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Characterization of Iberian turbid plumes by means of synoptic patterns obtained through MODIS imagery

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ABSTRACT

Turbid plumes formed by the main Iberian rivers were analyzed and compared in order to determine similarities and differences among them. Five Atlantic rivers (Minho, Douro, Tagus, Guadiana and Guadalquivir) and one Mediterranean river (Ebro) were considered. Plume extension and turbidity were evaluated through synoptic patterns obtained by means of MODIS imagery over the period 2003–2014.

River discharge showed to be the main forcing. In fact, the dependence of plume extension on runoff is moderate or high for all rivers, except for Ebro. In addition, most of river plumes adjust immediately to runoff fluctuations. Only the extension of Tagus and Guadalquivir plumes is lagged with respect to river runoff, due to the high residence time generated by their large estuaries.

Wind is a secondary forcing, being only noticeable under high discharges. Actually, the dependence of plume extension on wind is moderate or high for all rivers, except Guadalquivir and Ebro. All the Atlantic rivers show the maximum (minimum) near- field plume extension under landward (oceanward) cross-shore winds. The opposite situation was observed for Ebro River.

Tide is also a secondary forcing although less important than wind. Actually, the dependence of plume extension on tide is only high for Guadiana River. Nevertheless, all Atlantic river plumes still have some dependence on semidiurnal tidal cycle, they increase under low tides and decrease under high tides. In addition, Tagus River plume also depends on the fortnightly tidal cycle being larger during spring tides than during neap tides. This is due to particular shape of the estuary, where the river debouches into a semi-enclosed embayment connected to the Atlantic Ocean through a strait.

Ebro River constitutes a particular case since it has a low dependence on runoff and wind and a negligible dependence on tide. In fact, its plume is mainly driven by the Liguro-Provençal coastal current. Guadalquivir River also shows some unique features due to its high sediment load. It generates the largest Iberian plume in terms of turbid signal and extension even being the second smallest river in terms of discharge.

1. Introduction

Plumes tend to spread radially from river mouth (Yankovsky and Chapman, 1997) and their development can be influenced by river discharge, outflow inertia, rotation effects, wind stress, tidal component, bottom topography and river mouth shape (Sousa et al., 2014). Generally, Coriolis force tends to deflect plumes resulting in a displacement to the right in the Northern Hemisphere. Moreover, plume development alters regional current patterns in the upper layers, promoting the formation of plume jets of rapid transport, convergences and trapping at frontal boundaries on the edges (deCastro et al., 2006). In addition, Ekman transport in combination with Earth's rotation, induces the movement of surface water offshore (upwelling) or onshore (downwelling) (Alvarez et al., 2008). In spite of these general features, each system presents some unique features and, hence, must be individually studied.

Several authors have demonstrated a good relation between surface salinity (a natural tracer of river plumes) and the characteristic ocean color matter originated from fresh water runoff which can be remotely measured (Binding and Bowers, 2003; Dzwonkowski and Yan, 2005). Therefore, some rivers worldwide shown a good correlation between the area influenced by freshwater (salinity plume) and the area occupied by the suspension and dissolved material (turbid plume) both induced by river discharge. However, some differences from those two definitions of plumes should be put into a specific context (Hu et al., 2003; Saldías et al., 2012, 2016a). The turbid plume represents the

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oceanic area mostly affected by river discharge and the suspended and diluted material (nutrients, sediments, pollutants, organic material…) which change the water turbidity and the optical properties of the water (Walker, 1996; Tuner and Millward, 2002; Zheng et al., 2015). The turbid plume constituents often modulate geological and biogeochemical features, for example, the large amount of terrestrial nutrients increases the primary coastal productivity (Ribeiro et al., 2005) and the sediment load plays a key role in several important factors as light attenuation (Huret et al., 2007), transport of pollutants (Uncles et al., 1988), seagrass habitat (Longstaff and Dennison, 1999), abundance of fish and shellfish (Wilber and Clarke, 2001) and erosion-sedimentation processes (Heyes et al., 2004), among others. The clear definition of the river plume is based on the salinity differences. There is a formation of two distinguishable water masses where ocean water is characterized by high salinity values whereas the oceanic area occupied by river water presents low salinity. Therefore, the water mass affected by freshwater inputs presents a different stratification and circulation patterns respect to the surrounding ocean water due to the buoyancy associated with the low density of freshwater (Saldías et al., 2016b). In the plume area, stratification can be maintained by river inputs and the circulation is also affected by outflow inertia and buoyancy, promoting different thermohaline properties between the plume and the oceanic area (Costoya et al., 2016). The turbidity and salinity of plumes usually present a negative correlation because the areas more affected by river discharge have high sediment load (turbidity) and low salinities (Saldías et al., 2012, 2016a). This is more remarkable in the near-field region where the material from river discharge remains suspended. Thus, remote sensing data, such as MODIS imagery, have been successfully tested in numerous studies worldwide for the analysis of turbid plumes, for example: the Mississippi River plume (Miller and McKee, 2004; Shi and Wang, 2009), river plumes in the eastern coastal region of China (Wang et al., 2007), the Amazon River plume (Kilham and Roberts, 2011) and river plumes in the Bay of Biscay (Petus et al., 2010; Costoya et al., 2016). Ocean color imagery has become a very useful tool to perform synoptic studies of turbid river plumes due to the spatial and time resolution provided (Walker et al., 2005 in Mississippi River plume; Nezlin et al., 2005 in Southern California coastal river plumes; Thomas and Weatherbee, 2006 in Columbia River plume; Saldías et al., 2012 in turbid plumes off central Chile…).

