Influence of the oceanographic conditions during spring 2003 on the transport of the *Prestige* tanker fuel oil to the Galician coast

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Abstract

Hydrographic data collected during the cruise HIDROPRESTIGE were combined with meteorological and dynamic data provided by remote sensors and drifting/moored buoys, to describe the surface circulation of the Northern Iberian Basin in March–April 2003. Sea surface winds transported the floating *Prestige* oil slicks from the sinking area to the continental slope off the Rías Baixas in ½ month: the surface current intensity was 2% of the wind intensity and it was rotated clockwise 5º from the wind direction. Mesoscale cyclonic and anticyclonic structures west of 10ºW increased the residence time of oil patches in the Northern Iberian basin, as compared with the expected southwards flow of the Iberian Current (IC). On the other hand, the Iberian Poleward Current (IPC) formed a marked surface front with coastal waters, preventing the entry of fuel oil into the rías. PAHs in the surface layer during the cruise were <0.5 µg L^{-1}, except in the Galicia bank (~1 µg L^{-1}; where the *Prestige* tanker was still leaking) and the vicinity of Cape Fisterra (~1.5 µg L^{-1}; where the convergence front between the IPC and coastal waters vanished).

Keywords: *Prestige* oil spill, PAHs, wind and density–driven circulation, Iberian Current, Iberian Poleward Current

1. Introduction

The 26–years–old single–hulled *Prestige* oil tanker transported 77,000 tons of a Russian heavy fuel oil, type M–100 (González et al., this issue). It ruptured in a storm and started leaking 28 miles off the Galician coast on November 13, 2002. Six days later, it finally broke in two and sank in the southwestern flank of the Galicia bank (**Figure 1**), after spilling about 19,000 tons of oil in a 240 miles erratic course (Balseiro et al., 2003). After sinking, the fuel oil started to ooze from nine cracks in the bow (3819 m depth, 42º10′ N, 12º03′ W) and five cracks in the stern (3530 m depth, 42º12′ N and

12º02′ W) at an initial rate of about 125 tons/day. It reached the surface and drifted eastwards, threatening further damage to the North Western coast of Spain. Sealing of the cracks with the IFREMER's submarine *Nautile* reduced the leaking to less than 1 ton/day by June 2003. Only 14,000 tons of fuel oil remained in the wreck by September 2003.

Drifting of a floating pollutant such as the *Prestige* fuel oil on the ocean surface from the sinking area to the Galician coast results from the combination of 1) local wind stress, acting directly on the fuel oil patches or indirectly through the Ekman layer; 2) the basin–scale density–driven circulation of the Northern Iberian basin; and 3) the development of meso scale structures such as surface eddies and fronts (Santos et al., 2004).

According to buoy data and analysis of hydrographic fields, the surface circulation of the Northern Iberian basin is characterised by a year round weak southward flow (Pollard and Pu, 1985; Krauss, 1986; Sy, 1988; Pérez et al., 2001; Martins et al., 2002; Peliz et al., 2005) known as the Portugal (PC) or Iberian current (IC). Mazé et al. (1997) considered that 10º 30′ W is the eastern boundary of the IC. East of that longitude and north of 40ºN, a poleward flowing slope current carries warm and salty subtropical water along the Atlantic (Pingree and Le Cann, 1989; Frouin et al., 1990; Haynes and Barton, 1990) and Cantabrian (Pingree and Le Cann, 1990) coast of the Iberian Peninsula. It contrasts with the colder and fresher subpolar waters carried by the IC. From April–May to September–October, north easterly winds prevail in the Iberian basin (Wooster et al., 1976; Bakun and Nelson, 1991), producing a southward flowing surface current over the Western Iberian shelf and slope (Torres et al., 2003; Álvarez–Salgado et al., 2003). At this time of the year, the poleward flow appears as a subsurface counter current. On the contrary, it surfaces during fall, winter and spring, in response to the predominant south westerly winds and can be easily traced by a warm water signal over the Iberian slope in satellite AVHRR images (Frouin et al., 1990; Haynes and Barton, 1990; Pingree and Le Cann, 1990; García–Soto et al., 2002; 2004; Martins et al., 2002; Álvarez–Salgado et al., 2003; Peliz et al., 2002; 2005). It has been named Portugal Coastal Counter Current (PCCC; e.g. Álvarez–Salgado et al., 2003) or Iberian Poleward Current (IPC; e.g. García–Soto et al., 2002). The term "Navidad" (e.g. García–Soto et al., 2002) refers to the eastward extension of the IPC along the Cantabrian shelf and slope. The IPC is over 25–50 Km wide and propagates with velocities of 15–30 cm s^{-1} along the Western Galician slope (Martins et al., 2002; Álvarez–Salgado et al., 2003).

The coastal wind pattern observed over the Western Iberian shelf and slope also affects dramatically the exchange with the Rías Baixas, four large (>2.5 km^3) and V–shaped coastal embayments where mussels are intensively cultured on hanging ropes (Figueiras et al., 2002). Upwelling of the cold and nutrient–rich Eastern North Atlantic Central Water (ENACW) occurs in response to the predominant northerly winds during the spring and summer. ENACW upwelled over the shelf enters the bottom layer of the rías, forcing a compensating surface flow from the rías to the shelf (Rosón et al, 1997; Álvarez–Salgado et al., 2000; Souto et al., 2003; Piedracoba et al., 2005). On the contrary, downwelling of the warm and salty subtropical water carried by the IPC occurs in response to the predominant southerly winds during the autumn and winter. Continental runoff in Northern Portugal and Galicia is maximum during the time of development of the IPC (Nogueira et al., 1997). The cold and fresh water of the rivers Douro and Miño and the small rivers that drain into the Galician Rías Baixas constitute the Western Iberian Buoyant Plume (WIBP), which form a marked thermohaline front with the warm and salty subtropical waters carried by the IPC (Álvarez–Salgado et al., 2003). The front displaces from the shelf break to the interior of the Rías Baixas, depending on the relative intensity of the south westerly winds, which forces the inflow of IPC waters into the rías, and continental runoff, which forces the outflow of coastal waters from the rías. Álvarez–Salgado et al. (2000) demonstrated that the onshore Ekman transport (in m^3 s^{-1} (Km of coast)$^{-1}$) should be ≥7 (±2) times the continental runoff to the Ría de Vigo (in m^3 s^{-1}) to allow the penetration of the IPC into the middle ría (2.5 Km wide).

The oceanographic cruise HIDROPRESTIGE was executed in March–April 2003, at the time of the transition from the downwelling to the upwelling favourable season, when the spring phytoplankton bloom usually develop in the western coast of the Iberian Peninsula (Nogueira et al., 1997; Calvo–Díaz et al., 2004; Varela et al., this issue). At the time of the cruise, four months after the *Prestige* tanker sank, slicks of the *Prestige* fuel oil were still drifting to the Galician coast forced by the local winds, the basin scale IC and IPC and some conspicuous meso scale features such as a large cyclonic gyre in the Galicia bank and a thermohaline front off the Rías Baixas. The aim of this work is to characterise the hydrography and dynamics of the oceanic, slope and shelf surface waters from the Galicia bank to the mouth of the Rías Baixas at the time of the spring bloom. It complements the seasonal picture of the oceanographic conditions off Galicia given by Ruíz–Villarreal et al. (this issue).

