WINTER PATTERNS OF HYDROGRAPHY AND DYNAMICS OFF WESTERN GALICIA (NW SPAIN)


Key words: Shelf dynamics; Hydrographic survey; WIBP; IPC; Galicia; NW Spain.

ABSTRACT

In this paper, winter hydrography and dynamics off western Galicia is described combining on board and satellite measurements during downwelling season. In upper waters (0-50 m), four features have been distinguished by their different physical properties, being from coast to ocean: a local upwelling near Cape Silleiro originated by divergence of coastal currents, the Western Iberian Buoyant Plume (WIBP), mainly originated by the Miño runoff, a transitional frontal zone with great mesoscale activity, and finally the Iberian Poleward Current (IPC), which are representative of this zone in winter. The high correspondence between on board surface fluorescence and satellite chlorophyll a measurements is quantified. An analysis of spatial variability of central, intermediate and deep water masses is also included.

INTRODUCTION

The western coast of Galicia is located in a region with a shelf dynamics characterized by high seasonal variability (Varela et al., 2005), mainly forced by the strength and position of the Azores High. It can be roughly summarized as a spring–summer season dominated by upwelling favourable winds and an autumn–winter season with rather frequent downwelling favourable southerly winds. However, this scenario is too simple. Alvarez-Salgado et al., (2003) showed that 70% of wind variability is concentrated in periods <30 days. This means that wind pattern shifts at relatively short scales, causing a succession of upwelling-downwelling, generating a complex variability in hydrography and circulation. Although the short-scale variability has been extensively studied in the rias, there is a small number of works in the adjacent shelf, and mainly in summer. During this season, high continental runoff (River Miño is the major one that flows into the southern shelf study area) generates a brackish plume that spreads along coast. As this is a recurrent characteristic, also in the Portuguese coast, Peliz et al., (2002) referred it as

WIBP (Western Iberia Buoyant Plume). This feature has an associated northward jet and can interact both with the wind-driven circulation and also with the Iberian Poleward Current (IPC). This slope current that comes from subtropical origin is the other significant winter characteristic of this zone.

The interaction of cold (T<14°C) and brackish (S<35) WIBP with warm (T>15°C) and salty (S>35.8) IPC forms a marked density front near the coast. Its position offshore (clearly shown by IR satellite images) is strongly dependent on the balance between downwelling favourable southerly

Figure 1:
Image of sea surface temperature over studied area on 13 February 2009. WIBP and IPC are clearly recognized by low and high temperature values respectively. Lower panel: Positions of hydrographic stations.
winds (that trend to carry it out to the coast) and northward continental runoff that, driven by upwelling favourable northerly winds, trend to carry it out to the ocean (Álvarez–Salgado et al. 2000). Besides, the hydrodynamics of this front has important biogeochemical consequences, as it is associated to accumulation and growth of larval fish and phytoplankton (Santos et al., 2007), and thus high chlorophyll concentration, which contrasts with the oligotrophic conditions prevailing in the subtropical IPC and surrounding oceanic waters (Alvarez Salgado et al., 2003).

Remote sensing observations from satellite sensors can provide synoptic and frequent Sea Surface Temperature (SST) and chlorophyll $a$ overviews of the ocean (Robinson, 2004). Remote sensing data have been widely used on oceanography providing useful information on spatial distribution of plumes (Piola et al., 2008), characteristics of upper ocean structures and detection of SST fronts (Peliz et al., 2005).

In the framework of the formative assessment of Marine Sciences Degree students at University of Vigo, four oceanographic surveys at the Galician coast, named Forsagal, were conducted during February 2009. The main objective of the first cruise was to characterize the short-time-scale variability of the hydrographic structure and circulation at the adjacent shelf/slope of the Rías Baixas during the downwelling season.

