Rias appeared again with a temperature decrease till 14–15 °C.

The observed trend of the IPC evolution along the Galician coast may be explained in terms of meteorological forcing considering Ekman transport patterns (arrows in Fig. 2). In November 14 (Fig. 2(a)) transport was mainly directed southward piling surface waters up onto coast and creating downwelling conditions along the northern Galician shelf. The next day (Fig. 2(b)), negligible values of Ekman transport were measured along the northern coast without any prevailing direction. This situation agreed with a temperature increase at the area between Cape Vilano and Cape Ortegal showing an almost continuous temperature signal along the Galician coast. From November 16 on (Fig. 2(c–f)), northeasterly winds prevailed along the Galician coast (upwelling favorable conditions). The above mentioned gap with lower temperature values between capes at the northern shelf appeared again and a continuous SST decrease was observed at the Galician shelf showing the weakening of the temperature signal.

Previous studies have indicated the importance of wind forcing in controlling the IPC intrusion at the adjacent shelf. So, Gonzalez-Pola et al. (2005) found that downwelling pulses can reinforce the observed IPC signal at the western Cantabrian coast. Therefore, years of sustained and frequent downwelling events can be apparently related to intense penetration of the IPC. On the contrary, during upwelling events the IPC might loose its surface expression and become displaced offshore (Peliz et al., 2005) and the entrance in the Cantabrian coast can even stop (Ruiz-Villareal et al., 2006). In a short time scale, e.g. six days, this trend has been highlighted in the northern Galician shelf by means of the meridional component of Ekman transport (Q_y) and SST data measured near the Northern Galician Rias (Fig. 2(g)). A period of positive Q_y values (upwelling favorable) was observed during the three days previous to the cruise under study (18 November) agreeing with a decrease of surface water temperature that pointed out a relaxation of the poleward intrusion.

3.2. Influence of the IPC on the Northern Galician Rias

The general view offered in the previous section about the poleward evolution along the northern Galician region using satellite images and wind data, was also analyzed *in situ* by means of an oceanographic cruise carried out inside the rias. Surface isotherms (1 m deep) from CTD data (Fig. 3(a)) indicated an offshore temperature gradient ranging from 13.7 °C at the innermost zone of Ortigueira Ria to 15.4 °C at the adjacent shelf around Cape Estaca de Bares. Close to this cape the surface thermocline was observed: 1 °C (14.2–15.2 °C) in 1.4 km of distance. According to the previous discussion on SST maps, the observed surface temperature distribution was established by the IPC influence.

A three-dimensional draw of the intrusion was provided by means of TS diagrams of the water column corresponding to inshore and offshore areas of the Northern Galician Rias (Fig. 3(b)). A quasi-linear mixing was observed at the mouth of the three rias (Om, Bm and Vm, Fig. 1(a)) resulting from the fluvial influence, highlighted by the high flow of Sor River (Table 1) in the case of Bm station. Taking into account that at the northern Galician region upwelling favorable conditions were established four days before November 19 (Fig. 2), thermohaline variables at these stations could indicate the presence of upwelled water. Nevertheless, TS profiles showed that this water couldn't be associated with ENACW or IPC. Previous studies indicated that at the western Galician coast upwelled water (ENACW or IPC) could be identified inside the estuaries when favorable conditions persist at least that number of days (Alvarez-Salgado et al., 2000; Alvarez et al., 2005). At the northern Galician coast, Alvarez et al. (2009) pointed out an upwelling event after nine days of favorable winds although upwelled water corresponded to shelf bottom water which was not associated with ENACW or IPC.

Off Viveiro and O Barqueiro Rias (st. E and F, Fig. 1(a)) the presence of a warm and saline water mass with values around 15 °C and 35.60–35.65 was observed in the upper layers of the water column. These conditions were also observed around Cape Estaca de Bares (st. C and D, Fig. 1(a)) while off Ortigueira Ria surface temperature values were lower (14 °C) (st. A and B, Fig. 1(a)). These high water temperature values are similar to the ones observed for a summer situation due to solar heating (Alvarez et al., 2003, 2005), however, air temperature during the previous days of the cruise under study (November 18) never surpassed 10 °C. Therefore, these conditions can only be related to the IPC influence.