2. Materials and methods

Meteorological, hydrodynamic, hydrographic and chemical data have been combined in this work to provide a holistic view of the oceanographic conditions off Galicia at the beginning of the spring 2003. An oceanographic cruise was conducted to map the thermohaline structure of the water column and to derive the dynamic height field from the Galicia bank to the continental shelf off the Rías Baixas. The view obtained from the cruise was complemented with the time evolution of sea wind, sea surface temperature and dynamic height fields obtained from satellite–mounted sensors. Additional data provided by drifting and moored buoys and the operational model elaborated by MERCATOR, which assimilates sea level anomaly data from satellite altimetry and incorporates atmospheric forcing by winds (from the European Centre for Medium-range Weather Forecast; ECMWF), allow completing the picture.

2.1. The cruise HIDROPRESTIGE

The hydrographic stations in **Figure 1** were occupied during the cruise HIDROPRESTIGE, aboard *R/V* Cornide de Saavedra, from March 25 to April 7, 2003. It consisted of two legs. Leg A (March 26 to 31) comprised from the Galician shelf break to 13º W and from 41.5º N to 43.1º N, covering the Galicia bank, where the *Prestige* tanker sank. A total of 30 hydrographic stations, arranged in a 20nm x 20nm grid, were sampled, starting at the southeastern corner (stn 87) and ending at the southwestern corner (stn 116) completing a total of 6 meridional transect. Leg B (April 1 to 6) consisted of 85 stations arranged in a 5nm x 5nm grid, covering from the mouth of the Rías Baixas to the shelf break, following the same sampling design as in Leg A.

Full–depth conductivity–temperature–depth (CTD) profiles were recorded in all the hydrographic stations with a SEABIRD (SBE) 9/11 probe on Leg A and a SBE 25 probe on Leg B. The accuracy of the SBE temperature and salinity sensors was ±0.004ºC and ±0.005, respectively. The CTD profiles were processed first eliminating the spurious data and later applying a low–pass filter (UNESCO, 1988). Finally PSS–78 salinity and EOS80 potential density anomaly were computed following Fofonoff and Millard (1983) and IPTS–90 potential temperature and dynamic height were obtained following UNESCO (1991).

Samples for the analysis of polycyclic aromatic hydrocarbons (PAHs) in the surface layer (1 m depth) were collected with a 2 L topaz colour bottle mounted in a steel holder. The bottle was dipped when the vessel was about to stop, preferably windward to avoid the pollution produced by the vessel. Once the sample was on board, part of the water was drained to wash the bottle neck to avoid pollution due to the contact with the sea surface micro layer. Subsurface water samples were collected with a SBE 5 L Go–Flo bottle adapted for hydrocarbon sampling and transferred to a 2 L topaz colour bottle. After addition of 1 ml of a saturated solution of mercury chloride and 25 ml of hexane, the samples were kept in the dark until analysis in the base laboratory following the MARPOLMON protocol (UNESCO, 1984). The organic and aqueous phases of PAHs were isolated by separating funnels, and two additional extractions were made. The obtained extract was concentrated and the total PAHs content was determined by fluorescence (Ex/Em, 310 nm/360 nm). PAHs concentrations were referred to a chrysene standard (Ehrhardt et al., 1991). For comparative purposes, measurements of chrysene standards were made against aged *Prestige* oil extracted with hexane, resulting in a factor of 5.5±0.4 µg *Prestige* oil/µg chrysene.

2.2. Geostrophic field calculations

Temperature, salinity, density, and dynamic height data were optimal statistical interpolated into an even longitude–latitude 0.1° grid for Leg A and 0.04° grid for Leg B, with a characteristic scale of 36km for Leg A and 10 Km for Leg B. This parameter determines the wideness of the Gaussian function that represents the spatial correlation used to compute the interpolation weights (see Thiébaux and Pedder 1987 and Gomis et al. 2001 for computational details). The values of the characteristic scale have been obtained by iteration to minimize the interpolation error. Since this parameter is a representation of the scale of the processes in the studied area, a good starting point for the iteration is the Rossby radius of deformation. Finally, the fields were smoothed using a normal–error filter (Gomis et al., 2002) with a cut–off wavelength twice the mean separation distance among stations (80 Km for Leg A and 20 Km for Leg B).

Surface dynamic heights and the corresponding geostrophic velocity fields were referred to 1400 dbar both in Legs A and B. This reference level was chosen after examination of the density anomaly field to find the layers of maximum spatial homogeneity of density. For the stations of Leg B shallower than 1400 dbar, the dynamic height from the bottom to the reference level was extrapolated from the dynamic height of the closest surrounding stations deeper than 1400 dbar. In any case, geostrophic velocity fields only provide a qualitative description of the surface circulation of the study area.

The dynamic topography field produced from CTD data was split in five areas**,** which were individually interpolated to obtain the corresponding dynamic heights and geostrophic velocities. These areas were selected for two reasons: 1) due to the bad weather conditions, Leg B was not surveyed synoptically and was split into three areas (named III, IV and V in **Figure 1**); and 2) to maximize the temporal superposition between the AVISO (Archiving, Validation and Interpretation of Satellite Oceanography Data) sea level anomaly maps (see section 2.3) and the dates when Leg A was surveyed during the cruise, two more areas were defined (named I and II in **Figure 1**).

2.3. Complementary data

Near real time absolute dynamic topography maps derived from the sea level anomalies measured by the TOPEX/Poseidon and ERS–1/2 satellites were produced by AVISO (see http://www.jason.oceanobs.com/ for product details). They compare reasonably with the dynamic topography field produced from CTD data: a Spearman–rank correlation analyses yielded that r =+0.57 (n = 36, P< 0.01).

The wind field at 10 m above the sea level during the cruise was derived from the NASA/JPL's SeaWinds Scatterometer onboard the QuikScat satellite, with a spatial resolution of 1/4º x 1/4º and an accuracy of ±2 m s^{-1} in the range of 3 to 20 m s^{-1}. QuikScat data were complemented with the meteorological station on the mooring off Cape Silleiro (http://www.puertos.es), at 42º6′ N, 9º23′ W in 323 m water (**Figure 1**). Whereas the QuikScat data were appropriate to analyse the meteorological conditions of Leg A, the station off Cape Silleiro provided a suitable picture of the temporal variability during Leg B. Note that QuikScat data are not valid within 25 Km off the coastline.

The mooring off Cape Silleiro also consisted of an AANDERAA UCM–60 acoustic current meter, with water temperature and salinity sensors attached, deployed at 3 meter depth. Therefore, it provided a complete view of the time evolution of the surface hydrography and dynamics of coastal waters. In addition, a SERPE–IESM SC 40–G lagrangian buoy was also deployed during the cruise at 42º 00′ N and 10º 45′W and was recovered 35 days later in the coast, allowing to track its trajectory from the area covered during Leg A to the area covered during Leg B.

