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Comparative analysis of upwelling influence between the western and northern coast of the Iberian Peninsula

I. Alvarez [a,b,*], M. Gomez-Gesteira [a], M. deCastro [a], M.N. Lorenzo [a], A.J.C. Crespo [a], J.M. Dias [b]

[a] EPhysLab (Environmental Physics Laboratory), Universidade de Vigo, Facultade de Ciencias, Ourense, Spain
[b] CESAM, Universidade de Aveiro, Departamento de Fisica, Aveiro, Portugal

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ABSTRACT

Upwelling conditions have been simultaneously analyzed along the western and northern coast of the Iberian Peninsula in terms of wind forcing and water temperature response. The wind forcing analysis showed that the season under more upwelling favorable conditions corresponds to spring–summer (April–September) along the western coast and only to summer (June–August) along the northern one. Taking into account the upwelling period common to both coasts (June–August), it was observed that the occurrence of upwelling events simultaneously along both coasts is the most probable situation (~46%) followed by upwelling unfavorable conditions also along both coasts (~26%). The analysis of sea surface temperature data also showed the existence of an upwelling season in spring–summer along both coasts, although upwelling events are more frequent and intense along the western coast than along the northern one. Chlorophyll concentrations showed a high seasonal variability at the western coast with the highest concentrations values in spring–summer months while at the northern coast the maximum values were observed in spring and autumn.

1. Introduction

Cape Finisterre marks an abrupt change in the coastline orientation of the northwestern coast of the Iberian Peninsula (IP) splitting this region in two different domains (Fig. 1): the Atlantic coast which lies in the N–S direction and the Cantabrian coast which lies in the W–E direction. These regions have an important hydrologic and biogeochemical activity, mainly attributable to coastal upwelling processes, and have been extensively studied during the last decades (Fraga, 1981; Botas et al., 1990; Borja et al., 1996, 2008; Bode et al., 2002). Several studies have been carried out in terms of wind-driven upwelling showing that the wind field is far from homogeneous in these areas and that wind observations at a single point, coastal or offshore, will not necessarily be representative of coastal conditions over a significant distance. In fact, some recent works carried out around the Galician coast (Torres et al., 2003; Gomez-Gesteira et al., 2006; Alvarez et al., 2008a) have shown that the upwelling frequency and intensity are influenced by the coastal orientation which modulates wind direction and intensity changing the upwelling favorable conditions prevalence at each coastal region. Coastal upwelling occurs mainly during the spring–summer months along the western and northern coast of the IP (Fraga, 1981; Botas et al., 1990; Borja et al., 1996, 2008; Lavin et al., 1998; Bode et al., 2002; Garcia-Soto et al., 2002; Llope et al., 2006; Alvarez et al., 2008b, 2010; Fontan et al., 2008). This upwelling generates an important primary production related to the presence of Eastern North Atlantic Central Water (ENACW, Fiuza, 1984; Ríos et al., 1992) near the coast, which can be upwelled inside the rias located in the region. Nevertheless, previous studies have shown that the mean long-term wind field's summer and winter patterns are not necessarily representative of particular years when summer-like upwelling patterns may also dominate in winter. Thus, wind patterns may alternate producing brief episodes of upwelling at the northern or western coast, or a combined pattern may occur producing weak upwelling on both coasts (Torres et al., 2003). In addition, along the western coast these upwelling events are more probable than along the northern one (Gomez-Gesteira et al., 2006; Alvarez et al., 2008a, 2008b) reaching probabilities around 60% and 30%, respectively, in summer. Although this coastal upwelling is basically a spring–summer process, it can also be observed in autumn–winter (Santos et al., 2001, 2004; Alvarez et al., 2003, 2009; Borges et al., 2003; deCastro et al., 2006, 2008a). This autumn–winter events can also be related to the presence of ENACW near coast (deCastro et al., 2006), although some authors have found different upwelled waters related to the Iberian Poleward Current (IPC, Frouin et al., 1990; Alvarez et al., 2003; Prego et al., 2007) and to shelf bottom seawater (Alvarez et al., 2009).

