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Seasonal and interannual variability of the Douro turbid river plume, northwestern Iberian Peninsula

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ABSTRACT

The Douro River represents the major freshwater input into the coastal ocean of the northwestern Iberian Peninsula. The seasonal and interannual variability of its turbid plume is investigated using ocean color composites from MODIS (Moderate Resolution Imaging Spectroradiometer) sensor aboard the Aqua and Terra satellites (2000–2014) and long-term records of river discharge, wind and precipitation rate. Regional climate indices, namely the Eastern Atlantic (EA) and North Atlantic Oscillation (NAO), were analyzed to identify the influence of atmospheric variability on the generation of anomalous turbid river plume patterns. The connection between the monthly time series of normalized water leaving radiance at 555 nm (*nLw(555)*) and river discharge is high ($r = 0.81$), which indicates a strong link between river outflow and turbidity levels in the river plume. The equivalent result is found between precipitation and *nLw(555)* time series, but the peak correlation was found with a 1-month lag, revealing the importance of the river dams on the outflow regulation ($r = 0.65$). Lag correlations between *nLw(555)* and EA index show a peak at 1-month lag ($r = 0.51$). The relation between NAO index and Douro river discharge is considerable (-0.50), for a time lag of 1-month as well. However, the correlation coefficient between *nLw(555)* and NAO index presents a maximum peak for a longer period ($r = -0.42$ at 3-month). Anomalous turbid plume patterns, not related with estuarine outflow, are found during autumn 2004. A coccolithophore bloom is proposed as a plausible explanation for these unexpected turbid patches.

1. Introduction

River plumes are closely associated with a wide range of physical and biogeochemical shelf processes near river mouths (Dyer, 1973; Dzwonkowski and Yan, 2005). The spreading and variability of buoyant plumes depend on complex interactions among topographic constraints, ambient flow and high variability of dominant forcing: river discharge, wind stress, Coriolis effect and tides (Fong and Geyer, 2001; García Berdeal et al., 2002; Garvine, 1974; Hetland, 2005; Horner-Devine et al., 2015; Yankovsky and Chapman, 1997). The high variability of the main driver, i.e. freshwater discharge, often results in significant structural and dynamical differences among river plumes (Horner-Devine et al., 2015).

Some studies along the NW Iberian Peninsula have highlighted the importance of river runoff and estuarine plumes on local coastal circulation patterns (Peliz et al., 2002; Relvas et al., 2007; Santos et al., 2004; Torres and Barton, 2007). The freshwater discharge presents a marked annual cycle, with peak values during winter and lower flow during summer (Azevedo et al., 2008; Mendes et al., 2014). These seasonal fluctuations produce a variable estuarine outflow that modulates coastal circulation and biogeochemistry in the region (Picado et al., 2014) – the river outflow is a major supplier of sediment and nutrients into the coastal ocean. Moreover, the Douro estuarine plume is the major contributor to the Western Iberian Buoyant Plume (WIBP), which is an accumulation of a less dense water mass originated from all river outflows along the northern Portuguese coast that under persistent downwelling-favorable wind conditions flows northward as a classic coastal-attached buoyant plume (Mendes et al., 2016; Otero et al., 2008, 2009; Santos et al., 2004).

The Douro River is 927 km long, drains to the NW coast of Portugal and has a catchment basin that is the largest in the Iberian Peninsula (97,682 km^2). The Douro estuary is 21.6 km long, being delimited upstream by a dam that leads to an artificial separation from the river (Fig. 1). The daily mean freshwater discharge ranges from zero to >13,000 $m^3\ s^{-1}$ (Azevedo et al., 2010), with an average of 708 $m^3\ s^{-1}$. Rainfall episodes enhance river plume outflow, with a significant supply of nutrients and suspended matter to the continental