Finally, the continental discharge of the river Oitaven–Verdugo, which drains into the Ría de Vigo, is used as a proxy to the time evolution of the freshwater flow to the Galician Rías Baixas. The river Oitaven–Verdugo is partly regulated by the Eiras reservoir (flow data provided by the Seraguas, the company in charge of the reservoir) and partly free (flow calculated with the method described by Ríos et al., 1992).

3. Results and Discussion

3.1. The surface circulation of the Galicia bank

The Galicia bank was sampled during an abrupt transition in the wind regime. South easterly winds of 7 m s^{-1} blew over the bank before the beginning of the cruise

(**Figure 2a**). The wind pattern changed dramatically on March 27–28, when a cyclonic wind cell was observed over the bank (**Figure 2b**) and, after that, north easterly winds of 9 m s^{-1} prevailed in the area (**Figure 2c**). Despite the unstable meteorological conditions, AVHRR images at the beginning (**Figure 3a**) and the end (**Figure 3b**) of the cruise revealed the presence of a persistent sea surface temperature minimum over the bank, accompanied by a surface salinity minimum (**Figure 4a**). These minima were associated to a cyclonic gyre that described an ellipse oriented along the isobaths of the bank, the most remarkable structure observed in the surface dynamic height and geostrophic velocity fields derived from satellite altimetry (**Figure 4**) and CTD data (**Figure 5a**). Dynamic topography maps at different depths (not shown) revealed that the cyclonic gyre affected not only the surface but the whole 500 m of the water column over the Galicia bank. A smaller anticyclonic gyre was insinuated to the northeast. The geostrophic flow field was such that the strongest velocities (16 cm s^{-1} to the north west) occurred between this pair of gyres.

A possible origin of this structure is the interaction between the IPC and the intricate topography of the NW Iberian coast, which promote eddy shedding (Peliz et al., 2003). Pingree and Le Cann (1992a) described for the first time the formation of long–living (> 9 months) anticyclonic eddies of 50–60 Km, rotating at maximum velocities of 30 cm s^{-1}, which sometimes form anticylonic–cyclonic pairs of eddies during the separation of the IPC from the continental slope at some salient capes early in the winter. They coined it as SWODDIES (Slope Water Oceanic EDDIES). Most of the studies on SWODDIES have been conducted in the Bay of Biscay (e.g. Pingree and Le Cann, 1992a; 1992b; García–Soto et al., 2002; Fernández et al., 2004). Martins et al. (2002) observed that, although surface drifters deployed in the IPC are usually trapped to the continental slope in the region off the Rias Baixas (42º–43ºN), some of them separated from this current being involved in anticyclonic as well as cyclonic eddies and meanders. Examples of the detachment of anticylonic–cyclonic pairs of eddies from the IPC in the Northern Iberian basin have been given by Peliz et al. (2005) in ~40ºN during January 1997 and 2002. Dipoles detached at the early winter usually comprise a small cyclone and a large anticyclone, which migrate westwards at about 2 cm s^{-1} (Pingree, 2003). In the case of the dipole apparently observed over the Galicia bank during the early spring 2003, it was composed of a large cyclone and a small anticyclone and its size was about twice the regular size of a SWODDY.

A second alternative for the development of the cyclonic gyre is that a branch of the IPC separated from the slope off 42ºN and flowed north westwards turning around the eastern flank of the Galicia bank. This IPC branch would interact with the IC flowing south eastwards surrounding the western flank of the bank, to form the cyclonic structure observed over the seamount. It is well known that the interaction of seamounts with ocean currents produces a wide variety of processes that include the formation and shedding of cyclonic and anticyclonic eddies, which can be transiently trapped over the seamount (see Mouriño et al., 2001 and references therein). The interannual variability of the IPC is related to the North Atlantic Oscillation (García–Soto et al., 2002; Álvarez–Salgado et al., 2003) and 2002/2003 corresponded with the fourth strongest development of its Cantabrian extension over the last 25 years as shown by satellite observations and SST measurements (García–Soto, 2004). The intensity of the IPC during that year probably contributed to the observed circulation pattern by preventing the southward penetration of the IC east of the Galicia bank, a probable pathway in moderate NAO years (Peliz et al., 2005).

The sea surface velocity plots elaborated with the operational model of MERCATOR suggest a separation of the IPC from the slope in the vicinity of Cape Fisterra after the change in the wind regime from southerly to northerly on March 27–28 (compare **Figure 6a** with **6b** & **c**). However, the model is not able to reproduce the cyclonic gyre observed over the Galicia bank. A process orientated study is required to unequivocally resolve the causes and persistence of this conspicuous circulation pattern. In any case, from the view point of the *Prestige* oil spill, the residence time in the Northern Iberian basin of an oil slick trapped in the cyclonic and anticyclonic gyres observed during March–April 2003 increases relative to a situation dominated by the southward flowing IC. An increased residence time would eventually favour the eastward drifting of the oil slicks by transient westerly winds and, therefore, the probability that it reach the Galician and/or Cantabrian coasts.

3.2. The surface circulation of the Galician continental slope and shelf

Winds in the coastal area (**Figure 7a**) reproduced the pattern observed in the open ocean (**Figure 2**): southerlies prevailed from March 25 to 29 and northerlies from March 29 to April 7, when leg B was occupied. The average wind speed during Leg B was 7.4 m s^{-1}, with a peak of > 10 m s^{-1} on April 2. The AVHRR images of **Figure 3** show a wedge of warm water extending northward between the Iberian shelf break and the eastern flank of the Galicia bank. In contrast, colder and fresher (< 34.8; **Figure 4**) surface waters were observed on the continental shelf off the Rías Baixas. This synoptic picture is complemented by the time evolution of sea surface temperature and salinity recorded by the mooring off Cape Silleiro, in the shelf break (**Figure 7b**). Salinity ranged from 34.7 (characteristic of WIBP waters) to 35.7 (characteristic of IPC waters). Abrupt transitions occurred on March 26–27, when salinity increased from 34.8 to 35.4 (ΔS= +0.6) and on April 2–3, when it decreased from 35.7 to 34.7 (ΔS= –1.0). These changes were not related with continental runoff but with the local wind regime, predominantly south westerly on March 26–27 and north easterly on April 2–3 (**Figure 7a**).