* Corresponding author at: EPhysLab (Environmental Physics Laboratory), Universidade de Vigo, Facultade de Ciencias, Ourense, Spain.
Tel.: +34 988 387 244; fax: +34 988 387 227.
E-mail address: ialvarez@uvigo.es (I. Alvarez).

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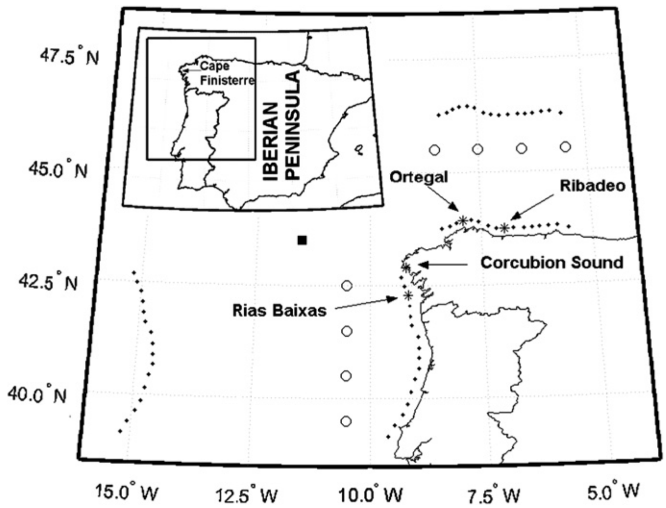

Fig. 1. Map of the western and northern coast of the Iberian Peninsula. The black square and circles represent the points where Ekman transport data were considered. Black points represent the location where SST data were obtained. Asterisks represent the points where chlorophyll data were considered.

Most of the studies described above were mainly focused on the western or northern coast of the IP separately and therefore have different databases and temporal scales, making the comparison between both coasts more difficult.

The aim of the paper is a comparative analysis between upwelling features along the western and the northern coast of the Iberian Peninsula. The comparative analysis was carried out in terms of upwelling indices calculated from Ekman transport data (UI_{ET}). In addition, upwelling trends were also calculated along the northwestern coast from 1967 to 2008. The upwelling implications in the ecosystem were characterized by means of the sea surface temperature (UI_{SST}) and chlorophyll concentrations. Thus, wind-induced upwelling conditions and water response to this forcing will be analyzed simultaneously along both coasts.

2. Data and methods

Ekman transport data provided by the Pacific Fisheries Environmental Laboratory (PFEL) (http://www.pfeg.noaa.gov) were considered over the last 42 years (1967–2008). The PFEL distributes environmental index products and time-series databases to cooperating researchers, taking advantage of its long association with the U.S. Navy's Fleet Numerical Meteorology and Oceanography Centre (FNMOC). FNMOC produces operational forecasts of the state of the atmosphere and the ocean several times daily and maintains archives of several important parameters. These parameters are model derived products which are routinely distributed to researchers. For our purposes six-hourly Ekman transport data model derived from Sea Level Pressure were considered at 4 points selected along the western coast of the IP (42.5°N, 41.5°N, 40.5°N, 39.5°N along 10.5°W) and 4 points selected along the northern one (8.5°W, 7.5°W, 6.5°W, 5.5°W along 45.5°N) (Fig. 1, circles) on an approximately $1^\circ \times 1^\circ$ grid. A control point was also considered at 43.5°N, 11.5°W (Fig. 1, black square). These data sets were averaged to obtain daily series.

