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ORIGINAL PAPER

Drought variability and change across the Iberian Peninsula

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Abstract Drought variability and change was assessed across the Iberian Peninsula over more than 100 years expanding through the twentieth century and the first decade of the twenty-first century. Daily temperature and precipitation data from 24 Iberian time series were quality controlled and homogenized to create the Monthly Iberian Temperature and Precipitation Series (MITPS) for the period 1906–2010. The Standardized Precipitation Index (SPI), driven only by precipitation, and the Standardized Precipitation Evapotranspiration Index (SPEI), based on the difference between the precipitation and the reference evapotranspiration (ET_0), were computed at annual and seasonal scale to describe the evolution of droughts across time. The results confirmed that a clear temperature increase has occurred over the entire Iberian Peninsula at the annual and seasonal scale, but no significant changes in precipitation accumulated amounts were found. Similar drought variability was provided by the SPI and SPEI, although the SPEI showed greater drought severity and larger surface area affected by drought than SPI from 1980s to 2010 due to the increase in atmospheric evaporative demand caused by increased temperatures. Moreover, a clear drying trend was found by the SPEI for most of the Iberian Peninsula at annual scale and also for spring and summer, although the SPI did not experience significant changes in drought conditions. From the drying trend identified for most of the Iberian Peninsula along the twentieth century, an increase in drought conditions can also be expected for this region in the twenty-first century according to future climate change projections and scenarios.

1 Introduction

Global climate system is being modified due to anthropogenic climate change altering the atmospheric system beyond its natural climate variability. Global temperature increased +0.89 °C over the period 1901–2012 and global precipitation showed non-significant changes from 1900 according to the Intergovernmental Panel on Climate Change (IPCC) (Hartmann et al. 2013). Additionally, it is expected that the extra heat induced by global warming will increase the rate of dryness, reinforcing drought severity (Trenberth et al. 2014). However, there is still low confidence in the projected future changes of drought patterns (Hartmann et al. 2013) mainly due to some discrepancies in the interpretation of the results on a global-scale since the middle of the twentieth century (Dai 2012; van der Schrier et al. 2013; Sheffield et al. 2012). In fact, drought trends can substantially be affected by technicalities such as the dataset used, the index used to define drought, the chosen time-scale or the calibration period (Trenberth et al. 2014). Despite these uncertainties, regional dryness seems to be increasing in many parts of the world. For example, there is medium confidence about an increase in dryness in East Africa; high confidence in the Mediterranean and West Africa and it is likely that the frequency and intensity of drought has increased in the Mediterranean and West Africa but decreased in central North America and north-west Australia since 1950 (Hartmann et al. 2013).

The Mediterranean basin, including the whole Iberian Peninsula, is an area of special interest for climatologists due

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to its high climate vulnerability under the climate change context. This is caused by its location in the transitional area between temperate and tropical climates where water availability is already low under normal conditions and water demand is close to, or exceeds, natural availability (Iglesias et al. 2009). This transitional climate, with its characteristic warm-season aridity, is experiencing an increase of temperature and a decrease of precipitation that will enhance the evapotranspiration rate (Hartmann et al. 2013). This is the case of the Iberian Peninsula, where temperatures clearly increased along the twentieth century (Brunet et al. 2006, Brunet et al. 2007), but inestimable changes have been found in precipitation patterns across time (Barrera-Escoda 2008, Saladié 2004).

As a consequence, droughts have become more common in some regions of the Iberian Peninsula such as in the northeastern area (Vicente Serrano, 2006) in Catalonia (Serra et al. 2006), in the Ebro basin (Vicente-Serrano and Cuadrat-Prats 2006), in some areas of Valencia region (Vicente-Serrano et al. 2004) and in the Tajo basin (Lorenzo-Lacruz et al. 2010). More frequent cycles of dry events have been identified in south-western Iberian Peninsula (Santos et al. 2010) and trend analysis on Iberian stream-flows revealed a generalized and significant trend of decrease in stream-flow in most parts of the Iberian Peninsula during the second half of the twentieth century, especially in winter and spring (Lorenzo-Lacruz et al. 2012). Moreover, Vicente-Serrano et al. (2014a) found that hydrological drought frequency and severity also increased in the past five decades across the Iberian Peninsula. Sousa et al. (2011) and Vicente-Serrano et al. (2011) have shown that droughts have not increase in the north-west of the Iberian Peninsula in contrast with the predominant trend to drier conditions observed in the twentieth century.

Climate models project a large increase in temperatures and a decrease in precipitation in the Mediterranean region (Hartmann et al. 2013) and also in the Iberian Peninsula at the end of the twenty-first century (Rodríguez-Puebla and Nieto 2010). Mean annual temperatures could increase more than 2 °C especially in the interior of the Iberian Peninsula by the end of the twenty-first century while annual precipitation could decrease more than 10 % in the southern region (Coll et al. 2015), although large uncertainties are still affecting the model outputs (Mishra and Singh 2011; Rammukainen 2010). Under these conditions, current drought conditions are expected to worsen over the Iberian Peninsula along the twenty-first century.

Changes in climate patterns together with an increasing probability of drought occurrence may worsen the conditions of available freshwater resources for consumption, crops irrigation or tourism and leisure in the Iberian Peninsula. In this way, changes in land cover, land use and human activities could play an important role in the evolution of dry conditions (SREX 2012). These changes could include an increase of the irrigated surface, an increase of the forested area in the Iberian

Peninsula (Vicente-Serrano et al. 2004), together with an increase of water demand for human activities in sectors such as urban consumption, industry or tourism among others. For this reason, water management strategies will become crucial in the Iberian Peninsula to guarantee water supply trying to minimize the environmental and socio-economic impacts when water demand is increasing progressively (Lorenzo-Lacruz et al. 2012).

The aim of this study is to analyse the temporal evolution and the spatial coverage of droughts occurred across the Iberian Peninsula over more than 100 years (1906–2010) by calculating the most widely used drought indices to determine drought fluctuations and trends under current climate change conditions. At the same time, the driest/wettest years are clearly identified and the surface area affected by drought is accurately analysed. Therefore, the role of the reference evapotranspiration on drought severity is also assessed from drought variability and trends under climate change conditions.

2 Data and methods

2.1 Instrumental climate data

The monthly dataset employed in this study resulted from an update of the Spanish Daily Adjusted Temperature/Precipitation Series (SDATS/SDAPS; Brunet et al. 2006, Brunet et al. 2007) merged with two Portuguese time series obtained from the Climatology and Climate Change Research Group of the Instituto Dom Luiz (Lisbon University). We wanted to ensure a reasonably well-spaced distribution of stations across the Iberian Peninsula (Fig. 1 and Table 1), following the criteria expressed in Brunet et al. (2006) of prioritizing quality and temporal continuity over number of stations.