**MATERIALS AND METHODS**

Two parallel hydrographic zonal sections separated 25.8 km (at 42.10 and 41.87 $^\circ$N) were made on board R/V Sarmiento de Gamboa during Forsagal 09-I Cruise, carried out from 10 to 13 February 2009 between Miño River and Cape Silleiro (figure 1). 10 and 14 stations closely spaced (5′ y 7 km) were occupied on the southern and northern transect respectively. On board sampling was made fast enough with the aim of keeping its synoptic nature, in order to compare results with satellite images. A CTD probe Seabird 9 plus was employed to measure the physical properties of fully depth water column at 24 Hz frequency. In order to check the Seabird Conductivity sensor, 280 samples were collected with a 24 Niskin bottle (10 l) rosette, and analyzed on board with a Guidline 8410A Portasal salinometer, giving very good agreement ($r^2>0.990$).

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**Figure 2:**

a) Components of the Wind field and daily upwelling index, before and during (10-13 February) Forsagal Cruise.

b) Daily precipitation over the studied area.
Geostrophic velocity was estimated by derivation of the geopotential anomaly field between adjacent stations relative to 600 db. This reference pressure was chosen because it lies within the transition between the southward Eastern North Atlantic Central Water of subpolar origin (ENACWsp) and the northward Mediterranean Water (MW), accordingly with Peliz et al. (2002). In depths shallower than the reference level, the extrapolation approach of Reid and Mantyla (1976) was used. The error in determination of geostrophic velocities has been estimated in $\pm 2$ cm/s.

Remote wind speed ($W$) and rainfall data were obtained from a station located at Ons Island, belonging Galician Meteorological Service (www.meteogalicia.es). This station is fairly representative of the shelf conditions in our area of interest, according with Herrera et al. (2005). A low-pass filter $A_{24}^2$ (Godin, 1972) with a cutoff frequency $\tau = 30$ h was applied to the wind data in order to facilitate the interpretation of the wind pattern. Daily upwelling index ($I_W$) was roughly estimated from wind by Bakun’s (1973) method:

$$I_W = -\frac{\tau_W}{(\rho_W \cdot f)} = - \frac{1000 \cdot \rho_a \cdot C_D \cdot W \cdot W_y}{(\rho_W \cdot f)} \text{ m}^3 \text{ s}^{-2} \text{ km}^{-1}$$

(1)

where $\rho_a$ is the density of air (1.2 kg m$^{-3}$ at 15°C), $C_D$ is an empirical dimensionless drag coefficient ($1.4 \cdot 10^{-3}$ according to Hidy, 1972), $f$ is the Coriolis parameter ($9.8 \cdot 10^{-5}$ s$^{-1}$ at 42° latitude), $\rho_W$ is the density of seawater (1025 kg m$^{-3}$, and $W$ and $W_y$ are the average daily module and northerly component of the wind. Negative (positive) values indicate downwelling (upwelling).

Satellite data recorded from Moderate Resolution Imaging Spectrometer (MODIS) and Medium Resolution Imaging Spectrometer (MERIS) over the study area were acquired on 13 February. Sky conditions over the water were cloud-free at the time of MODIS and MERIS overpasses. Semi-analytically computed (OC3) (O’Reilly et al., 2000) surface chlorophyll a concentrations were extracted from MODIS image (1 km spatial resolution). MODIS data regarding SST were generated using the calibrated algorithm of Brown and Minnet (1999). SST (in HDF format) and MODIS chlorophyll a products were available to download in Ocean Colour Web. Beam 4.2 (Brockmann Consult and contributors, Germany) software was used for the analysis of the imagery. MERIS data were first masked for glint risk, land, bright, coastline and invalid pixels. The MERIS product for chlorophyll a...
Figure 4: Upper hydrography and dynamics distributions along northern Cape Silleiro (200 m) and southern Rio Miño (50 m) transects. a, e). Temperature. b, f). Salinity. c, g). Sigma-t. d, h). Meridional geostrophic currents.
Mean values of MERIS chlorophyll $a$ concentrations were computed of the same pixel to the sampling stations and its 8 surrounding pixels (approximately 0.8 km$^2$ surface area). MERIS mean chlorophyll $a$ concentrations were compared with the available in-situ chlorophyll fluorescence measurements and the MODIS derived chlorophyll $a$ data.