Upwelling Index from Ekman transport data (UI_{ET}) can be calculated as the transport component in the direction perpendicular to the shoreline (Bakun, 1973; Nykjaer and Van Camp, 1994; Gomez-Gesteira et al., 2006). Ekman transport components can be defined in terms of wind speed, W, the seawater density, $\rho_w = 1025$ kg m^{-3}, a dimensionless drag coefficient, $C_d = 1.4 \times 10^{-3}$, and the air density, $\rho_a = 1.22$ kg m^{-3}, by means of

$$Q_x = \frac{\rho_a C_d}{\rho_w f}(W_x^2 + W_y^2)^{1/2} W_y \quad \text{and} \quad Q_y = -\frac{\rho_a C_d}{\rho_w f}(W_x^2 + W_y^2)^{1/2} W_x$$

f is the Coriolis parameter defined as twice the vertical component of the Earth's angular velocity, Ω, about the local vertical given by $f = 2\Omega \sin(\theta)$ at latitude θ. Finally, x subscript corresponds to the zonal component and the y subscript to the meridional one. Although the shoreline angle along the western and northern coast of the IP changes slightly from the northern to the southern limit and from the western to the eastern limit, macroscopically it can be considered approximately 90° and parallel to the equator, respectively. Thus, $-Q_x$ can be directly considered as the UI_{ET} along the western coast and Q_y along the northern one. Positive (negative) UI_{ET} values mean upwelling favorable (unfavorable) conditions.

The prevalence of upwelling favorable conditions can be characterized by the probability of finding consecutive days under these upwelling favorable conditions ($UI_{ET} > 16$ m^3 s^{-1} km^{-1}). Note that the threshold (16 m^3 s^{-1} km^{-1}) correspond to winds with intensity lower than 1 m s^{-1} to remove calms.

The real impact of upwelling events can be quantified by means of a new term defined as Upwelling Impact (U_{Imp}). This term can be calculated taking into account the upwelling intensity and the number of days under upwelling favorable conditions by means of the expression $U_{Imp} = \sum_{i=1}^{N} n_i \langle UI_{ET} \rangle_i^F / N_d$. n_i is the number of consecutive days under upwelling favorable conditions considering $n_i \geq 4$. In fact, previous studies around the northwestern coast of the IP proved that upwelled water can be easily identified when upwelling favorable conditions persist for more than 3–4 days (Alvarez-Salgado et al., 2000, 2006; Alvarez et al., 2005). $\langle UI_{ET} \rangle_i^F$ is the mean intensity of UI_{ET} during these days, N is the number of events per year and N_d is the number of days of the period under study.

Weekly mean SST data was obtained from night time measurements carried out by the Advanced Very High Resolution Radiometer on board NOAA series satellites (http://poet.jpl.nasa.gov). Data are available since 1985 with a spatial resolution of 4 km. For each grid point, an SST value is computed as the average of all cloud-free multichannel measurements available for 1 week. Two discrete sets of points placed along the northwestern coast of the IP were generated (Fig. 1, black points). Along the western coast, 16 points were considered at 20 and 500 km from the coast and along the northern one, 16 points were placed at 20 and 300 km from the coast. The distance of the oceanic points from the northern coast has been considered lower in order to avoid the possible effects of the French coast. Discretization effects were smoothed by calculating the SST monthly values at each point as the average of its nearest neighbors in latitude or longitude, depending on coast orientation. The distance between adjacent points is approximately 20 km.

The SST Upwelling Index (UI_{SST}) can be calculated as the SST difference between coastal and oceanic points at the same latitude (western coast) or longitude (northern coast). Along the western coast of the IP the distance of the oceanic points has been considered taking into account that the general patterns of the spatio-temporal variability of the index are similar within the range 400–1000 km offshore (Nykjaer and Van Camp, 1994; Santos et al., 2005; deCastro et al., 2008b). Along the northern coast this difference cannot be considered as an absolute Upwelling Index since temperature also changes with latitude due to differences in solar heating. In order to compare the UI_{SST} calculated along both coasts of the IP, a previous analysis was carried out to characterize these temperature changes in latitude. Four control points were considered along 43.5°N and 46.5°N