Climatological long-term time-series are often affected by non-climatic factors which can modify the actual climate signal across time. Then, quality control and homogenisation procedures are required to avoid potential erroneous climate conclusions (Aguilar et al. 2003). Daily maximum and minimum temperatures and daily precipitation across Spain were adjusted for the period 1850–2005 in the original SDATS/SDAPS series (Brunet et al. 2006). The series were submitted to quality control (QC) following Aguilar et al. (2002) and were homogenized applying the Standard Normal Homogeneity Test (SNHT) (Alexandersson and Moberg 1997). The SNHT was designed to detect and correct abrupt shifts and artificial trends in the time series applying an iterative process from a candidate time series together with a group of reference time series. All time series are used as candidate and reference series during the process due to the probability to find a break point at the same time in all time series is really low. Then, the iterative comparison between candidate and
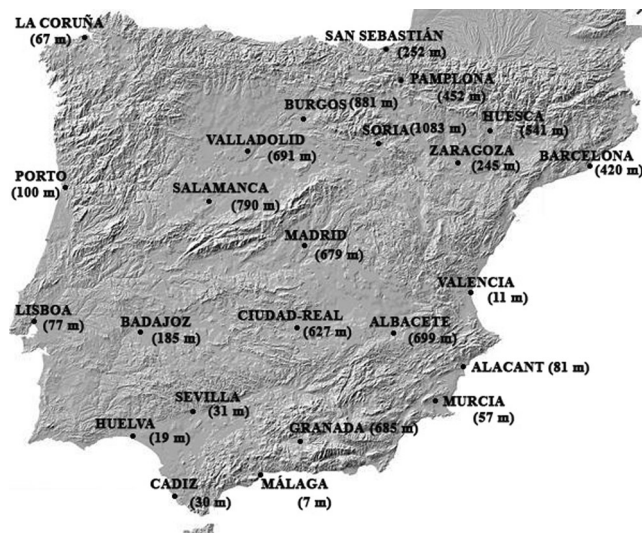
Fig. 1 Map showing the locations of meteorological stations and the elevations spread over the Iberian Peninsula (Coll et al. 2015)

controlled following the same procedures applied to SDATS/SDAPS and, even though a new homogenization process was not conducted, the homogeneity of the new segments was assessed via pairwise visual comparisons. As no obvious new breaks were encountered, these recent data were then added to SDATS/SDAPS. The two Portuguese series (Lisboa and Porto) were also quality controlled and homogenized using the SNHT method before integration to the new dataset. For this purpose, a group of six best correlated time series from within Iberian Peninsula (Pearson's $r > 0.7$) were used as reference series to ensure an appropriate homogenisation for the whole period.

Most of the selected time-series included a number of missing values in monthly mean temperature and monthly accumulated precipitation (Figs. 2 and 3). The percentage of missing data according to monthly mean temperature and monthly accumulated precipitation availability for each time series was less than 5 % for most of the time series, although between 5 and 10 % of data were missing for a few stations (Fig. 3), and Pamplona and San Sebastián series had almost 20 % of missing data. As the computation of drought indices required data continuity, a multiple regression approach was used to interpolate isolated occurrences of missing values. We used a multiple linear regression approach based on the four most highly

reference series is suitable to detect non-climatic forcing factors.

For this study, SDATS and SDAPS series were updated to 2010 with data made available by Agencia Estatal de Meteorología (AEMET). Newly available data were quality

Table 1 Iberian stations network. Name of station, current geographical location (latitude, longitude and altitude) and length of record (temperature and precipitation) are shown

Location	Latitude	Longitude	Altitude (m)	Temperature	Precipitation
Albacete	38° 57′ 08″ N	01° 51′ 47″ W	698.6	1893–2010	1894–2010
Alicante	38° 22′ 00″ N	00° 29′ 40″ W	81.5	1893–2010	1894–2010
Badajoz	38° 53′ 00″ N	06° 49′ 45″ W	185	1864–2010	1876–2010
Barcelona	41° 25′ 05″ N	02° 10′ 36″ E	420.1	1885–2010	1855–2010
Burgos	42° 21′ 22″ N	03° 36′ 57″ W	881	1870–2010	1870–2010
Cadiz	36° 27′ 55″ N	06° 12′ 37″ W	30	1850–2010	1853–2010
Ciudad Real	38° 59′ 22″ N	03° 55′ 11″ W	627	1893–2010	1894–2010
Granada	37° 08′ 10″ N	03° 37′ 52″ W	685	1893–2010	1894–2010
Huelva	37° 16′ 48″ N	06° 54′ 35″ W	19	1903–2010	1903–2010
Huesca	42° 05′ 00″ N	00° 19′ 35″ W	541	1861–2010	1861–2010
La Coruña	43° 22′ 02″ N	08° 25′ 10″ W	67	1882–2010	1882–2010
Madrid	40° 24′ 40″ N	03° 40′ 41″ W	678.9	1853–2010	1854–2010
Malaga	36° 39′ 57″ N	04° 28′ 57″ W	6.5	1893–2010	1894–2010
Murcia	37° 58′ 59″ N	01° 07′ 14″ W	57	1863–2010	1863–2010
Pamplona	42° 46′ 06″ N	01° 38′ 21″ W	452	1880–2010	1880–2010
Salamanca	40° 56′ 50″ N	05° 29′ 41″ W	789.8	1893–2010	1894–2010
San Sebastian	43° 18′ 24″ N	02° 02′ 22″ W	251.6	1893–2010	1894–2010
Sevilla	37° 25′ 15″ N	05° 53′ 47″ W	31	1893–2010	1894–2010
Soria	41° 46′ 29″ N	02° 29′ 01″ W	1083	1893–2010	1894–2010
Valencia	39° 28′ 48″ N	00° 22′ 52″ W	11.4	1864–2010	1884–2010
Valladolid	41° 38′40″ N	04° 44′ 35″ W	691.4	1893–2010	1894–2010
Zaragoza	41° 39′ 43″ N	01° 00′ 29″ W	245	1887–2010	1891–2010
Porto	41° 08′ 00″ N	08° 36′ 00″ W	100	1901–2010	1906–2010
Lisboa	38° 43′ 00″ N	09° 09′ 00″ W	77	1855–2010	1863–2010

Fig. 2 Potential vs. available monthly simultaneous temperature and precipitation (left axis) and the number of available stations (right axis) in the Iberian Peninsula (1850–2010)