Figure 5:
Upper panel: Colour Image of surface Chlorophyll $a$ (mg/m$^3$) obtained from Meris on 13 February 2009, showing the conspicuous front separating coastal WIBP (>2 mg/m$^3$) waters from IPC oceanic waters (<2 mg/m$^3$). Surface currents in both transects are also shown. Longitude of arrows is proportional to currents, with a maximum northward value of 13 cm/s (IPC) and a maximum southward value of 10 cm/s (in the coastal current off River Miño mouth). Lower panel shows the bathymetry.
RESULTS AND DISCUSSION

Meteorological conditions

The cruise took place 2 days after a strong downwelling event ($I_w < -900 \text{ m}^3\text{s}^{-1}\text{km}^{-1}$, $W_y > 7 \text{ m/s}$, with peaks of 18 m/s on 9 February, figure 2a). The conditions during the realization of both zonal sections (11-12-13 February) were slightly upwelling ($I_w < +400 \text{ m}^3\text{s}^{-1}\text{km}^{-1}$). Averaged rainfall ten days before survey was 4.2 mm/day, including a strong peak of 10.7 mm/day on 9 February (figure 2b). These are optimal conditions to WIBP development, as can be seen in IR satellite image (figure 1), with temperatures smaller than 12ºC. Plumes of Douro and Miño Rivers are distinguished by even colder values ($\sim 11ºC$) surrounding WIBP. Between both water bodies, an abrupt thermal frontal zone is observed at ($\sim 9.4ºW$), with great mesoscale activity.

Hydrography and dynamics

Surface fluorescence and salinity values in southern and northern legs are shown in figure 3a. Coastal ambient (WIBP) is traced by low salinity and high fluorescence values (between 9,0 and 9,5º). Southern leg has lower salinity as well as higher fluorescence values than the Northern one due to its localization close to River Miño. Frontal zone separating coastal and oceanic is located between 9,3-9,5º. Waters of oceanic influence are located westward 9.5º where low values of fluorescence and high salinities in both legs are very similar. The correspondence between surface in situ fluorescence (F, averaged over upper 5 m) and satellite chlorophyll $a$ ($Cla$) values is reasonable ($Cla = 0.65 + 2.16 \cdot F$ ; $r=0.85$, $n=23$, figure 3b) and can be extrapolated for direct estimation of chlorophyll $a$ from future fluorescence measurements on board R/V Sarmiento de Gamboa. In the vicinity of station RM1 around Miño plume, chlorophyll $a$ values are anomaly higher (up to 8 mg/m$^3$) than expected by the in situ fluorescence (0.81 AU, figure 3a, which would correspond a value of 2.4 mg/m$^3$ of chlorophyll $a$ in the fitting model $Cla$ versus $F$). This fact is due to additional coloured dissolved organic material (i.e. yellow substances) associated to Miño runoff. As this water body is usually related with optical complex waters, it has not been taken into account in the correlation of figure 3b.

Figure 4 (a, b, c, d) shows the distribution of physical properties in the upper waters (0-200 m) along northern transect off Cape Silleiro. Coastal domain (WIBP, up to CS4) is clearly seen in all distributions by low temperature ($<12ºC$), salinity and thus density waters. The surface thermal front (figures 1 and 4a) can be also followed on subsurface waters until bottom. Sloped up isopycnals offshore caused by plume (figure 4c) are consistent with a moderate northward coastal jet (11 cm/s, figure 4d), which can be also traced until 50 m depth. Between stations CS4 and CS12 there is a transitional zone from coastal to IPC waters, showing large mesoscale activity, mainly in temperature, companied with short scale changes in direction of meridional velocity. Finally, IPC can be traced from 70 km offshore with a maximum northward speed of 13 cm/s at surface (figure 4d). The vertical structure of this current is manly barotropic, as northward velocity has constant with depth. The offshore extension of the leg was not enough to sample all the IPC.