The surface dynamic height and geostrophic velocity fields derived from the CTD casts collected from April 4 to 6 (area V in **Figure 5b**) pointed to the presence of the IPC off the Rías Baixas, with maximum geostrophic velocities of 20 cm s^{-1} at 9º30"W. As indicated above, the IPC also appeared in the sea surface velocity plots elaborated with the operational model of MERCATOR (**Figure 6**). At the beginning of the survey, March 26 (**Figure 6a**), the model produced a well defined IPC. During the following days, April 2 (**Figure 6b**) and April 9 (**Figure 6c**), when the wind regime reversed, the IPC can still be seen flowing northwards but with a reduced velocity and displaced offshore. Accordingly, the surface velocity recorded at the Silleiro buoy (**Figure 7c**) was always northward, independently of the local wind direction (**Figure 7a**). It reached 18 cm s^{-1} on March 27–30 (in response to southerly winds) and reduced to <10 cm s^{-1} on April 1–7 (after the reversal to northerly winds on March 29). During April 1–7, the surface current exhibited a marked offshore component, specially on April 2, at the time at the abrupt salinity decrease (**Figure 6b**).

According to Frouin et al. (1990), the IPC results from the combination of the onshore Ekman transport induced by the dominant southerly winds during the autumn and winter and the geostrophic adjustment of the large–scale oceanic zonal flow. Therefore, the density–driven component of the IPC seems to be strong enough to allow that the poleward slope current coexists with relatively strong northerly winds, just decreasing in intensity and displacing offshore. Observations made by Santos et al. (2004) confirmed the presence of the IPC during the winter despite northerly winds were dominant during that cruise. The spring in the Northern Iberian margin is characterised by changing wind conditions, as corresponds to the transition from the downwelling to the upwelling favourable seasons (Alvarez–Salgado et al., 2003). Therefore, it is expectable that the IPC is visible as a coherent surface current at this time of the year, as observed by Mazé et al. (1997) in May 1989, Castro et al. (1994)

in May 1991 and Fiúza et al. (1998) in May 1993. Reversal of the surface circulation to the southward flowing Portugal or Iberian Coastal Current (ICC), characteristic of the upwelling season, only occurs after intense and persistent northerly winds (Álvarez–Salgado et al., 2003). Peliz et al. (2005) speculated that part of the IPC flow during the summer is advected offshore.

The relatively high continental runoff during April 2003 also contributed to the seaward migration of the WIBP to the shelf–break (Álvarez Salgado et al., 2000), where it formed a convergence front with the IPC. As suggested by the trajectory of the surface SERPE–IESM SC 40–G lagrangian buoy (**Figure 5a**), this front is able to protect the Rías Baixas against the eventual penetration of a float. Note that when the drifting buoy reached the slope off the Rías Baixas on April 26, it moved along shore despite the strong westerly component of the local wind, which should introduce it into the rías (average April 26–30, 6±1 m s^{-1}). The lagrangian buoy reached the coast on April 30, 42 Km north of Cape Fisterra. Complex empirical orthogonal functions (CEOFs) and Spearman–rank correlation analyses were applied to the drifter and wind velocities for a) the drifting period in the open ocean (west of 10ºW) and b) the drifting period over the continental slope and shelf (east of 10ºW). For the first case, 99% of the variability was explained by a CEOF that indicated that the current intensity was 2% of the wind intensity and it was rotated clockwise 5º from the wind direction. The Spearman–rank correlation was r = +0.43 for the zonal component and r = +0.47 for the meridional component (n = 239, P < 0.01), suggesting that the buoy trajectory was driven by the wind blowing over the surface layer in the Northern Iberian basin. For the second case, the relation between intensities decreased to 1% and the drifter direction was rotated clockwise 54º from the wind direction. The Spearman–rank correlation was as low as r = +0.20 for the zonal component and r = +0.44 for the meridional component (n = 90, P < 0.01), suggesting that, on the slope and shelf other factors such as the density driven basin–scale circulation and the river discharge became relevant. The same argument was used by Balseiro et al. (2003) and Montero et al. (2003) to justify why the oil patches did not penetrate into the Rías Baixas during November 2002. Although the wind/water velocity ratios observed either in the open ocean or the shelf are within the 1–6% range reported in the literature, it should be noted that they were lower than the 3.3% assumed in the model of Montero et al. (2003) and the ~3% estimated by Garcia–Soto (2004) in the Cantabrian region.

3.3. The concentration of PAHs in the surface layer of the NW Iberian Basin

Figure 4b shows the distribution of dissolved/dispersed PAHs in the surface layer of the study area. In general, the concentrations were very low, <0.5 µg L^{-1} (chrysene units). Significantly higher levels were recorded in three conspicuous areas: **1)** the southern Galicia bank (~1.0 µg L^{-1}), where the bow and stern of the *Prestige* tanker were still leaking fuel oil, which emerged to the surface, at the time of the cruise; **2)** Cape Fisterra (~1.5 µg L^{-1}), where the IPC extends from the slope to the coast because of the reduced continental inputs north of the Rías Baixas; and **3)** the mouth of the Ría de Vigo (~1.5 µg L^{-1}), an area of intense maritime traffic.

The *Prestige* oil spill consisted of a complex mixture of saturated (23%) and aromatic (53%) hydrocarbons, and asphaltenes and resins (24%). The aromatic fraction was mainly composed of the water soluble alquil–naphthalenes and alquil–phenanthrene (Alzaga et al., 2004). Experiences to determine the water soluble fraction of the *Prestige* fuel oil indicated that only 0.4 $^{0}/_{00}$ was soluble (CSIC technical report nº 13) and that this fraction dissolves in the water column in about 1 day (unpublished data). The dispersion of the *Prestige* oil patches by the surface currents of the Northern Iberian basin, together with the low solubility of the *Prestige* oil, the rapid evaporation of naphthalene, and the biodegradation by the natural bacterial populations of the area, readily able to degrade crude oil (Medina–Bellver et al., 2005), should be reasons behind the low PAHs concentrations recorded either in the area where the *Prestige* sank or near the coast. In addition, by the time of the cruise, the cracks if the bow and stern of the *Prestige* tanker were practically sealed. Accordingly, PAHs levels reported in April 2003 were much lower than those reported in previous surveys in the area during December 2002 and February 2003 (González et al., this issue). Specially remarkable are the significantly higher PAHs levels observed off Cape Fisterra, because it has been demonstrated that they unequivocally corresponded to the *Prestige* oil spill (Varela et al., this issue).

4. **Conclusions**

Three main conclusions can be derived from this work:

1) *Prestige* oil patches in open ocean waters of the Northern Iberian basin were displaced by the wind blowing over the surface layer with a velocity of 2% the wind speed and rotated clockwise 5º from the wind direction. This dependence was altered by:
2) transient mesoscale cyclonic and anticyclonic structures in the vicinity of the Galicia bank, which tended to increase the residence time of oil patches in the Northern Iberian basin, as compared with the expected southwards flow of the Iberian Current (IC); and
3) the combination of a well–defined Iberian Poleward Current (IPC) and a marked convergence front between the IPC and the Western Iberian Buoyant Plume (WIBP) waters, which prevented the entry of *Prestige* oil patches into the Rías Baixas.