Availability of monthly temperature and precipitation data in the Iberian time series (1850-2010)
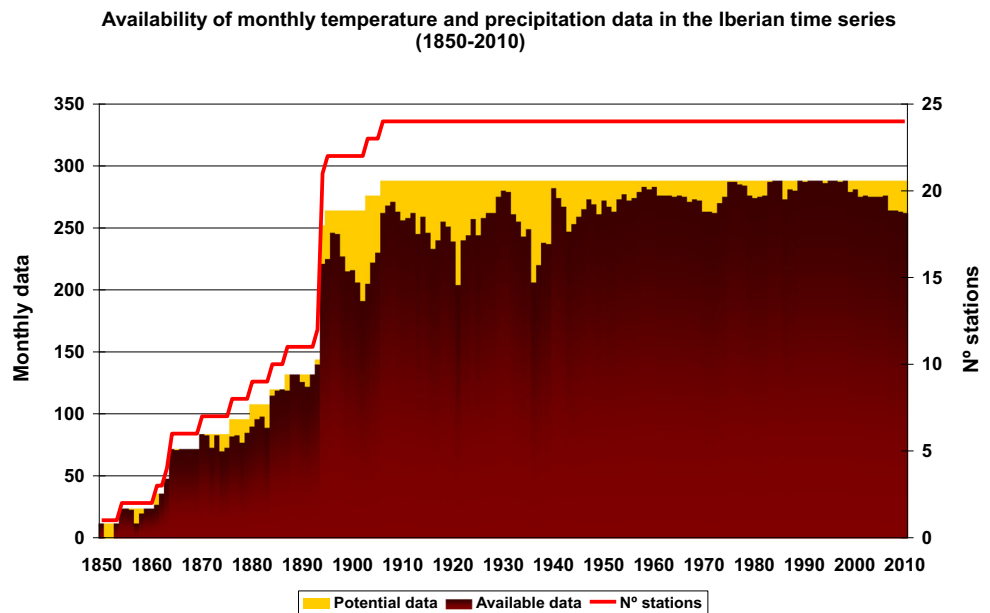
correlated time series (Pearson's $r > 0.7$), following Vicente Serrano (2006).

After the infilling process, maximum continuity in monthly temperature and precipitation was ensured from 1906 to 2010 for the 22 of the 24 time-series selected to represent the Iberian Peninsula. No attempt was made to fill long missing periods (such as those between 1850 and 1905 in most of the time-series (see Fig. 2). This resulted not only in the shortening of the study period but also in the rejection of two time series, Pamplona and San Sebastian, reducing the number of available data integrating the new Monthly Iberian Temperature and Precipitation Series (MITPS) to 22 instead of the potential 24. The limitation of the common period to 1906–2010 and the rejection of two time series ensured reliability and robustness of the MITPS dataset. The final 22 individual

time series were used to compute the regional Iberian temperature and precipitation time series for the entire Iberian Peninsula applying the Jones and Hulme (1996) method. Temperature and precipitation were separated into its two components: the climatology and the anomaly, which was based on the 1961–1990 reference period (Coll 2014).

2.2 Drought indices

The Standardized Precipitation Index (SPI) and the Standardized Precipitation Evapotranspiration Index (SPEI) were used to assess drought variability and change across the Iberian Peninsula for the period 1906–2010. The SPI (McKee et al. 1993) was designed to quantify the precipitation deficit for multiple time scales in order to reflect the impact of

Fig. 3 Percentages of missing data for each time-series in terms of monthly mean temperature and monthly accumulated precipitation from 1906 to 2010
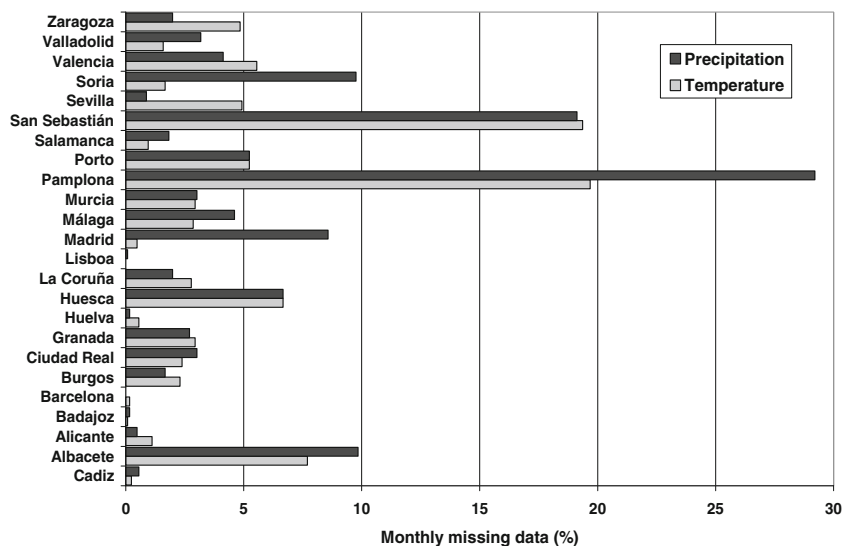
drought on regions or particular systems such as water resources or soil moisture. For instance, soil moisture conditions respond to precipitation anomalies on a relatively short time scale, while ground water, streamflow and reservoir storage reflect longer-term precipitation anomalies. This is the main advantage of the SPI, which is crucial for applying the appropriate drought mitigation or adaptation measures to manage different typology of droughts and minimize their effects. The SPI algorithm converts precipitation data to probabilities from long-term past records to transform them to standardized series (expressed in z-units) with an average of 0 and a standard deviation of 1 (Vicente-Serrano et al. 2014b). Although it is widely used, the main criticism of the SPI is that its calculation is based only on precipitation data knowing that other relevant variables as temperature, evapotranspiration, solar radiation or wind speed among others can have an important role when a drought event is developing (Dai 2012, Sheffield et al. 2012).

The SPEI (Vicente-Serrano et al. 2010) is based on the original SPI calculation procedure, but the difference between precipitation and reference evapotranspiration (ET_0) is estimated in its algorithm. The SPEI introduces the sensitivity of drought severity to changes to the atmospheric evaporative demand (Vicente-Serrano et al. 2014a), allowing users to quantify the effect of warming-induced drought stress (e.g. Breshears et al. 2005, Beguería et al. 2014, Vicente-Serrano et al. 2014a). Climatological information is only required to compute the SPEI (temperature and precipitation), which is often available and of reasonable quality and can also be calculated at different time-scales. The values are converted to standard deviations with respect to average values as used for the SPI to obtain the standardized series (expressed in z-units). The SPI and SPEI drought categories according to drought severity are shown in Table 2.

In this study, the SPI and SPEI were computed for the 22 locations spread over the Iberian Peninsula and for the 3-, 6-, 12-, and 24-month time scales by using the calibration period 1906–2010 (the whole period) to calculate the main parameters of the respective algorithms. Using the whole period under study as the calibration period of drought indices was necessary to avoid the exclusion of some remarkable dry/wet periods in a changing climate affecting negatively the results of the observed trends (Trenberth et al. 2014).

As mentioned above, the estimation of ET_0 is required to compute the SPEI drought index. There are different methods to compute ET_0 and the use of one or another ET_0 estimation method strongly depends on the long-term available data to compute them (Vicente-Serrano et al. 2014a). For this study, the only appropriate method to compute ET_0 was Thornthwaite's method (Thornthwaite, 1948) since no long and high quality series of observed wind speed, relative humidity, solar radiation and cloud cover were available for the period under study (1906–2010). Therefore, other more robust methods such as Penman-Monteith were unfeasible to be applied here (Coll 2014). Thornthwaite's method only requires mean monthly temperature and radiation (estimated as a function of temperature and geographical coordinates).