Several studies (Frouin et al., 1990; Haynes and Barton, 1990) have found that around the western Galician margin, IPC can be identified by means of thermohaline measurements as a high salinity water body located along the shelf break. The highest salinity values

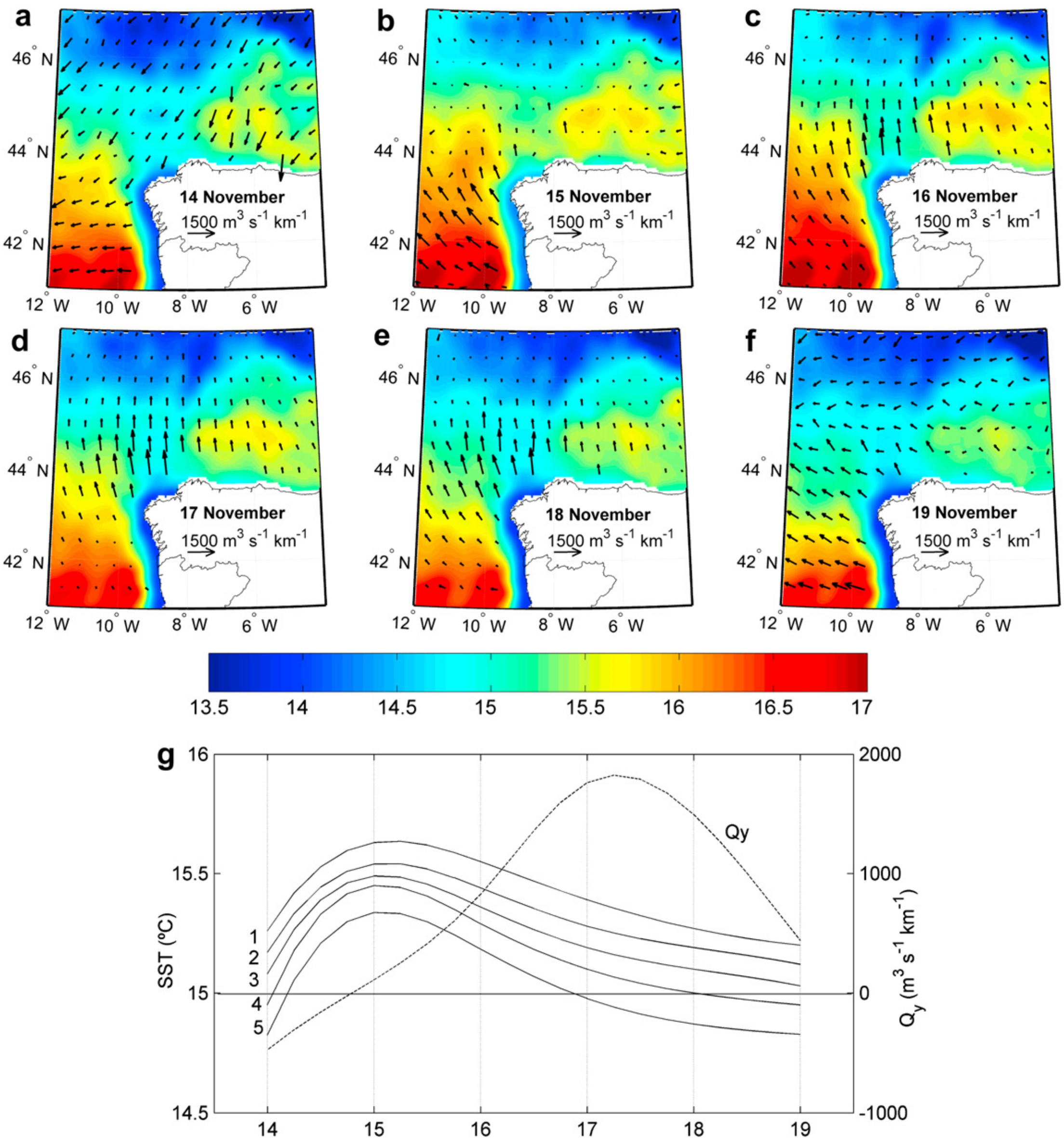

Fig. 2. (a–f) SST images (color maps) and Ekman transport patterns (black arrows) along the Galician coast from November 14–19. SST images correspond to the date shown in each frame. (g) Evolution of SST data in front of the northern Galician coast (numbers, Fig. 1(b)) and meridional component of Ekman transport (Q_y) (dashed line) from November 14–19. Q_y was calculated by averaging data at the 5 control points located along the northern Galician coast (black dots, Fig. 1(b)). Ekman transport was calculated by averaging transport data for the two previous days to the date shown in each frame.

