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The use of circulation weather types to predict upwelling activity along the western Iberian Peninsula coast

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ABSTRACT

Coastal upwelling is a phenomenon that occurs in most western oceanic coasts, associated with coastal surface water divergence and consequent ascension of colder and nutrient-rich waters from deeper levels. In this work, we evaluate the intra- and interannual variability of the upwelling index (UI) off the western coast of the Iberian Peninsula considering six locations at various latitudes along the 10°W meridian: Rias Baixas (42°N), Aveiro (41°N), Figueira da Foz (40°N), Cabo da Roca (39°N), Sines (38°N) and Sagres (37°N). In addition, the relationship between the variability of the occurrence of several circulation weather types (CWTs) and the UI variability along this coast was assessed in detail, allowing to discriminate which types are frequently associated with strong and weak upwelling activity. It is shown that upwelling activity is mostly driven by wind flow from the northern quadrant, for which the obtained correlation coefficients (for the N and NE types) are higher than 0.5 for the six considered locations.

Taking into account these significant relationships, we then developed statistical multi-linear regression models to hindcast upwelling series (April–September) at the referred locations, using monthly CWTs frequencies as predictors. Modeled monthly series reproduce quite accurately observational data, explaining more than 60% of the total variance, presenting skill-scores against the climatology also above 60%, and having relatively small absolute errors. However, despite the ability of our models in representing the interannual variability of UI, they do not reproduce accurately most UI peaks, that occur typically in July. This may be due to the role played by mesoscale phenomena not represented in the statistical models, namely sea breezes that result from the intensified thermal low, which enhances coastal meridional winds and hence upwelling.

1. Introduction

Classifications of atmospheric circulation have been developed to reduce the continuum of atmospheric circulation patterns into a reasonable and manageable number of discrete classes (Huth et al., 2008). Different methods exist for the classification of Circulation Weather Types (CWTs), as was shown by Huth et al. (2008), and Philipp et al. (2010).

Most CWTs classifications are developed for a specific region and result from the examination of synoptic weather data, usually on regular gridded fields, often based on sea level pressure or geopotential height at 500 hPa (Yarnal, 1992). They are typically defined for each day or group of consecutive days as a simple way to reflect the local circulation that actually occurred (e.g. Hess and Brezowsky, 1952; Kruizinga, 1979; Jones et al., 1993; Philipp et al., 2007). The use of objective methods to classify CWTs, such as those based on indices derived from atmospheric pressure fields, represent an advantage over more subjective studies of CWTs such as Lamb Weather Type (LWT) classification (Lamb, 1972) and the Grösswetterlagen catalogs (Hess and Brezowsky, 1977). Objective classification schemes, based on circulation indices, were initially developed for the British Isles (Jenkinson and Collison, 1977; Jones et al., 1993) in order to automatically reproduce the subjective LWT classification.

In recent years, the usefulness of CWTs classifications has been investigated for a wide range of applications, in scientific domains from climate (e.g. Ramos et al., 2010; Lorenzo et al., 2011), to environmental areas such as air quality (e.g. Demuzere et al., 2008) and forest fires (Kassomenos, 2010), to extreme events such as floods (e.g. Prudhomme and Genevier, 2011), droughts (e.g. Paredes et al., 2006; Vicente-Serrano et al., 2011), lightning activity (e.g. Ramos et al., 2011) or even avalanches (Esteban et al., 2005). Furthermore, several studies discuss that changes in the climate variables at the Earth's surface are usually a result of changes in the frequency of occurrence of CWTs (e.g. Fowler and Kilsby, 2002; Goodess and Palutikof, 1998; Kysely, 2008; Jones and Lister, 2009).

In this study, we used an automated version of synoptic CWTs that was initially developed for the British Isles (Jones et al., 1993),

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and later adapted with success to western Iberian Peninsula (Trigo and DaCamara, 2000; Ramos et al., 2010). This classification describes the regional atmospheric circulation in terms of a small set of relatively simple circulation parameters.

The Iberian Upwelling System (IUS) occurs on the western coast of the Iberian Peninsula, corresponding to the northern limit of the Eastern North Atlantic Upwelling System, prolonged to the south by the Canary Upwelling System (Barton et al., 1998). Coastal upwelling is a phenomenon that occurs at the western coasts of continental masses due to the presence of the mid-latitude high-pressure systems over the ocean that generate equatorward winds along the eastern boundary of the ocean basin. In the Northern Hemisphere, southward winds along any continental western coast can induce, through the Coriolis effect, an offshore advection of water from the upper layers. This flow in turn gives origin to an equatorward current due to the tilt of the sea level consequent of coastal divergence, and this gives rise to the upwelling of colder and nutrient-rich waters from deeper layers (e.g. Wooster et al., 1976). On the contrary, during periods without upwelling, the prevailing circulation at the western Iberian Peninsula coast is a northward current in the upper layers (Haynes and Barton, 1990; Frouin et al., 1990). The Eastern North Atlantic Upwelling System is one of the four major upwelling systems of the world, including California (USA western coast), Humboldt (off the coasts of Peru and Chile) and Benguela (off southwestern Africa) (e.g. Chavez and Messié, 2009). These regions are the most biologically productive regions of the world ocean and crucial for fisheries, due to the phytoplankton blooms associated with the enrichment of the surface waters with nutrients from below (e.g. Pauly and Christensen, 1995).