Although most of the studies recommended the use of Penman-Monteith model to compute ET_0 (Dai 2011, van der Schrier et al. 2011 among others), there are some disagreements related to the influence of the ET_0 estimation method applied on long-term drought trends. For instance, Dai (2011, 2012) and van der Schrier et al. (2013) concluded that the specific formulation of the ET_0 equation had no relevant effect on the magnitude of global drought by using the Self-Calibrating Palmer's Drought severity Index (Sc-PDSI) (Palmer 1965), but Sheffield et al. (2012) found substantial differences by using the same drought index for drought severity computation, but different datasets. Moreover, Vicente-Serrano et al. (2014a) concluded that the increased drought severity found in streamflows across the Iberian Peninsula in the past five decades was independent of the model used to quantify the reference evapotranspiration after testing several ET_0 estimation methods in SPEI series. Regarding the findings discussed from all these studies about ET_0 estimation methods, Thornthwaite's parameterisation could imply some limitations when computing ET_0 due to the shortcomings described above. However, it could be a valid alternative to compute ET_0 for drought analysis across the Iberian Peninsula taking into account the lack of long-term high-quality data for other climatic variables required to compute more robust ET_0 models for the whole period under study. Despite this, drought trends should be treated taking into account that the equation used to calculate ET_0 could potentially influence long-term trends in SPEI series.

2.3 Trend calculation

The evolution of annual and seasonal (winter; DJF, spring; MAM, summer; JJA and autumn; SON) temperature and precipitation series for the whole Iberian Peninsula as well as the seasonal (3-month) and annual (12-month) SPI and SPEI time series for each station was assessed by computing trends for the period 1906–2010. The nonparametric Mann-Kendall test (Kendall 1970) was used to compute the significance of trends, while the magnitude of change was estimated by using

Table 2 Drought classification according to SPI/SPEI categories based on McKee et al. (1993)

Categories	z-units
Extremely wet	$\geq +2$
Severely wet	$\geq +1.5$ to $< +2$
Moderately wet	$\geq +1$ to $< +1.5$
Near normal	> -1 to $< +1$
Moderately dry	> -1.5 to ≤ -1
Severely dry	> -2 to ≤ -1.5
Extremely dry	≤ -2

a regression analysis. The Mann-Kendall test is a more robust statistical technique than parametric tests to estimate the trends significance and, according to Mann, the null hypothesis of randomness assumes that there is no trend due to data are a sample of n independent random variables. When a trend exists, the time series can be explained by the linear regression $Y_t = a + bt + \epsilon_t$, where ϵ_t denotes a white noise process, and a and b are regression parameters that are often computed by using a least square estimator. However, the least square estimator of b is vulnerable to gross errors and the associated confidence interval is sensitive to non-normality of the parent distribution (Kendall, 1970). In this study, the estimator of b was used, which is based on Kendall's rank correlation (Wang and Swail 2001). The statistical significance of trends was fixed at the 95 % ($p < 0.05$).

3 Results

3.1 Climate variability across the Iberian Peninsula, 1906–2010

3.1.1 Temperature and precipitation variability

Annual temperature variability showed different warm and cold periods along the 20th and the first decade of the twenty-first century (Fig. 4). The first warming period occurred between 1904 and 1929, but temperatures stabilized during the 1930s. A short warming period was found in the 1940s, while a short cooling period occurred between 1948 and 1973. The largest warming episode was identified from 1973 to 2010 recording the warmest years between 1996 and 2010, being 2006 the warmest year of the entire regional Iberian time series (Coll 2014).

Figure 4 also shows the seasonal temperature variability across the Iberian Peninsula from 1906 to 2010. The first period of a clear warming in winter did not begin till 1970 followed by a stabilization of temperatures between 1980 and 1990. Another warming period occurred from 1991 to 1998, but temperatures stabilized during the last years of the time-series. The variability of spring temperatures was greater than in winter due to the warming period occurred from 1939 to 1945, although temperatures stabilized until 1961. A cooling period was found from 1962 to 1971, but a clear warming period was recorded between 1972 and 1997, being 1997 the warmest spring across the Iberian Peninsula. A slight decrease of temperatures occurred during the last years of the time-series (Coll 2014). Summer temperatures showed a short warming period from 1912 to 1921, but temperatures stabilized until 1939. As occurred in spring, a warming period was found between 1939 and 1949, but a cooling period started in 1950 lasting until 1977. From then, a

clear warming period was identified until 2005. The summer of 2003 was the warmest summer recorded in the Iberian Peninsula with an anomaly of almost +3 °C. Finally, autumn temperatures showed a warming period from 1919 to 1947 followed by a cooling period until 1976, and the last warming period was found between 1977 and 2010 (Coll 2014).

Annual precipitation anomalies showed a high interannual variability (Fig. 5) and some dry and wet periods were identified. Dry conditions extended from 1906 to 1935, but wet conditions became more frequent between 1936 and 1942, although dry conditions came back from 1943 to 1958. Very wet years were identified in 1960s and early 1970s, but a prolonged drying period was found by the end of 1970s until the 1990s. The first decade of twenty-first century was generally dry being 2005 the driest year of the Iberian time series. As occurred at annual scale, seasonal precipitation anomalies showed a very high interannual variability (Fig. 5). Winter precipitation was generally low from 1906 to 1935, but a combination of dry and wet winters appeared between 1936 and 1958. Wetter conditions became more frequent in 1960s and 1970s while dry winters came back in 1980s, 1990s and 2000s with the exception of the wettest winters ever recorded in the Iberian Peninsula (1979, 1996 and 2010). Spring precipitation showed a balanced combination of wet and dry springs for most of the whole time series. However, wetter springs appeared between mid-1940s and early-1960s while drier springs were more frequent from the early-1980s to late-1990s. Summer precipitation presented a high interannual variability identifying dry summers in 1910s, mid-1920s, mid-1930s, mid-late-1940s, 1960s and between 1978 and 2010. However, wet summers also occurred in 1982, 1983, 1987, 1988, 1992, 1997, 2002 and 2010, being 1992 the wettest summer of the time series. Finally, autumn precipitation showed dry conditions in late-1910s, between late-1920s and 1950s and in the 1970s. Otherwise, wet conditions dominated in the mid-1900s, early-1920s, 1960s and 1980s, but a high interannual variability was found during the last three decades of the time series (Coll 2014).