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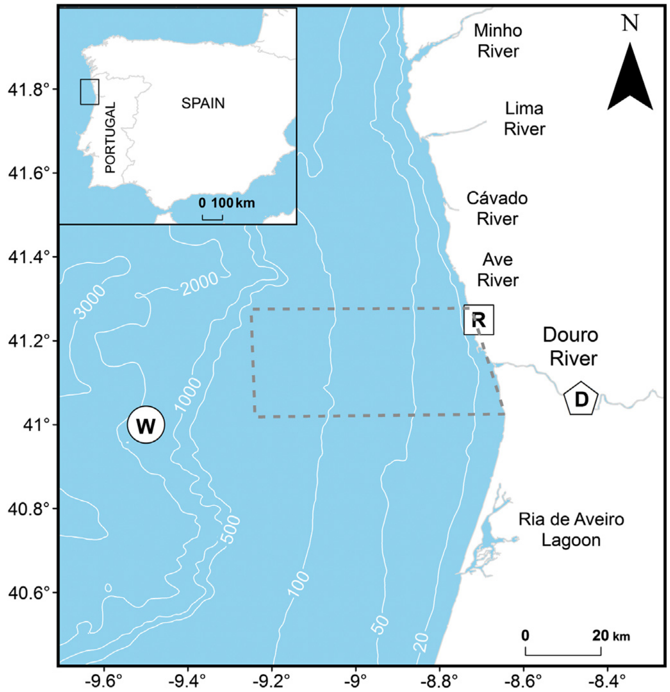

Fig. 1. Study area with location of the main rivers near the interest point (Lima, Cávado, and Ave rivers and Ria de Aveiro coastal lagoon). Wind and precipitation data stations are marked with a white circle (W) and square (R), respectively. The black pentagon (D) represents the location of the downstream Douro River dam. The dashed black box near the river mouth represents the near-field area of Douro River influence. Bathymetry, from General Bathymetric Chart of the Oceans (GEBCO), is shown with white lines (contours in meters).

shelf. The Douro River delivers about 87% of the fluvial sediments discharged into the NW Iberian coast (Dias, 1987) and the current deficit of sediments discharged by its estuary is commonly referred as a primary reason for severe erosion along southward beaches (Dias, 1990; Oliveira et al., 1982; Veloso-Gomes et al., 2004). Douro River runoff also poses a particular relevance on the coastal biogeochemistry, in particular during upwelling winter events (Picado et al., 2014; Prego et al., 2007; Ribeiro et al., 2005; Santos et al., 2004). Also, vertical stratification, enhanced by the plume, plays a key role on larvae retention (Santos et al., 2004). In these upwelling winter events, buoyant water (rich in nutrients) stimulates phytoplankton growth (Chícharo et al., 2003; Prego et al., 2007; Santos et al., 2004), contributing to an increase of primary production. Recently, Mendes et al. (2014) described the mean-state patterns of the Douro River plume through ocean color imagery, highlighting that the turbid plume is readily detected when the river flow exceeds 500 $m^3\ s^{-1}$. River discharge and wind are the main drivers of the plume, whereas tidal effect is most important near the estuary mouth. An offshore plume expansion is observed under northerly winds and high river discharges. A northward coastal-attached plume is commonly observed under downwelling-favorable winds. An offshore plume detached from the coast is observed under seaward winds, while westerly winds (onshore) tend to favor the freshwater accumulation near shore and to decrease the cross-shore advection (Mendes et al., 2014).