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Figure captions

Fig. 1. Map of the study area during cruise HIDROPRESTIGE, March 25–April 7, 2003, aboard *R/V* Cornide de Saavedra**.** Leg A (March 25–31) comprised from stn 87 to 116, in the Galicia Bank area; Leg B (April 1 to 7), comprised from stations 1 to 86, in the continental shelf and slope off the Rías Baixas. Crosses, CTD stations; black circles, stations where samples for PAHs analyses were collected; white circle, Seawatch buoy of Puertos del Estado off Cape Silleiro. The –100, –1000 and –2000 m isobaths are indicated. The place where the *Prestige* tanker sank on November 19, 2002, is also shown. Stations within square I) were occupied between March 26 and 27, square II) between March 28 and 31, square III) between April 1 and 2; square IV) between April 2 and 4 M and square V) between April 4 and 6.

Fig 2. Sea wind fields derived from the Quickscat for (**a**) March 24; (**b**) March 28 and (**c**) March 30, 2003. Error, ±2 m s^{-1}, ±20°.

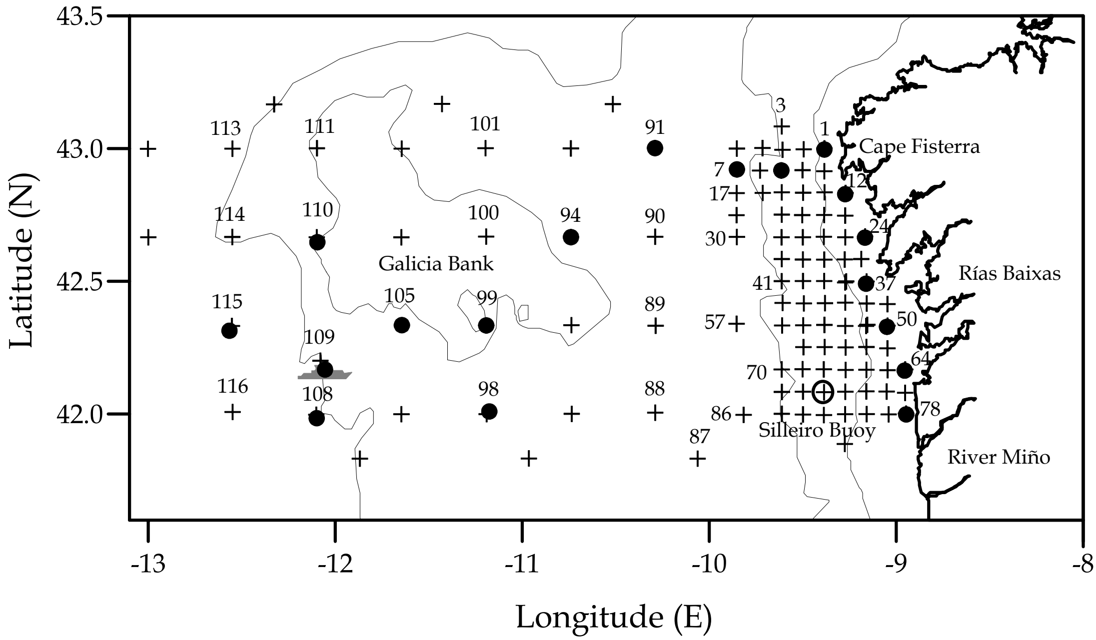
Fig. 3. Dynamic height topography maps (cm) for (**a**) March 26; and (**b**) April 2, 2002 as obtained from satellite altimetry data. Absolute dynamic topography was preferred to maps of sea level anomalies to damp high–frequency variability. AVISO formal mapping error <50%. AVHRR sea surface temperature images underlay the dynamic height topography maps. They were kindly provided S. Groom and P. Miller (Remote Sensing Data Analysis Service, PML, UK). The –100, –1000 and –2000 m isobaths are indicated. The place where the *Prestige* tanker sank on November 19, 2002, is also shown.

Fig. 4. Surface distributions of (**a**) salinity; and (**b**) dissolved PAHs. Black circles, small size, PAHs <0.5 μg L^{-1}; medium size, 0.5 < PAHs < 1.0 μg L^{-1}; and large size, 1.0 < PAHs < 2.0 μg L^{-1}.

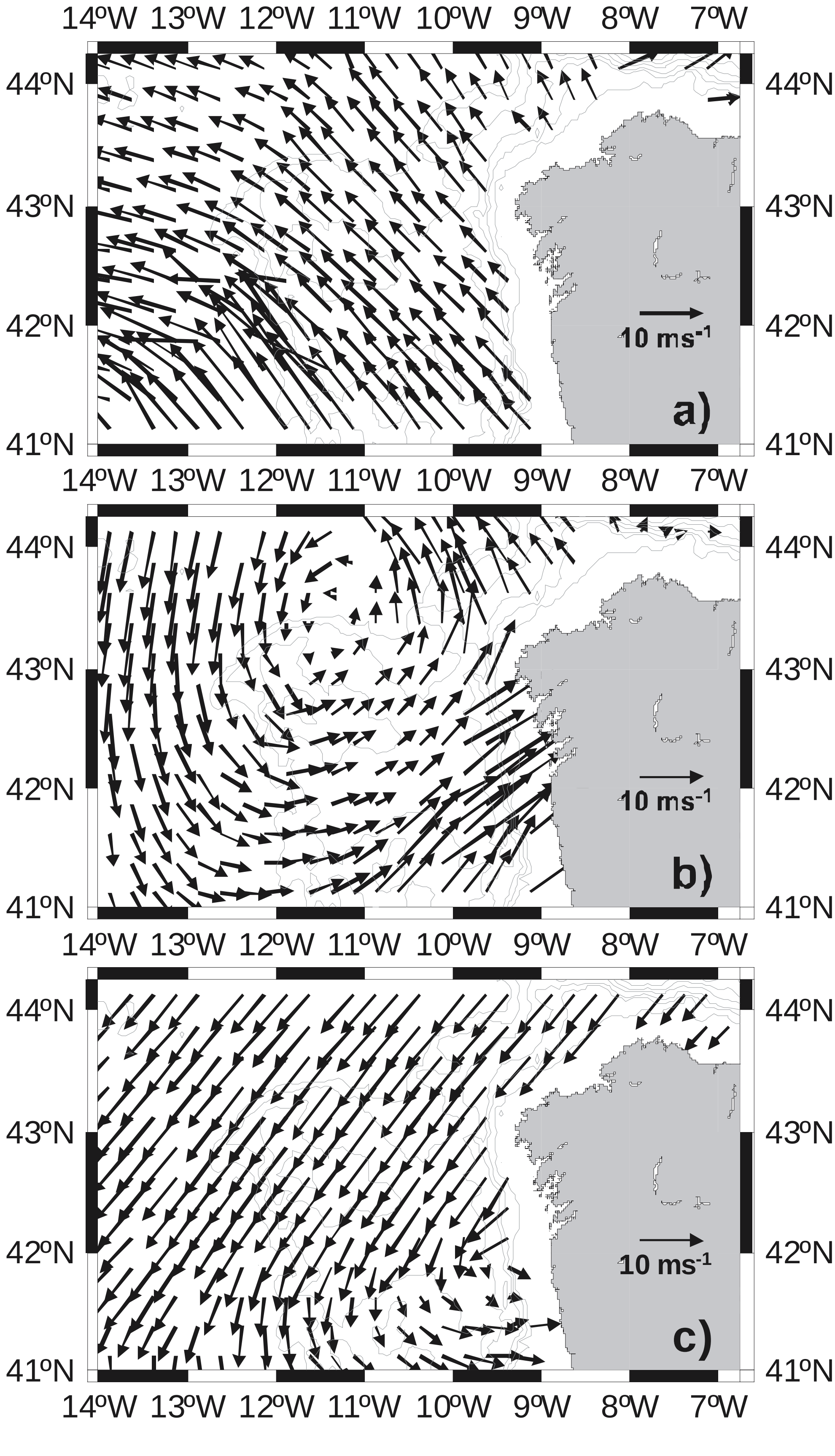
Fig. 5. Dynamic height topography (cm, red lines) and geostrophic velocity (cm s^{-1}, red arrows) maps at 10 m depth derived from CTD data collected (**a**) during Leg A and (**b**) Leg B (referred to 1400 db). The trajectory of the surface drifting buoy (grey line) deployed at 42º 30′ N and 10º 45′W on March 27, 2003 (green triangle) is also shown. The Quikscat sea wind intensity and direction (black arrows) is superimposed. The –100, –1000 and –2000 m isobaths are indicated. The place where the *Prestige* tanker sank on November 19, 2002, is also shown (yellow star).

