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Identification of drought phases in a 110-year record from Western Mediterranean basin: Trends, anomalies and periodicity analysis for Iberian Peninsula

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ABSTRACT

The Iberian Peninsula (IP), located in a transition area between temperate and subtropical latitudes, has marked temporal and spatial variability of precipitation between its various climatic zones. Therefore, the peninsula is particularly sensitive to climate change owing to frequent periods of precipitation deficit together with societal dependence on water. In this study, we address meteorological droughts of the peninsula between 1901 and 2010, using the Global Precipitation Climatology Center database. First, we carried out a statistical classification of the peninsula according to annual precipitation cycle. The spatiotemporal variability of droughts was evaluated using the Standardized Precipitation Index (SPI) by determining the evolution of areas affected by severe and extreme drought. Subsequently, we calculated the overall trend of precipitation and anomalies to investigate whether an observed drought increase is attributable to a decrease of precipitation or an increase of precipitation extremes. Finally, we examined periodicities of precipitation anomalies via wavelet analysis, relating these to large-scale modes such as the North Atlantic Oscillation (NAO). The results show an increase in the area affected by severe and extreme drought, particularly on Atlantic-facing slopes. The mainland areas have longer and more intense periods of drought, with an average SPI of −0.52 and 4-month duration. Over the 110 years analyzed, we observed weak trends of annual precipitation in the extreme northwest and southern IP. However, in the last decades of the series, long periods of strong negative anomalies are seen, interspersed with years of strong positive anomalies, suggesting an increase in precipitation pattern extremes. Finally, the relationship between the NAO index and precipitation anomalies on the Atlantic seaboard is highlighted. Thus, in both series we found a 5–6-year periodicity in their first years, with a diminishing cycle period reaching a periodicity of 2–3 years in the final years. This confirms the existence of regular temporal cycles in which droughts alternate with wet periods modulated by large-scale modes.

1. Introduction

Precipitation is an element of climate systems that contributes most to the availability of water resources (Randall et al., 2007). The rainfall regime in the Mediterranean basin is characterized by strong temporal variability, with recurrent and severe drought. This region is highly vulnerable and sensitive to climate change that reduces water availability. Several studies show a downward trend in precipitation patterns (Goubanova, 2007; De Luis et al., 2009), together with an increase in the number of extreme precipitation events. This contributes to a concentration of precipitation in a small number of events, which increases the frequency and severity of drought (Ramos and Martínez-Casasnovas, 2006; Lana et al., 2009).

On the Iberian Peninsula (IP), the amount and spatiotemporal distribution of precipitation are very irregular (Trigo and DaCamara, 2000; Trigo et al., 2004). The predominant atmospheric circulation patterns and their interaction with the complex topography of our study area determine the climatic distribution. Different regions are characterized by multiple variants of wet-oceanic, mountainous, and semiarid climates. On average, most precipitation is recorded during the winter months on the central and western IP (De Luis et al., 2010). In these areas, which are open to prevailing winds from the west, precipitation has a strong relationship with the Atlantic atmospheric circulation. However, the transitional seasons (spring and autumn) have the greatest precipitation of the year in eastern and northeastern areas (Lionello et al., 2006; López-Moreno et al., 2010), which are less exposed to influence from the Atlantic.

Another of the most important determinants of the precipitation distribution on the IP is the topography. Thus, in areas exposed to prevailing flows from upwind moisture sources, orographic ascent of the air

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and condensation develop upwind, which produce significant increases in precipitation. By contrast, downwind areas have a downsloping rain-shadow effect (Romero et al., 1999; Costa et al., 2010).

Interannual irregularity of precipitation on the IP is also evident, with significant drought following above-average precipitation cycles. Because of the serious social and economic impacts of drought, several studies have deepened understanding of the interannual variability of precipitation (Vicente-Serrano, 2006b; Vicente-Serrano and Cuadrat-Prats, 2007; Sousa et al., 2011). Various climate prediction models suggest that droughts are increasing in southern Europe as a result of the diminishing magnitude and frequency of precipitation (Houghton et al., 2001). Studies have documented dry periods on the IP in recent decades and centuries (Martín-Vide and Barriendos, 1995; Saz, 2003; Vicente-Serrano, 2006a). These dry periods on the peninsula are largely determined by variability in atmospheric patterns over the North Atlantic (Martín-Vide and Fernández, 2001; Barriendos and Llasat, 2003).

Variability of atmospheric circulations is one of the most important factors for determination of changes to precipitation spatial distribution. Temporal variability of precipitation on the IP during winter and spring can be explained by changes in large-scale modes, especially over the western peninsula (Trigo and Palutikof, 2001). Among these modes, the North Atlantic Oscillation (NAO) is the principal element that determines the winter rainfall regime on the IP. The NAO, which is associated with variation of the westerlies throughout the North Atlantic, refers to meridional oscillation of action centers near the Icelandic low and Azores high (Van Loon and Rogers, 1978). The NAO is strongly related to precipitation in western portions of the IP that are clearly influenced by the Atlantic. By contrast, in eastern zones close to the Mediterranean Sea, the NAO has little influence on climatic variability, because precipitation there is much more related to Mediterranean pressure systems and airflows (Martin-Vide and Lopez-Bustins, 2006).