Figure 4 (e, f, g, h) shows the distribution of physical properties in near surface (0-50 m) waters of southern transect. Miño River plume is also associated to cold and low salinity shallow waters in coastal zone. Minima of surface salinity and temperature are located at station 3 (14 km offshore), suggesting that River plume could have a westward movement during previous days. In contrast with southern leg, isopycnals near bottom (27.0) are strongly sloped up towards the coast between RM1 and RM2 stations, accordingly with the southward coastal current (figure 4 h). However, the slope changes abruptly between RM2 and RM4, forcing a change to the north in the direction of the meridional offshore current. On the other hand, dynamics in
the remaining oceanic waters is small, although northward IPC can be seen at the offshore end of the section.

There is an overall agreement between spatial distribution of surface geostrophic velocities at both legs and mesoscale features of color image (figure 5). Some examples of this concordance are the following: at the southern leg, the greatest northward speed (at ~9.1°W) is coincident with both the highest (>8 mg/m³) chlorophyll a as well as the lowest salinity (figure 3a) concentrations. In both sections, near the WIBP/IPC front, velocities are erratic, accordingly with the different nature of both water bodies. The opposite direction of coastal currents (northward in the northern leg and southward in the southern one) can be the cause of the appearance of a local divergence, followed by an upwelling of low chlorophyll a sub-surface waters centered at (42°N, 9°W, figure 5).

The averaged vertical upward velocity (w) associated to this local upwelling, estimated from vertical integration of two-dimensional continuity equation ($\partial v/\partial y + \partial w/\partial z = 0$) in the upper 50 m, resulted 14±4 m/day. In this case, 2D approach is realistic because an estimation of the coastal/oceanward geostrophic velocity (u) between both coastal stations (CSI and RM1, figure 1) gives negligible velocities over entire water column (0-50 m, not shown). This fact also means that the upwelled water can only flow horizontally in terms of v, i.e. either northward or southward. Moreover, the appearance of this local upwelling can be involved with abrupt changes in the bathymetry towards the direction of both opposite coastal currents (figure 5).

Horizontal and vertical integration of meridional velocity field yields a net northward transport across Silleiro leg of 0.9±0.1 Sv (1 Sv=10⁶ m³/s). Its main contribution is the IPC, which resulted 0.6±0.1 Sv. An overall mean IPC transport was estimated at 2.0±0.5 Sv by Torres and Barton (2006). This means that limited offshore extension of the leg only sampled about 30% of IPC.
Spatial differences in Water Masses

Potential Temperature/Salinity ($\theta$/S) diagram for the most external stations off Cape Silleiro (figure 6) shows the typical pattern off Western Galician. The straight line around $\sigma_1 \sim 27.1$ isopycnal constitutes the Eastern North Atlantic Central Water (ENACW, Fraga et al., 1982). All lines become a salinity minimum around $\sigma_1 \sim 27.2$ (~450 m), which corresponds to the lower limit of ENACW coming southward from subpolar origin (namely ENACWsp, Rios et al., 1992). This minimum is more evident towards oceanic stations, suggesting that mixing of this water mass is greater against slope, where flow is greater accordingly with (Huthnance et al., 2002). Below ENACWsp, diagrams reach a temperature maximum ($\sigma_1 \sim 27.5$, ~800 m) and then salinity maximum ($\sigma_1 \sim 27.7$, ~1200 m), corresponding to Mediterranean Water (MW). Salinity maximum is more evident towards coastal stations, suggesting Coriolis deflection of the northward MW core (Fraga et al., 1982). Below MW, diagrams are directed towards a temperature and salinity minima ($\sigma_1 \sim 27.85$, ~1800 m), resulting from mixing with water coming from Labrador Sea (LSW). In this part of diagram, spatial variability is negligible as LSW comes from longer distance than MW and ENACW.

As a conclusion, Forsagal 09-I cruise took place in winter, two days after a moderate southwesterly wind conditions. The hydrographic context (as deduced from surface and vertical distribution of temperature, chlorophyll $a$ and salinity) along with the dynamic context (as deduced from the current distributions) showed the influence of two water bodies of different nature (WIBP and IPC), separated by an abrupt frontal zone, and it is consistent with the previous prevailing meteorological conditions, which favoured northward displacement of both water bodies. Divergence of coastal currents and colour images are consistent with a local upwelling in the vicinity of Cape Silleiro, probably also supported by sudden changes in the along flow bathymetry.

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