3.1.2 Trend analysis

Despite these fluctuations, the general evolution of temperature anomalies for the whole Iberian Peninsula showed a statistically significant increasing trend of 0.13 °C/decade ($p < 0.05$) at annual scale for the period 1906–2010 (Coll 2014). Madrid, Sevilla and Murcia were the locations with the highest magnitude of change (Fig. 6). At seasonal scale, both spring and summer were the seasons with the highest rates of change of 0.14 °C/decade, meanwhile winter and autumn showed lower

Fig. 4 Annual and seasonal temperature anomalies (base-period 1961–1990) of the Iberian regional series for the period 1906–2010
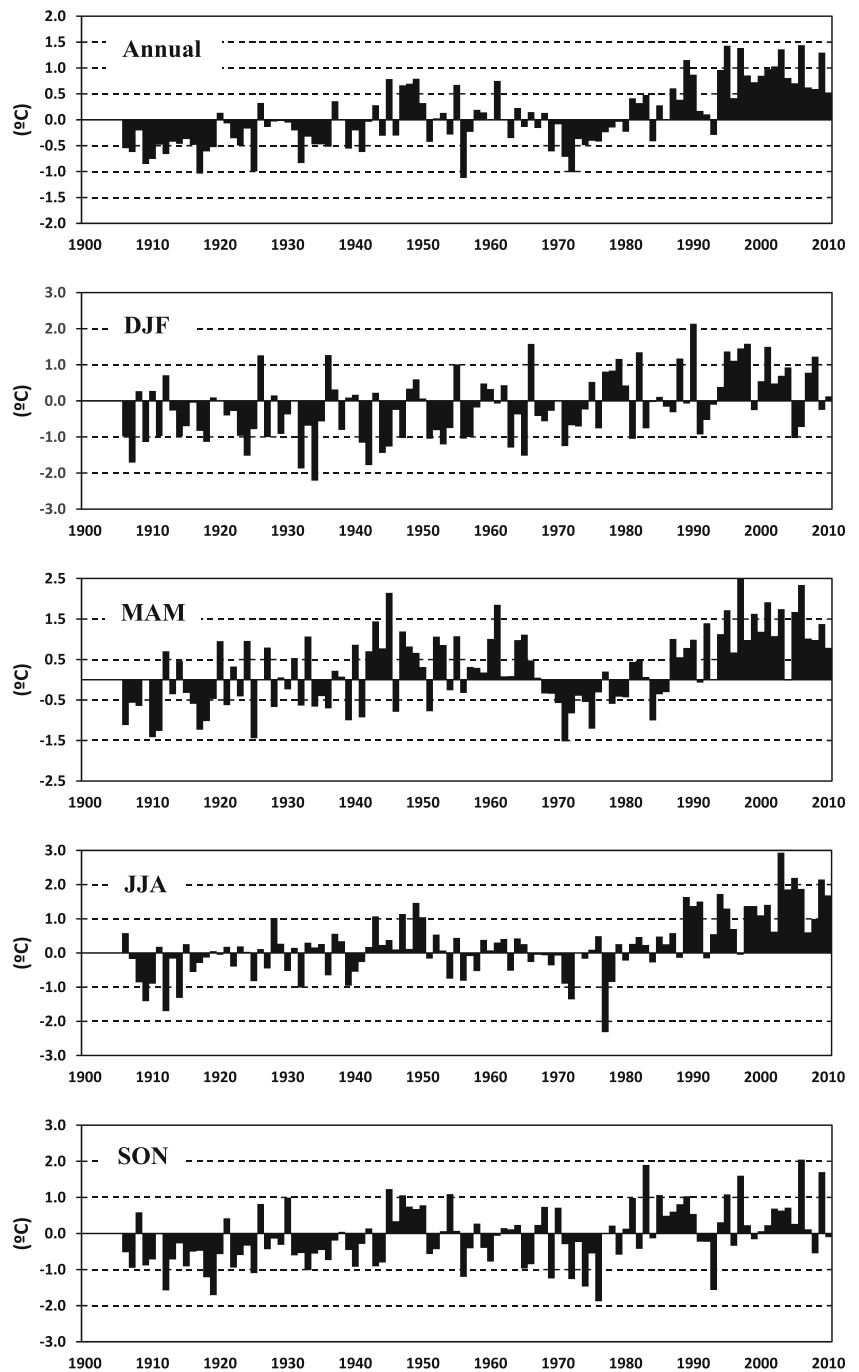

increasing trends of 0.12 °C/decade and 0.11 °C/decade, respectively. Largest trends were focused in the south, south-eastern and central Iberia especially in spring and summer, but all time series experienced statistically significant trends during all seasons (Fig. 6).

Trend analysis revealed a slight non-significant precipitation increase of 2.4 mm/decade at the annual scale for the whole Iberian Peninsula. Despite the non-significant increasing trend found in precipitation for the whole Iberian Peninsula at annual scale, the south and south-

eastern region presented drier conditions with a statistically significant decreasing trend in the representative station of Granada (Fig. 7). Otherwise, wetter conditions were found in the western Iberia were only statistically significant in Lisboa. In general, non-significant trends were found at seasonal scale, but drier conditions were detected in the southernmost Iberia in spring, being statistically significant in Cádiz and Granada, but wetter conditions were found to be statistically significant in Porto for autumn.

Fig. 5 Annual and seasonal
precipitation anomalies (base-
period 1961–1990) of the Iberian
regional series for the period
1906–2010
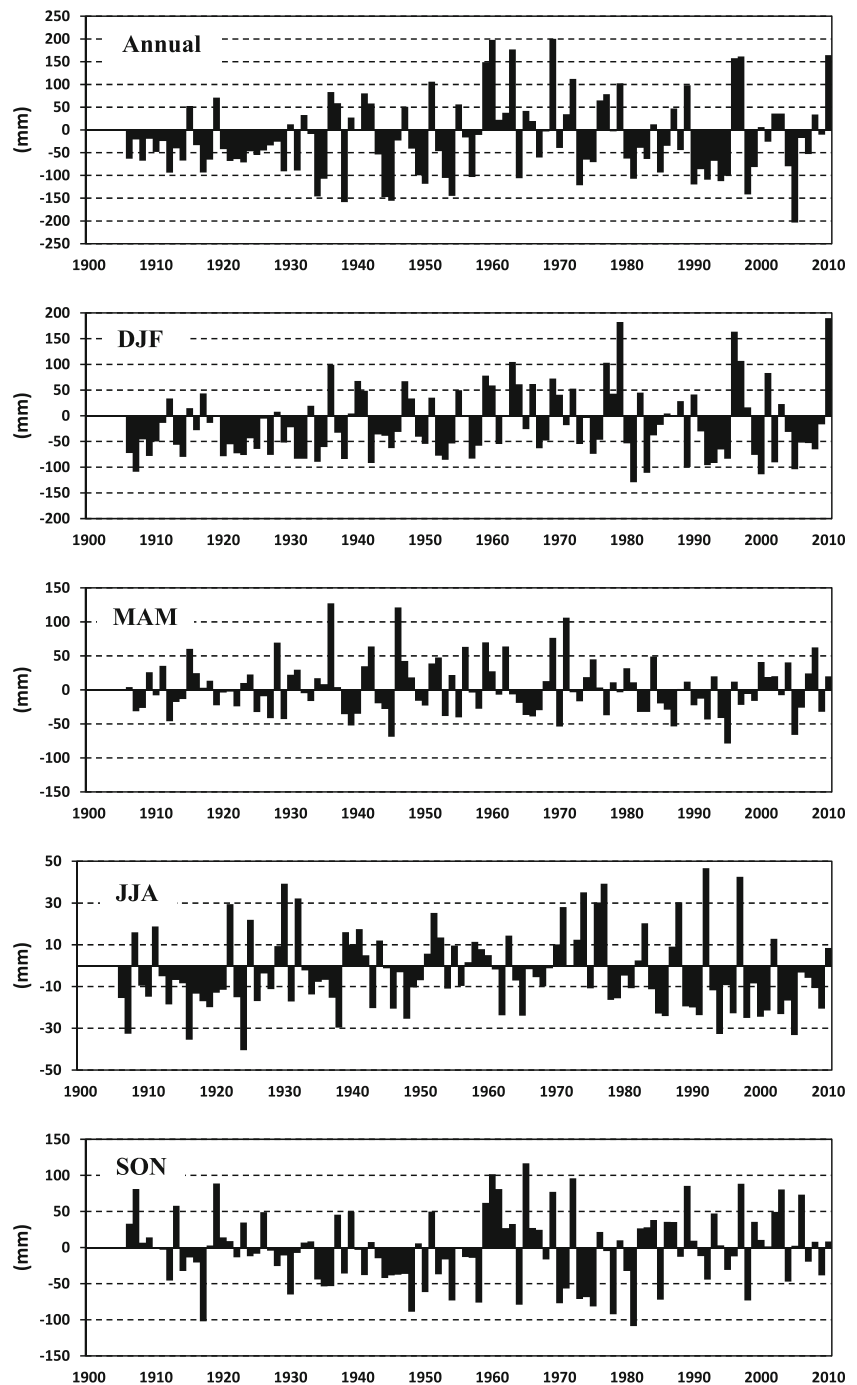
## 3.2 Drought assessment across Iberian Peninsula