Fig. 6. Sea surface velocity plots elaborated by MERCATOR using their operational model that assimilates sea level anomaly data from satellite altimetry and incorporates atmospheric forcing by winds (from the European Centre for Medium-range Weather Forecast; ECMWF). (**a**) March 26, (**b**) April 2 and (**c**) April 9, 2003.

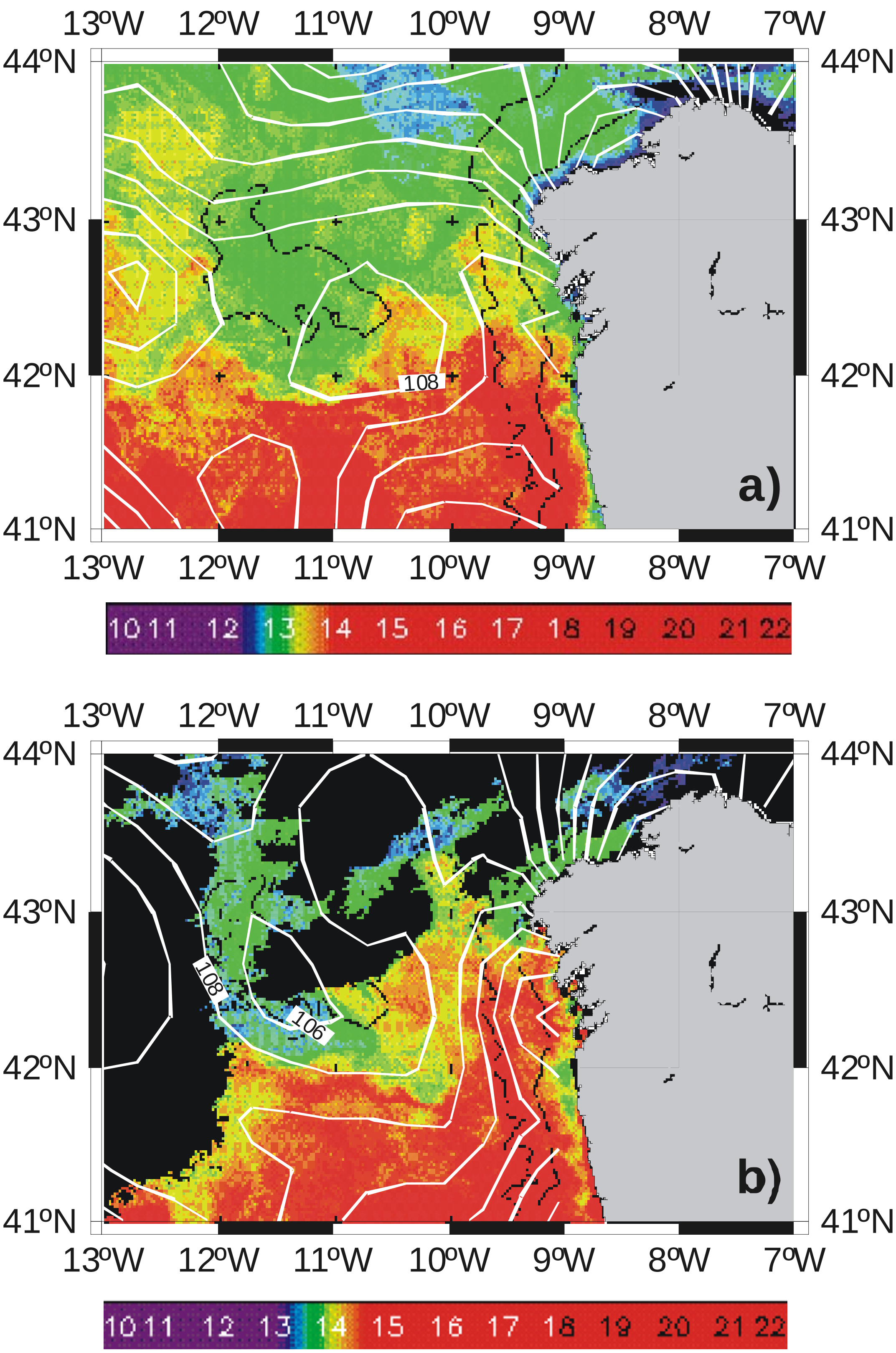
Fig. 7. Time evolution of (**a**) wind speed at 10 m above sea level (m s^{-1}) and River Oitabén–Verdugo flow (m^3 s^{-1}); (**b**) sea surface salinity (pss), solid line, and temperature, dotted line (ºC); and (**c**) sea surface current at 3 m depth (cm s^{-1}). Wind speed and sea surface salinity, temperature and current were taken from the Seawatch buoy of Puertos del Estado off Cape Silleiro (**Figure 1**). The data were filtered with a moving average filter $A_{24}{}^2A_{25}$ (Godin, 1991), with a cut–off frequency of 30 hours to remove tides and inertial components. The shadowed area indicates the dates of the cruise HIDROPRESTIGE.