Some important European rivers debouching into Atlantic Ocean are located in the Iberian Peninsula. In addition, it has an important ecological Delta on the Mediterranean coast in which the Ebro River debouches. The Iberian Peninsula coast is a rich environment with a high primary production that supports important socio-economic activities as tourism, fishing and aquaculture, among others, resulting fundamental for the economy of these areas. Usually, these activities are developed near the mouth of the most important rivers, namely, in the development area of their turbid plumes. The main characteristics of the principal Iberian rivers are summarized in Table 1.

Most of the previous studies carried out using MODIS imagery in the Iberian Peninsula only focus on the features of individual turbid plumes. Valente and da Silva (2009) and Fernández-Nóvoa et al. (2017) studied Tagus River plume using different procedures. Valente and da Silva (2009) analyzed the temporal variability of Tagus plume by means of time series of plume area using three years of MODIS imagery. They also analyzed the fortnightly cycle influence on Tagus plume development using consecutive cloud free images during summer months. Fernández-Nóvoa et al. (2017) characterized the Tagus turbid plume and evaluated how different drivers affect it from 2003 to 2013 using composites created averaging days under similar forcing conditions in order to obtain synoptic plume situations. Mendes et al. (2014) and Fernández-Nóvoa et al. (2015) also analyzed the plume behavior under different drivers using MODIS imagery for Douro and Ebro Rivers, respectively, from 2003 to 2011. MODIS ocean color images were also used as complement of numerical models in order to test their accuracy for the study of river plumes in the oceanic region of Basque Country (Ferrer et al., 2009) and in the NW coast of Iberian Peninsula (Mendes et al., 2016).

The aim of this study is to evaluate synoptic patterns of turbid plumes generated by the main rivers of the Iberian Peninsula, in order to analyze their response to the main forcing drivers. Plumes were analyzed and compared for Minho, Douro, Tagus, Guadiana, Guadalquivir and Ebro River by means of radiance data obtained from MODIS over the period 2003–2014. First of all, the capability of MODIS radiance to observe river plumes was tested by means of salinity data derived from COPERNICUS project. In spite of the relative geographic proximity of Iberian rivers, plumes are affected in a different manner by forcing and by coastal dynamics. The purpose of the study is twofold, finding common features among plumes and highlighting differences among them due to coastal currents, coastal and river mouth morphology or coastal wave regime among others.

2. Data and methods

2.1. Plumes under study

Areas selected to study the most important Iberian plumes are defined in Fig. 1 (empty black squares). Each area was chosen taking into account the region where the influence of each turbid plume is greater and avoiding, as far as possible, the influence of other minor river plumes in its proximity, which could partly mask the observed behaviors. The main characteristics of rivers under study: river mouth location, basin extension, river and estuary length, mean river discharge and plume implications on coastal area are summarized in Table 1.

2.2. Ocean color imagery

Images of turbid plumes were obtained through data provided by MODIS-Aqua and MODIS-Terra satellite sensors from 2003 to 2014. Daily high-resolution ocean color files were downloaded from NASA Ocean Color web site (http://oceancolor.gsfc.nasa.gov). Ocean Biology Processing Group (OBPC) at Goddard Space Flight Center processes and distributes these MODIS data.

Downloaded L1A files are unprocessed instrument data at full resolution, time-referenced and annotated with ancillary information, including radiometric and geometric calibration coefficients and georeferenced parameters. L1A files were processed to L1B files using SeaDAS software (SeaWIFS Data Analysis System, version 7.1, Baith et al., 2001), following standard procedures recommended for processing raw data files. Finally, L2 ocean color images with 500 m of resolution were obtained from L1B files following the methodology described by Mendes et al. (2014) and by Fernández-Nóvoa et al. (2017). This resolution allows resolving > 90% of the optical variability of the plumes (Aurin et al., 2013).

MODIS allows obtaining images provided by several normalized water leaving radiances (nLw). However, taking into account the spatial resolution provided, coverage and correlation with river discharge, nLw555 and nLw645 are the most suitable bands to study Iberian turbid plumes, as pointed out by Fernández-Nóvoa et al. (2017). nLw 555 band provides a stronger turbid signal but some river plumes along Iberian Peninsula can be overestimated due to bottom influence or turbidity caused by upwelling or re-suspension processes since this band has a high penetration into water (*e.g.* Ebro plume, see Fernández-Nóvoa et al., 2015 or Tagus plume, see Fernández-Nóvoa et al., 2017). nLw645 signal is weaker than nLw555 signal, but it has lower water penetration solving the problems commented above (Chen et al., 2007; Lahet and Stramski, 2010). Therefore, the band centered at 645 nm was selected to analyze the variability of Iberian plumes.

Daily nLw645 images obtained from Aqua and Terra satellites were merged to obtain a larger percentage of available pixels in order to increase the precision and robustness of the study. This process is possible due to the small differences between the daily data of both