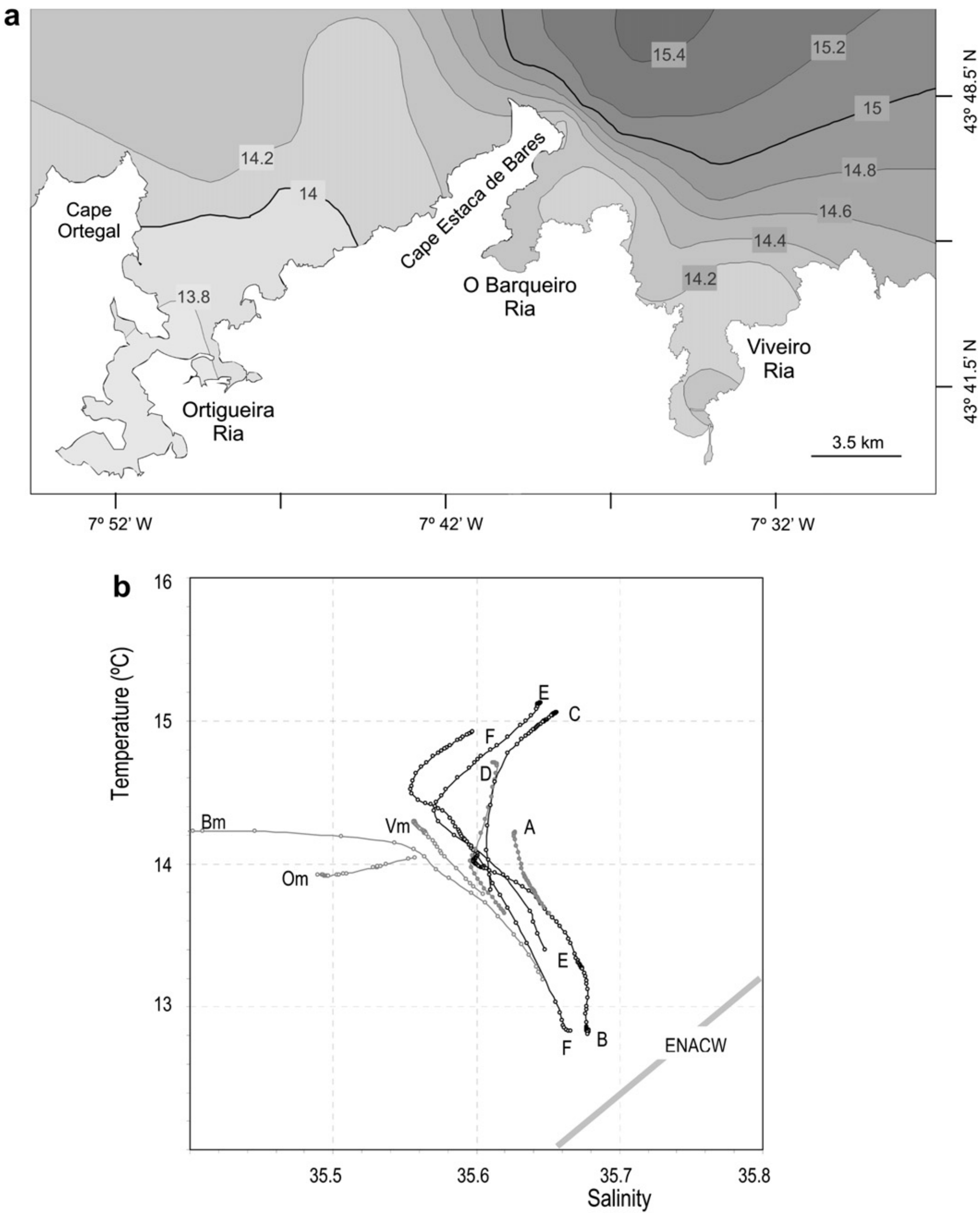

Fig. 3. (a) Temperature distribution at the surface layer (1 m depth) measured at all the sampling stations shown in Fig. 1(a) in November 18. (b) TS diagram of the water column corresponding to inshore and offshore areas (Fig. 1(a)). Ria-mouth stations were named: Om, Bm and Vm (refered to Ortigueira, Barqueiro and Viveiro Rias, respectively) and offshore stations: A, B, E and F. Two stations located at the adjacent shelf around Cape Estaca de Bares (st. C and D) were also considered.