(Álvarez-Salgado et al., Figure 1)



(Álvarez-Salgado et al., Figure 2)



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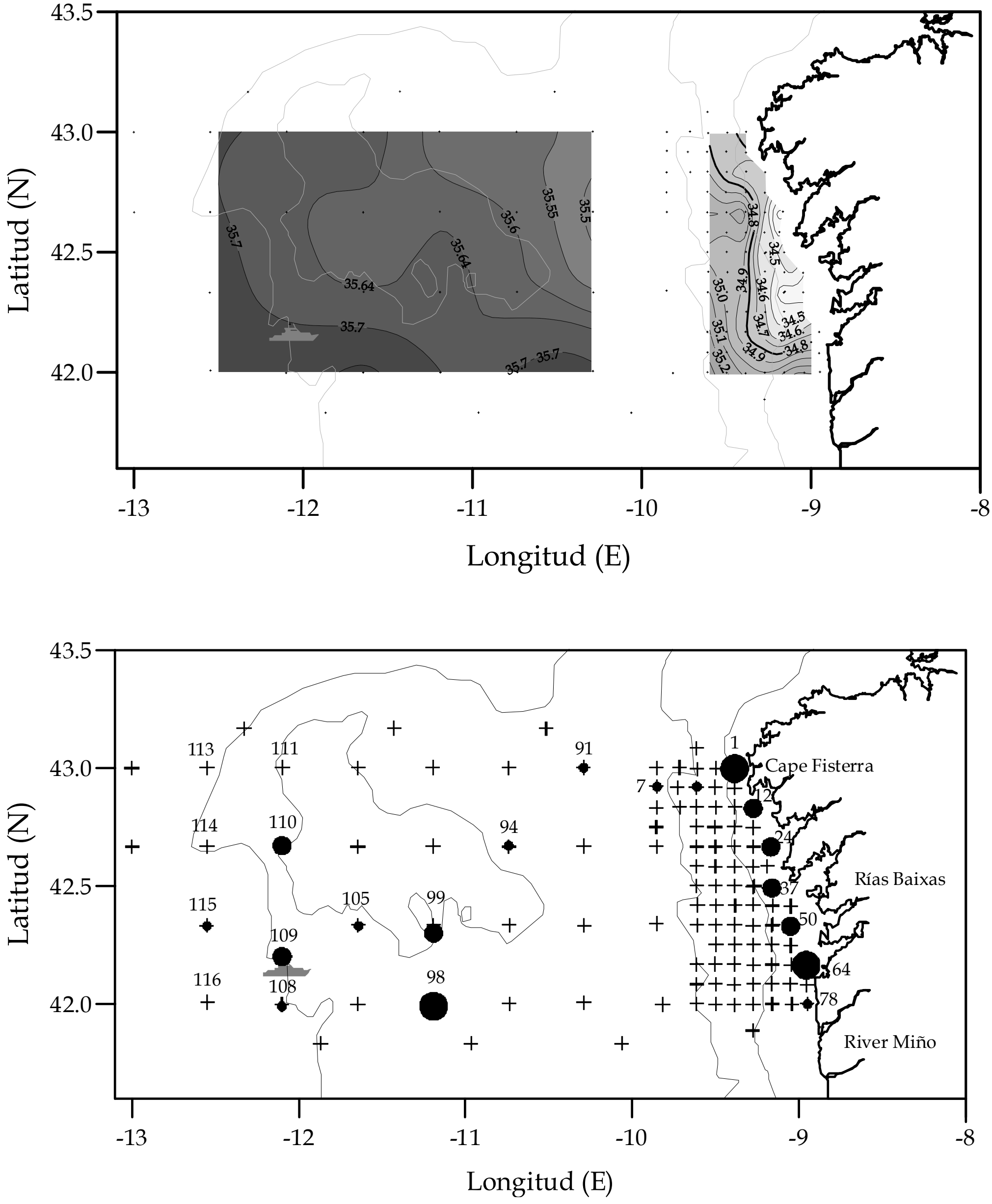

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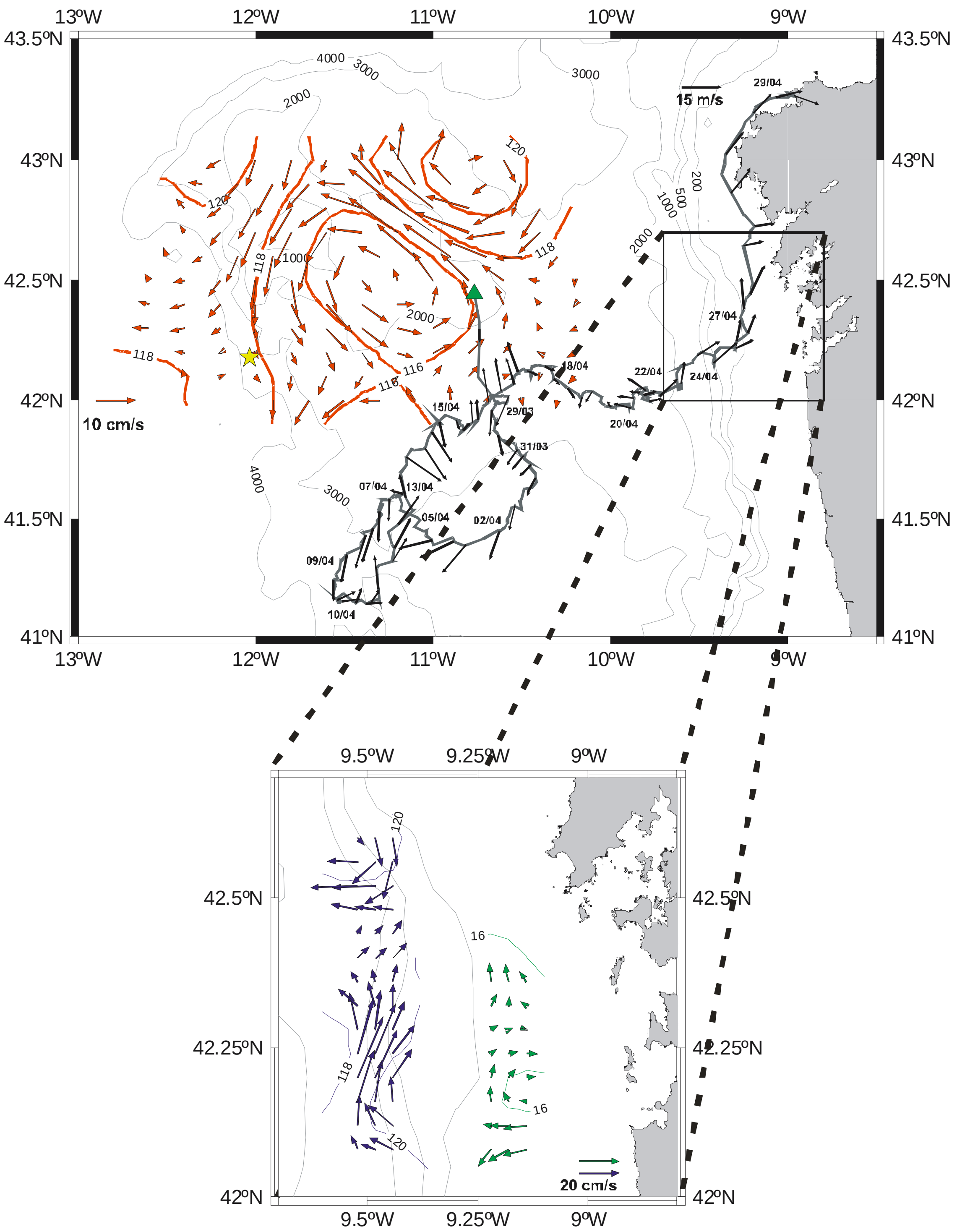