3.2.1 Drought variability

Fluctuations in drought conditions were identified from the 3-,
6-, 12- and 24-month SPI (Fig. 8) and SPEI (Fig. 9) computed
from the regional series of temperature and precipitation
across the Iberian Peninsula for the period 1906–2010.
Temporal frequency in dry conditions was larger in short time
scales than in long time scales, although drought variability

showed similar behaviour in all time scales along the whole
period. Abnormally dry decades occurred in the 1920s, 1940s
and 1950s while abnormally wet conditions appeared in 1910,
1930, 1960 and 1970. Both the SPI and SPEI drought indices
showed similar drought fluctuations across time, but the SPEI
showed larger drought severity than the SPI mainly during the
last three decades of the period (1980s, 1990s and 2000s) for
all time scales (Coll 2014).

Both the SPI and SPEI were also able to identify the
major dry conditions reached in the Iberian Peninsula

Fig. 6 Magnitude of change in annual and seasonal temperature (in °C/decade) for the period 1906–2010. *Plus marks* are referred to statistical significance at the 95 % level. Spatial interpolation is applied by using the Kriging method
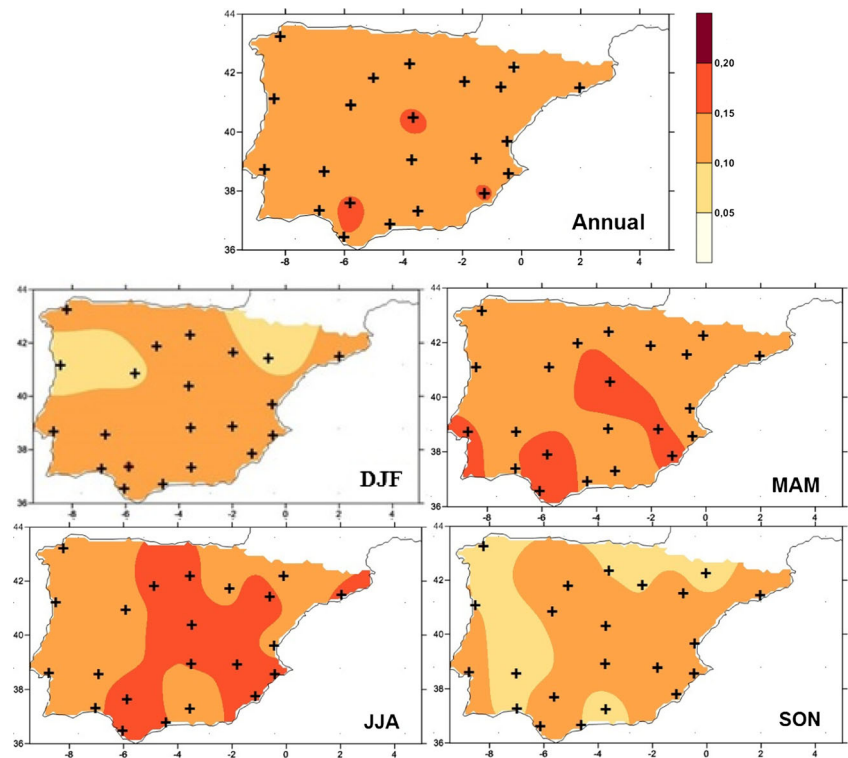

during the period under study for most of the time scales for years 1945, 1995 and 2005. As an example, Fig. 10 shows the maximum drought severity reached for the three driest conditions (October 1945, October 1995 and August 2005) identified from annual SPI and SPEI series. Drought severity was classified according to the SPI and