(~35.9) can be measured around 100 m deep decreasing upward where the maximum temperature values (~16.5 °C) can be found. Recently, Huskin et al. (2003) and Torres and Barton (2006) characterized a poleward intrusion in October–November 1999 at the shelf break off Galician coast (between 8.5 and 9.5°W). IPC salinity and temperature values at surface layers were very similar to the ones observed in November 2008 at the northern Galician shelf.

The hydrographical and biogeochemical patterns were also analyzed along the main channel of the Northern Rias (st. 3 to st. 7, Fig. 1(a)) to better characterize the influence of the IPC. Only the Barqueiro Ria is shown (Fig. 4). The highest salinity (35.6) and temperature (15 °C) values were observed close to the mouth of the ria (st. 7, Fig. 4) decreasing innerward and showing that IPC is only present at the external part. The same pattern was also observed at

Table 1
Discharge and chemical concentrations for the rivers running into the Northern Galician Rias on November 17, one day before the sea cruise.

Ria	River	Flow ($m^3 s^{-1}$)	Temp. (°C)	Diss. O_2 (μM)	O_2 satur. (%)	Nitrate (μM)	Nitrite (μM)	Ammonium (μM)	Phosphate (μM)	Silicate (μM)	Chlorophyll (μg L^{-1})
Ortigueira	Mera	4.05	12.1	323	96	79.7	0.3	3.4	0.11	156	0.4
O Barqueiro	Sor	12.33	12.3	329	98	41.5	0.0	0.2	0.15	91	0.1
Viveiro	Landro	7.68	12.0	320	95	76.4	0.1	0.8	0.14	142	0.4