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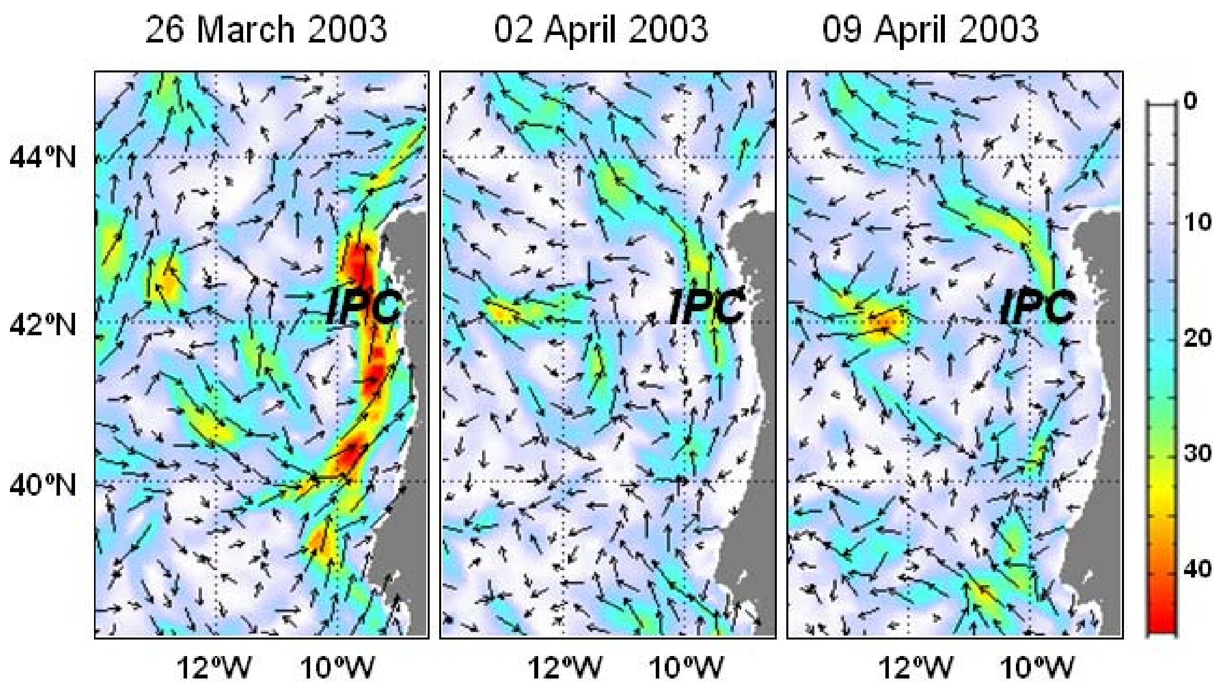

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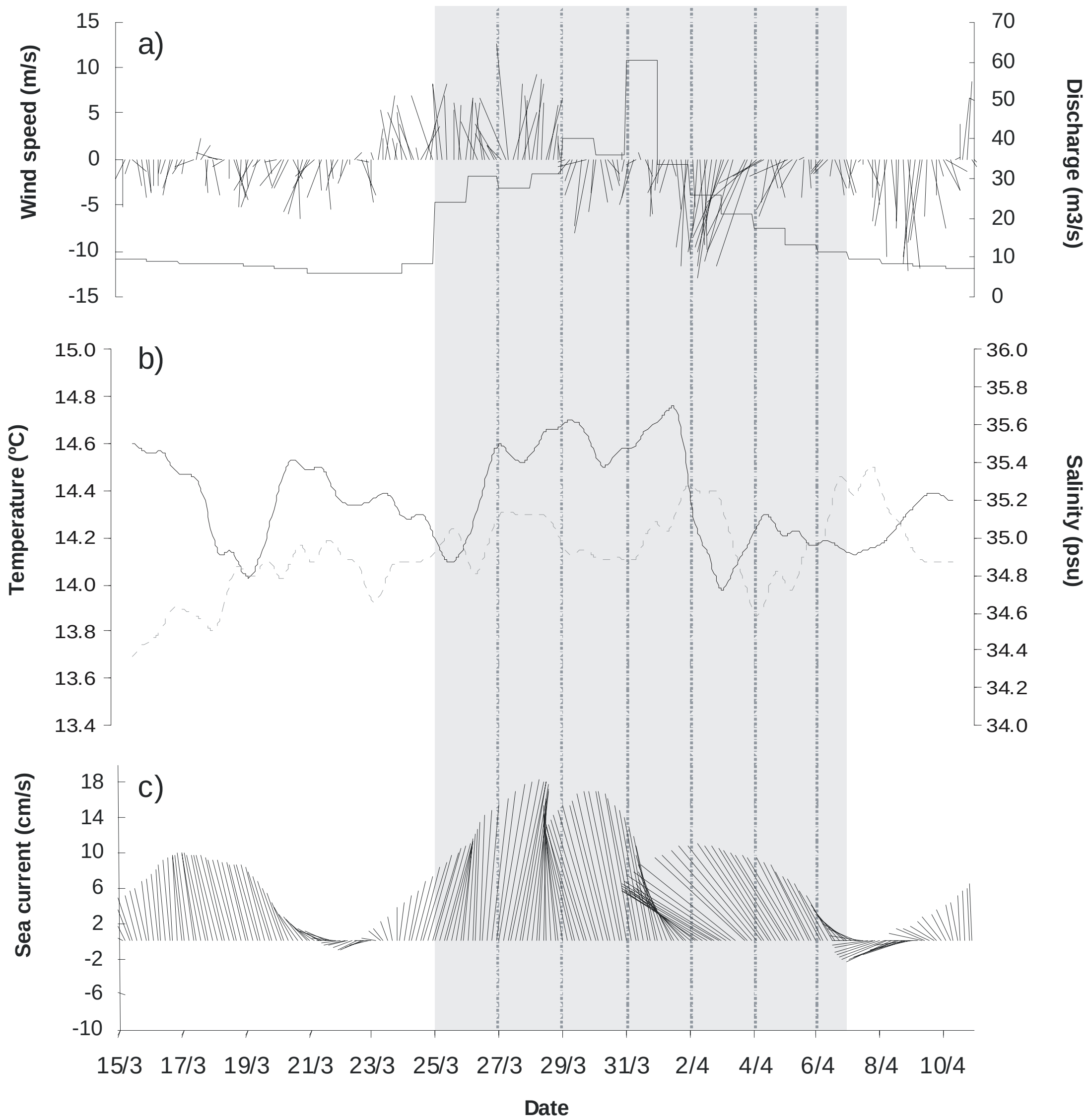

(Álvarez-Salgado et al., Figure 7)