Fig. 7 Magnitude of change in annual and seasonal precipitation (in mm/decade) for the period 1906–2010. *Plus marks* are referred to statistical significance at the 95 % level. Spatial interpolation is applied by using the Kriging method
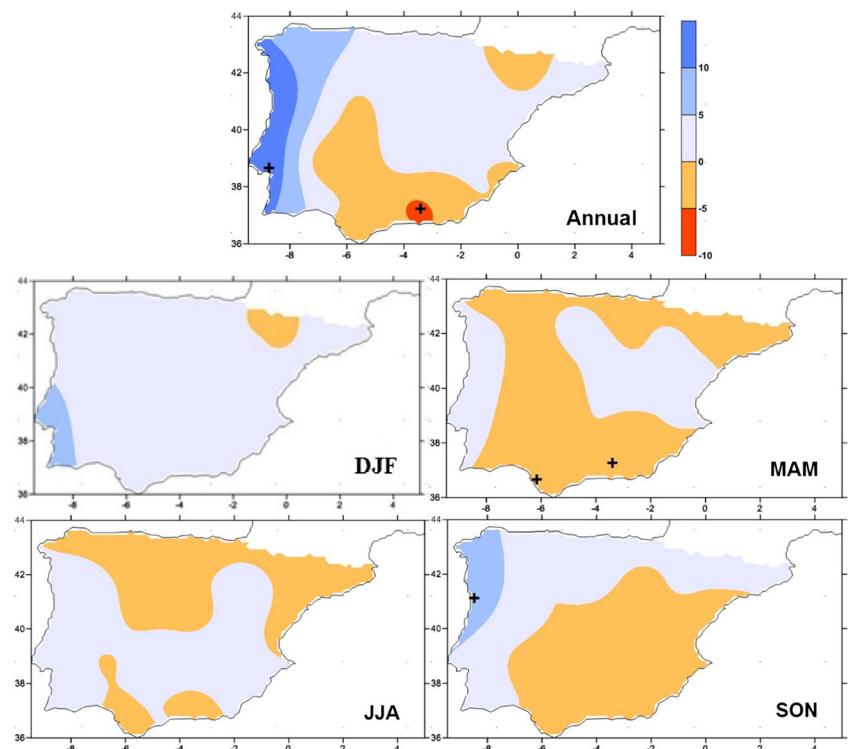
Fig. 8 Drought variability from
the 3-, 6-, 12- and 24-month SPI
computed from the Iberian
regional time series
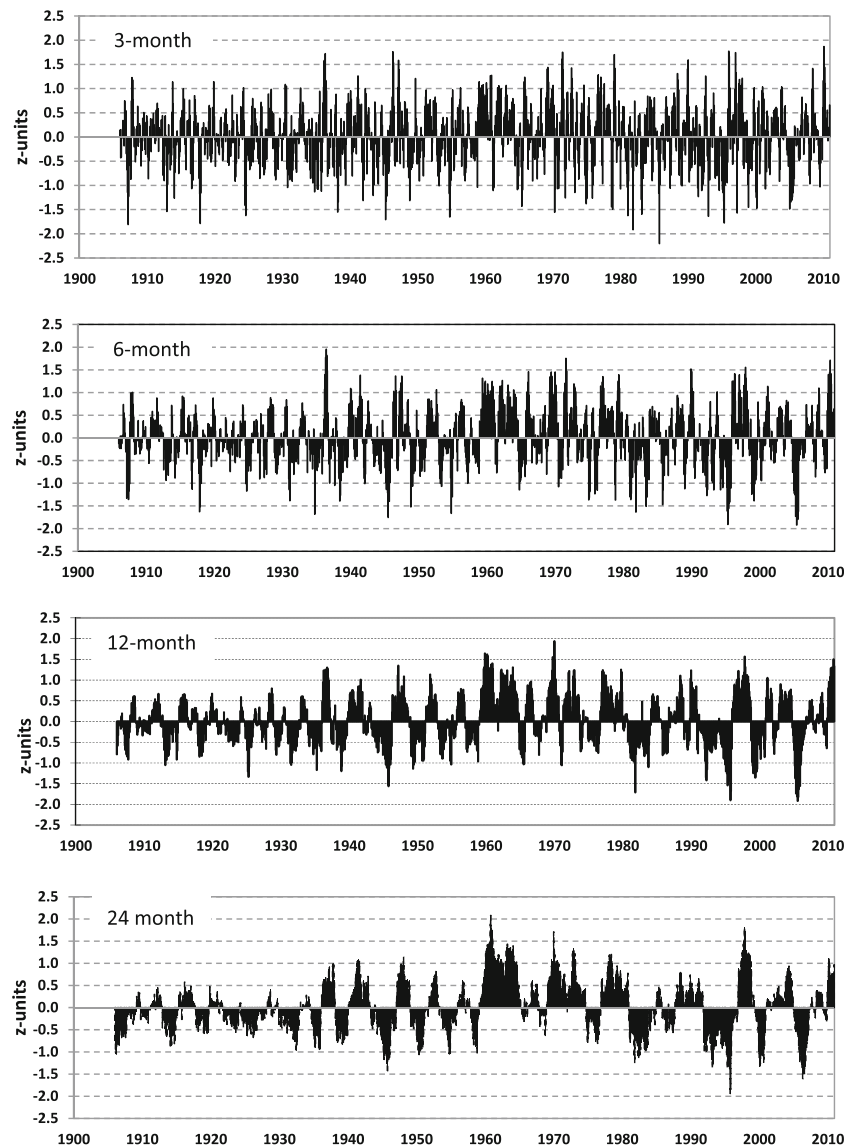
SPEI drought categories in Fig. 10 (see also Table 2). Similar drought severity was found for both the SPI and SPEI indices during October 1945. The extremely dry conditions affected the south and the south-western Iberia extending to the central region, meanwhile slightly dry conditions were focused in the Mediterranean region and also in the north-western area. Nevertheless, the Mediterranean region and the southern Iberia were affected by extremely dry conditions in October 1995 according to the SPI, although the central and south-western regions were also affected by extremely dry conditions according to the SPEI. Only some areas of north-western Iberia were affected by slightly dry conditions. The next driest conditions occurred in August 2005, when both the SPI and SPEI identified extremely dry conditions for most of the Iberian Peninsula with the exception of some areas in the north and in the central Mediterranean coast. The SPEI

again showed larger drought severity than the SPI during the driest conditions found across the Iberian Peninsula, especially for those produced during the last decades of the period.

3.2.2 Spatial coverage distribution

The spatial distribution of dry conditions in the Iberian Peninsula across time by using the SPI and the SPEI drought indices is approximated in Fig. 11, taking into account the percentage of stations simultaneously affected by different categories of drought. 100 % of stations were affected by dry conditions during a few months in 1935, 1981, 1995, 1999 and 2005 in both SPI and SPEI time series. Severely dry conditions were found in more than 50 % of stations during 1945, 1949, 1992, 1995 and 2005, although 70 % of stations reached this drought category in 2005. More than

Fig. 9 Drought variability from the 3-, 6-, 12- and 24-month SPEI computed from the Iberian regional time-series
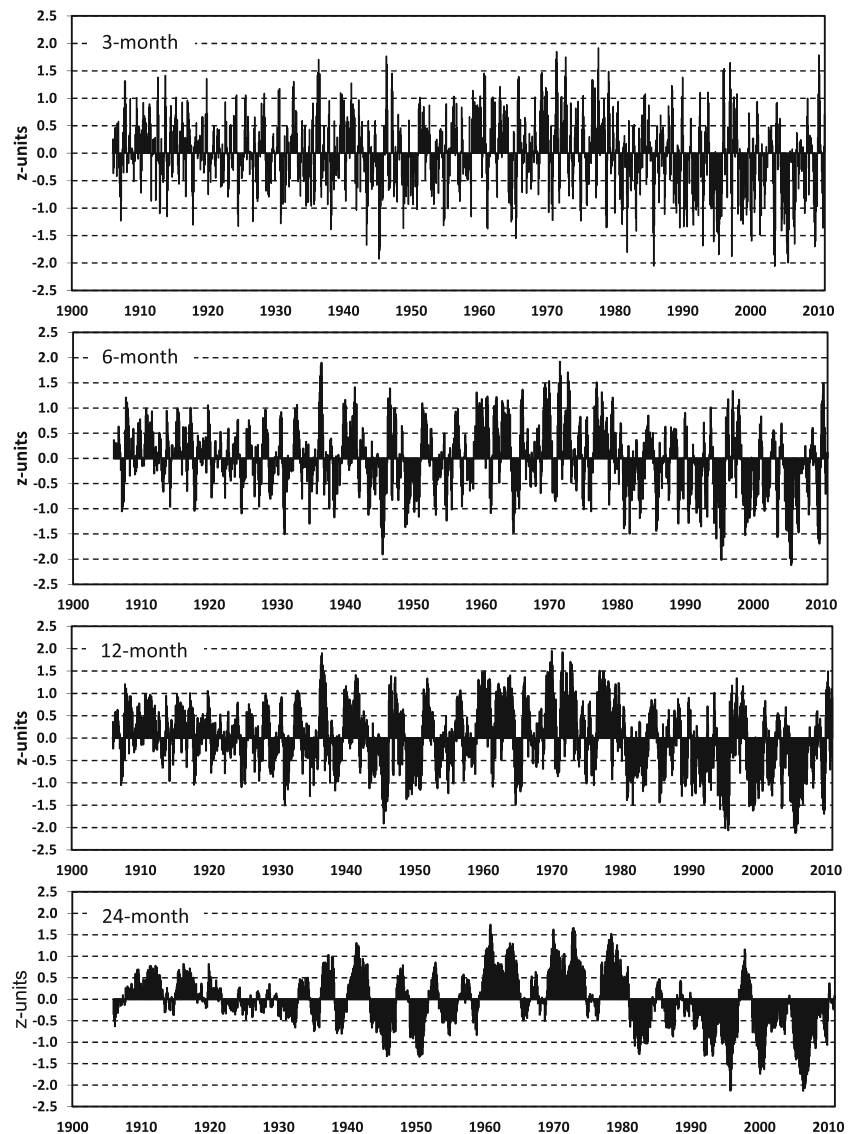
25 % of stations were under extremely dry conditions in 1945, 1949, 1981, 1992, 1995 and 2005, but more than 40 % of stations reached this category only in 1995 and 2005 (Coll 2014). Both drought indices found similar surface area affected by drought in the Iberian Peninsula across time but, just like the differences between the SPI and the SPEI in terms of drought severity (section 3.2.1), the area affected by drought was also larger in the SPEI than in the SPI during the 1980s, 1990s and 2000s.