In the western Iberian sector, the atmospheric and oceanic circulation and hydrology undergo strong seasonality. The Azores High generally migrates northward in late spring and summer, positioning itself just off the Iberian Peninsula, and giving rise to northerly, upwelling-favorable winds typically between May and September (Fiúza, 1983). These intense winds occur in episodes or events, acting over the ocean surface for several days at a time, but alternating with relaxation periods, where winds weaken or are rather south- or southwest-oriented (Peliz et al., 2002). After about 1 day of northerly winds acting over the ocean surface, the band of cold water begins to form at the coast, eventually producing finger-like structures called filaments that spread west and southwest (Haynes et al., 1993). These upwelling events in the IUS have been thoroughly characterized, both in terms of their main physical processes (Fiúza et al., 1982; Álvarez-Salgado et al., 1993; Peliz et al., 2002; Torres and Barton, 2007) as well as some of the associated biological processes (Santos et al., 2001; Queiroga et al., 2007; Arístegui et al., 2009; Oliveira et al., 2009). However, upwelling events depend not only on large-scale atmospheric circulation, but also on the coastal ocean mesoscale variability (e.g. Relvas et al., 2007, 2009) as well as on interannual to interdecadal atmospheric variability, detailed next.

Due to their importance in the maintenance of the associated marine ecosystems, upwelling regions have been the subject of study for the assessment of long-term trends and significant changes in past decades. One of the first important works on this matter was that of Bakun (1990), where the four upwelling systems were under scope and, based on observations for period 1946–1988, the author found that all systems showed an alongshore wind stress intensification trend during summer, which would implicate an upwelling intensification. Regarding a more regional scale and for a longer period, Lemos and Pires (2004) found a weakening trend for the longer 1941–2000 period for western Iberian Peninsula when analyzing both meridional wind component and SST datasets, although punctuated by strong interannual variability. The analysis of annual or seasonal signal tendency may hide different behaviors at the monthly scale. Thus, Alvarez et al. (2008) confirmed this negative tendency for period 1967–2006 for months March, April and July–December, but found a positive trend for the remaining months, concluding that there is no clear seasonal trend in upwelling intensity in past decades. On the other hand, Santos et al. (2005), based on a shorter satellite-based SST dataset, reported an upwelling regime shift in the early 1990s to stronger upwelling events, after a positive maximum of the North Atlantic Oscillation (NAO) winter index, corroborated by stronger coastal zonal gradients in summer from 1992 onwards. Furthermore, Borges et al. (2003) found a higher frequency in northerly wind occurrence during winter, and consequently an increase in winter upwelling events. Santos et al. (2011) also studied the dependence of upwelling trends (western coast of the Iberian Peninsula) taking into account different fitting trend methodologies. The difficulty to assess trends of upwelling activity has been summarized recently when Narayan et al. (2010) showed that there can be large discrepancies when analyzing trends derived from upwelling indicators (wind stress and SST), with both depending on the dataset used.

The major aims of this paper are twofold: first to study the relationship between the CWTs and upwelling variability along the western coast of the Iberian Peninsula and secondly to develop statistical models to hindcast upwelling series, using frequencies of CWTs as predictors. The remainder of the paper is organized as follows: in Section 2, different data sets and the methodologies used in the analysis are described. In Section 3.1 we characterized the seasonal and interannual distribution of the upwelling index in the western coast of the Iberian Peninsula, while in Section 3.2 we characterize in detail the circulation weather types and its variability. In Section 3.3 we studied the relationship between the upwelling index and circulation weather types and in Section 3.4 the statistical modeling of the upwelling index by means of circulation weather types frequencies is presented. Finally, Section 4 concludes.

2. Data and methods

2.1. Upwelling index

The upwelling index (UI) is a measure of occurrence of upwelling. There are, in general, two ways to compute this quantity, both already used for the IUS: (1) the Ekman transport perpendicular to the coastline, that is, generated by the alongshore wind stress component (e.g. Alvarez et al., 2008); and (2) the difference between coastal (10–50 km) and oceanic ($\sim$500 km) SST (e.g. Santos et al., 2005). Both methods have advantages and caveats and some of these are discussed here. The first method, despite being based on the known effect of wind stress over the ocean surface and adjacent layers, which is the main driver of upwelling, does not account for the effects of capes and other coastal features, or mesoscale phenomena of which upwelling is also dependent on (Peliz et al., 2002; Relvas et al., 2009). The second approach is more of a proxy for upwelling occurrence, since upwelling is not the only cause for offshore–onshore SST differences; SST is strongly influenced by other phenomena such as river discharge in coastal areas and large-scale circulation offshore (Gómez-Gesteira et al., 2008).

In this study, the UI was provided by the Spanish Institute of Oceanography (IEO—http://www.indicedeafloramiento.ieo.es) and was computed by means of geostrophic winds following the method by Bakun (1973) and adapted later to the Iberian Peninsula by Lavín et al. (1991, 2000) (see formulation used by IEO below). The geostrophic winds were computed from 6-hourly atmospheric sea level pressure (SLP) fields (at a 1° resolution) obtained from the U.S. Navy Fleet Numerical Meteorology and Oceanography Center (FNMOC) for the 1967–2011 period. The use of the FNMOC SLP fields to compute the UI index has been used widely in different studies (e.g. Bograd et al., 2009; Macías et al.,