The Eastern Atlantic (EA) and North Atlantic Oscillation (NAO) are two of the most representative regional patterns of atmospheric variation in the Northern Hemisphere, impacting the local precipitation and river discharges, and with higher amplitude during winter (deCastro et al., 2008a, b; deCastro et al., 2006a, b; Lorenzo and Taboada, 2005; Trigo et al., 2004; Zorita et al., 1992). Several works have shown a significant correlation between NAO index and precipitation in Galicia during winter (northwest of Iberian Peninsula) (Esteban-Parra et al., 1998; Lorenzo and Taboada, 2005; Zorita et al., 1992). Trigo et al. (2004) found that river discharge is significantly correlated with the NAO index in winter (for the period 1973–1998) with a 1-month lag peak (−0.76 for Douro, −0.77 for the Tagus and −0.79 for the Guadiana river). Furthermore, deCastro et al. (2006a, b) found significant correlations between Minho river discharge and (DJF) NAO index for the period 1970–2005 with a 2-month lag peak, showing a decreased correlation in the last years, which is in agreement with the decreased trend in spatial correlation found by Trigo et al. (2004). Regarding EA variability, Rodriguez-Puebla et al. (1998) found correlation with the annual precipitation for Iberian Peninsula for April EA, while deCastro et al. (2006a, b) showed a negative correlation between Minho River discharge and (DJF) EA with a peak at 1-month lag. In addition, they are connected to different types of wind patterns, which influence the plume propagation. Upwelling along this area is a frequent phenomenon during the spring–summer months, when northerly winds prevail along the shelf. However, persistent northern and northeasterly winds are also observed during winter, inducing upwelling events (Álvarez et al., 2009; deCastro et al., 2008a, b), with similar patterns to those observed during summer, when precipitation and river discharge are minimum.

The Douro estuarine plume was studied by Mendes et al. (2014) to obtain a synoptic picture of the propagation of the plume using satellite imagery. However, no previous investigation is available on how this estuarine plume is influenced by changes in the main forcing from winter to summer conditions or even during peak freshwater discharge and wind. This study intends to be a step forward in the study of the Douro Estuarine plume at seasonal and interannual scales of variability, and their relationship with the atmospheric forcing.

Data and methods are described in Section 2. The results and discussion are presented in Section 3, highlighting the dominant spatio-temporal plume patterns along the coast and their connection with wind and climate indices at interannual scale. Finally, the principal conclusions are presented in Section 4.

2. Data and methods

2.1. Ocean color imagery

Satellite ocean color imagery provides unique information for detecting and monitoring the Douro River plume (e.g. Mendes et al., 2014). In general, ocean color images allow the resolution of submesoscale to small-scale features in river plumes (Aurin et al., 2013). The ocean color signal of river plumes, due to their high turbidity, is often well correlated with surface salinity, which is the natural tracer of freshwater buoyant plumes (e.g. Binding and Bowers, 2003; Burrage et al., 2008; Klemas, 2011; Molleri et al., 2010; Palacios et al., 2009; Piola et al., 2008; Saldías et al., 2016a). Thus, satellite-derived turbidity patterns become a direct proxy to identify river plumes on coastal areas (Fernández-Nóvoa et al., 2015; Mendes et al., 2014; Nezlin et al., 2005; Saldías et al., 2012; Saldías et al., 2016b).

All full-resolution L1A files from MODIS-Aqua and MODIS-Terra covering the Douro Estuary region (swaths inside the box 40°–43°N; 11°–7.5°W) and available from NASA (http://oceancolor.gsfc.nasa.gov) were used in this study. As MODIS imagery from Aqua is available from July 2002, previous data (Feb. 2000–Jun. 2002) correspond solely to MODIS-Terra. L1A files were processed using the SeaDAS (SeaWIFS Data Analysis System, version 6.4, Baith et al., 2001) software, following standard procedures for processing raw data files. L1B files were then converted to L2 files by applying a methodology similar to that provided by Mendes et al. (2014). The processing generates high-resolution (~500 m) daily *nLw(555)* (normalized water-leaving radiance at 555 nm; $mW\ cm^{-2}\ m^{-1}\ sr^{-1}$) images from February 2000 to December 2014. Swaths were mapped into a regular lat-lon grid (0.005° × 0.005°) and daily averaged images were generated when more than one existed for the same day. From all visible spectrum bands available in MODIS, the *nLw(555)* is the best proxy for mapping the Douro river plume – it