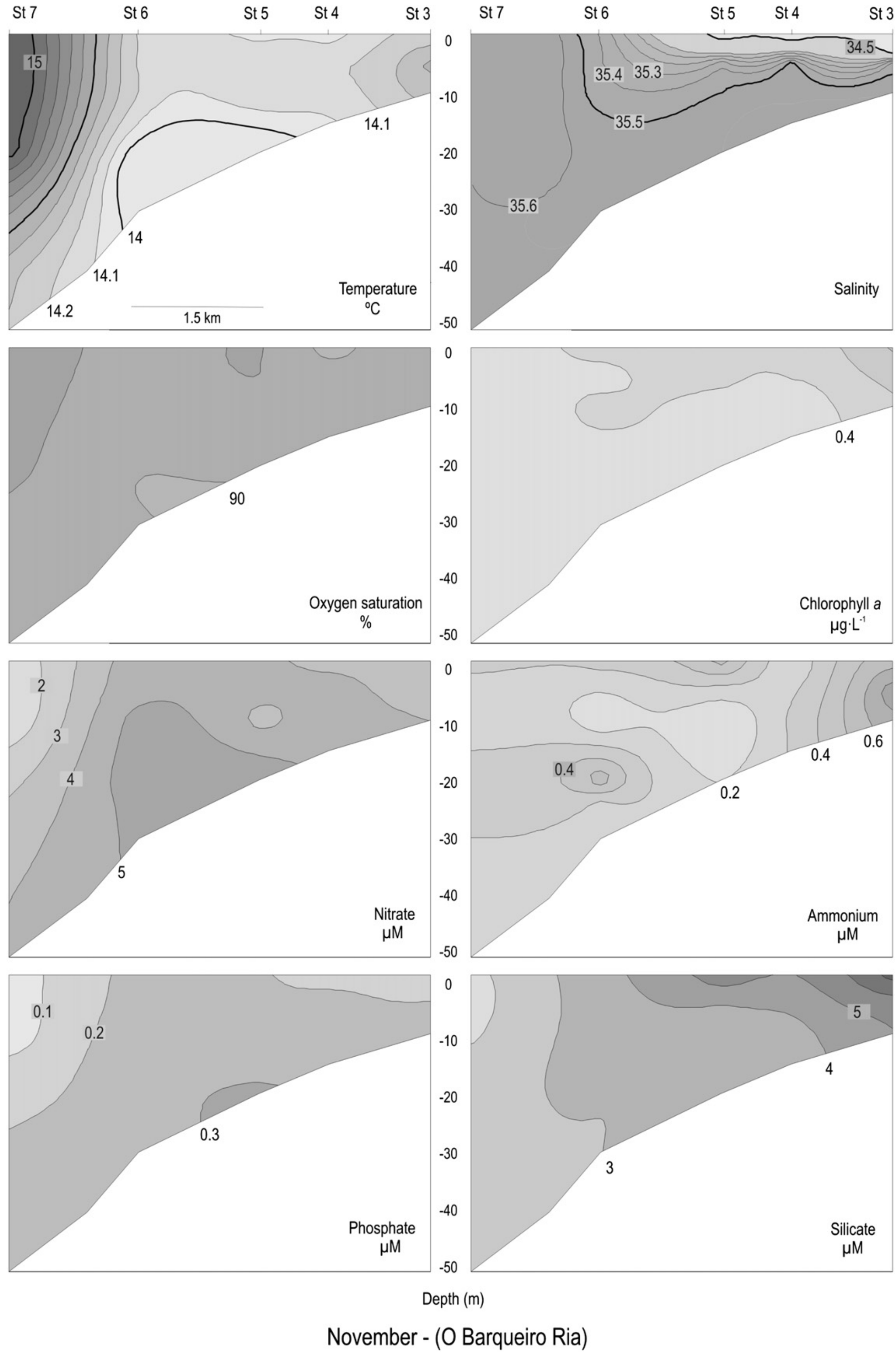

Fig. 4. Contour maps of temperature, salinity, oxygen, chlorophyll and nutrient salts along the main channel of the Barqueiro Ria corresponding to the cruise carried out in November 18.

Viveiro Ria (not shown). This situation can be explained due to the influence of river discharge at the inner part of the rias, which contributes to prevent the IPC penetration inside them. In fact, river discharge at O Barqueiro Ria measured the day before the cruise (Table 1) was two times higher than the annual average flow of about 6 $m^3 s^{-1}$. A similar situation was previously described at the western Galician rias where the river runoff originates a low salinity water plume which contributes to the formation of the Western Iberia Buoyant Plume (WIBP, Peliz et al., 2002). This buoyancy plume extends along the coast and under upwelling favorable conditions is advected offshore and can block the entrance of seawater throughout surface layers. Although the cruise at the Northern Galician Rias (November 18) was carried out after four consecutive days of upwelling favorable conditions, the effect of the river plume was only observed inside the rias (Fig. 4). It is necessary to take into account that the freshwater input at the western Galician rias (total annual average flow $\sim$134 $m^3 s^{-1}$) is higher than at the northern ones (total annual average flow $\sim$17 $m^3 s^{-1}$).

IPC also affect the biogeochemical properties. Southward of Cape Estaca de Bares, inside Barqueiro and Viveiro Rias, a river–ocean gradient of nutrient salts resulting from fluvial contributions (Table 1) was observed and exemplified by the Barqueiro Ria (Fig. 4). A little biological activity was found near surface (Varela et al., 2005), as shown in the chlorophyll concentrations. At the Ria mouth bottom, close to the thermohaline gradient resulting from IPC influence, there was a less dissolved oxygen depletion (90% of oxygen saturation) and a slight increase of nitrate and phosphate concentrations while the ammonium maximum was observed at 15–20 m deep. This situation corresponds to the typical "en echelon" distribution of organic matter remineralization in rias (Prego et al., 1999). Offshore the ria, near Cape Estaca de Bares, nutrient salts decreased (Fig. 4). The water mass was poor in nitrate (<2 μM), phosphate (<0.1 μM) and silicate (<2 μM) as it was already observed by Prego et al. (2007) during an IPC intrusion in the western Galician shelf. In the Northern Rias of Barqueiro and Viveiro biogeochemical patterns were disturbed by IPC influence while westward of Cape Estaca de Bares (Ortigueira Ria) this situation was not observed.

4. Conclusions

The intrusion of a warm water mass related to the IPC was characterized at the northern Galician shelf in November 2008. Sea Surface Temperature images showed that under upwelling favorable conditions the IPC presence was discontinuous along the Galician coast showing a temperature gap between Cape Vilano and Cape Ortegal and a weakening of the temperature signal along the northern coast. In addition, IPC was observed close to the mouth of the Northern Galician Rias of Barqueiro and Viveiro, around Cape Estaca de Bares, making the water poor in nutrients. The river discharge contributed to prevent the IPC entrance and the effect of the river plume was only observed inside the rias showing a slight biological activity and an estuarine stratification near surface. Taking into account these patterns described above, it is possible to see that particular coastal features as capes and rias play an important oceanographic role in relation to the occasional poleward intrusions near this coast. Consequently, more research would be necessary in order to establish the processes which affect the northern Galician coast in terms of water masses intrusion.

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