Trigo et al. (2004) demonstrated that the NAO impact on precipitation of the western IP had strong interdecadal variability. Although NAO variability mainly arises from internal atmospheric interactions, other factors may also affect atmospheric circulations, such as sea surface temperature (SST) anomalies (Hurrell et al., 2003). Peng and Whitaker (1999) and Peng and Robinson (2001) pointed out that extratropical storms and their associated eddies may be affected by anomalies of meridional SST gradients. On the other hand, airflows and surface air temperatures associated with NAO positive or negative phases produce anomalies of sensible and latent heats of the ocean surface, which change SST to the base of the mixing layer (Seager et al., 2000).

The focus of this work was to examine meteorological droughts on the IP over the last 110 years. Therefore, we established the following objectives. First, we classified the study area according to the annual precipitation cycle. The reason for this is that this cycle has a strong relationship with atmospheric patterns in each region; therefore, it is important to study drought in each of these areas individually. The second objective was the analysis of spatiotemporal variability of droughts in each identified area, using the same annual cycle. For this, we used the Standardized Precipitation Index (SPI) by determining the evolution of areas affected by severe and/or extreme drought. Subsequently, we calculated the total trend of precipitation and development of anomaly magnitude, to ascertain any increase in periods of drought and extreme precipitation. The final objective was extraction of the periodicities of precipitation, relating them to large-scale modes such as the NAO. We extracted the frequency of drought cycles in each area, relating them to the cycles of large-scale patterns such as the NAO, in order to determine how this index affects drought in those areas. The multiple methods used are described in individual subsections, with the structure of the paper as follows. Section 2 describes the data used. The classification of study area based on annual precipitation cycle is presented in Section 3. Section 4 describes the evaluation and monitoring of meteorological droughts, using the SPI index to estimate the extent of severe and extreme droughts. Annual precipitation trends and anomalies of precipitation trend are presented in Section 5. Section 6 shows temporal variability of precipitation related to NAO index using wavelet analysis. Results are discussed in Section 7, and conclusions are presented in Section 8.

2. Datasets

We used the Global Precipitation Climatology Center (GPCC) database, which provides gridded gauge-analysis products derived from quality-controlled station data from a variety of sources (Schneider et al., 2014). This database has been used in various studies for hydrometeorological model verification and water cycle studies (Nicholson et al., 2003; Krakauer and Fekete, 2014; Spinoni et al., 2014).

To characterize and classify the IP annual precipitation cycle, we used GPCC Climatology Version 2011 (GPCC_Clim) with 0.25° resolution (Meyer-Christoffer et al., 2011). This is based on 67,200 stations worldwide, with record durations of 10 years or longer for the target reference period January 1951 to December 2000. Additionally, to study precipitation cycles, IP monthly accumulated precipitation was extracted from the GPCC. This product covers the period 1901 to 2010, for which the monthly data coverage varies from 10,700 to more than 47,000 stations.

GPCC_FD was selected as the reference to analyze IP precipitation. This is considered the most accurate in situ precipitation reanalysis dataset of GPCC and is recommended for regional climate monitoring and analysis of historic global precipitation (Schneider et al., 2011). Sampling errors of the GPCC products dependent on ground station density and gridding method were determined at global scale using mean absolute error (MAE) (Becker et al., 2013). A potential source of uncertainty when using gridded precipitation datasets is fluctuation caused by variations in the numbers of observation stations, especially for small numbers (as in the first half of the 20th century) and regions with sparse data coverage. In such cases, time series cannot be considered homogenous (natural variations on climate), because each interpolated value is always dependent on station availability. To reduce this source of uncertainty, homogeneity of the GPCC_FD was evaluated using the nonparametric Kruskal–Wallis test (Partal and Kahya, 2006), with all time-series at each pixel considered homogeneous.

3. Rainfall annual cycle: cluster classification

Prior to drought analysis, we classified the IP based on annual precipitation cycle, owing to the strong spatiotemporal variability of precipitation on the peninsula. The annual precipitation cycle has a strong relationship with atmospheric patterns in each region, so it is important to study each region separately.

3.1. Cluster analysis

We performed non-hierarchical *k*-means clustering (Hartigan and Wong, 1979), which is widely used in climate studies (Awan et al., 2014) to distinguish areas within a study region with similar annual rainfall cycles. To this end, monthly climatological precipitation was extracted from GPCC_Clim. Before applying the cluster analysis, monthly rainfall data were transformed to Empirical Cumulative Distribution Functions (ECDF) at each pixel, according to DeGaetano (1998). Thus, regions with similar annual rainfall cycles were identified, without regard to precipitation amount.

Euclidean distance was chosen for classifying groups of data according to their similarity. One of the sources of subjectivity in this method is the requirement that the number of final conglomerations (k) is predetermined ahead of time. The selection of k can be done objectively by computing the minimum decrease of intragroup distances. Nevertheless, based on research experience, the decision regarding the number of groups is not a completely objective task because there is some subjectivity (Gong and Richman, 1995). In this study, the total within-