Both drought indices also identified 1945, 1995 and 2005 as the driest years (in terms of area affected by drought) in the Iberian Peninsula during the twentieth century and the first decade of the twenty-first century. For example, more than 50 % of the Iberian Peninsula was affected by severe or extreme dry conditions in October 1945, but this percentage increased in October 1995, when more than 70 % of Iberia was under severe or extreme dry conditions. Moreover, more

than 80 % of the Iberian Peninsula was affected by severe or extreme dry conditions during the last dry period in August 2005.

3.2.3 Drought trends

Drought trends were analysed across the Iberian Peninsula from the SPI and SPEI time series at annual and seasonal scales for the period 1906–2010 to find spatial differences in drought trends. The magnitude of change in annual (12 months) and seasonal (3 months) SPI and SPEI is shown in Fig. 12. The SPI did not show a clear change in drought patterns at the annual scale, although slightly wetter conditions were identified for large areas of the Iberian Peninsula reaching the maximum rates of change only in Lisboa and Ciudad Real (statistically significant; $p < 0.05$). Otherwise, a drying trend was found over most of the Iberian Peninsula

Fig. 10 Maximum drought
severity reached for the three
driest conditions identified over
the Iberian Peninsula from annual
SPI and SPEI series. Drought
severity was classified according
to the SPI and SPEI drought
categories (Table 2). Spatial
interpolation is applied by using
the Kriging method
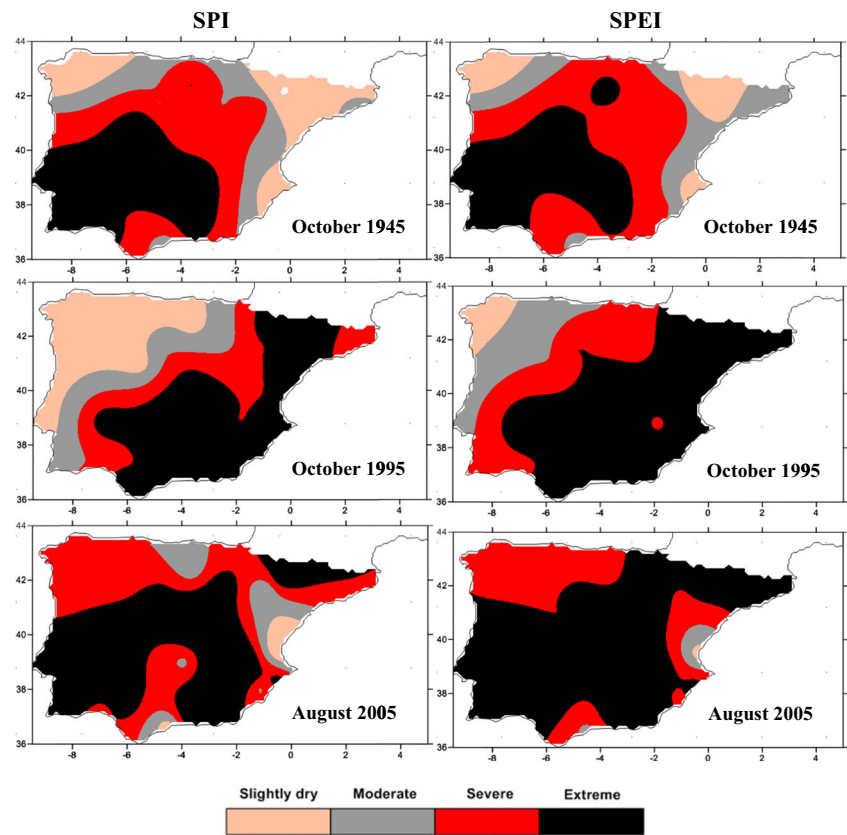
reaching maximum rates of change in the Ebro basin, central
and southern Iberia and, especially in the south-eastern area
according to the SPEI time series at the annual scale. The
magnitude of change became statistically significant in
Zaragoza, Huesca, Madrid, Sevilla and Cádiz, reaching the
maximum rates of change in Granada, Alicante and Murcia.
A non-significant wetting trend was only identified in the
westernmost region of the Iberian Peninsula.

At the seasonal scale, drying conditions were detected in
the southernmost area of the Iberian Peninsula in spring, being
statistically significant in Cádiz, Sevilla and Granada, mean-
while a statistically significant wetting trend was found only in
Porto for autumn. However, the SPEI series showed a clear
increase in dry conditions in spring especially in the southern
area being statistically significant in Cádiz, Huelva, Sevilla
and Málaga, but also in the Huesca time series (Pyrenees).
Nevertheless, the drying trend experienced a greater increase
in summer for most of the Iberian Peninsula, becoming statis-
tically significant in central Iberia, the Mediterranean region
and also in large parts of southern Iberia. Finally, a drying
trend affecting only the south-eastern area for autumn, but a
wetting trend appeared in the north-western Iberia. A clear
drying trend was not found for winter.

In summary, the SPI and SPEI identified similar dry con-
ditions from September to February in the Iberian Peninsula as
drought trends are mainly driven by precipitation during the

most rainy and cold part of the year. However, drying trends
are larger in the SPEI than in SPI at the annual scale and also
for spring and summer. These differences between the SPI and
SPEI could be associated with the major role of atmospheric
evaporative demand in explaining drought trends, which is
only included in the SPEI. Total precipitation is low from
March to August in the Iberian Peninsula, particularly com-
pared to winter and autumn precipitation, and temperature
increases have been greater during this warmest part of the
year (Fig. 4), reinforcing the drying trends in spring and sum-
mer. Although precipitation is the main variable to describe
drought variability derived from drought indices, the impor-
tance of reference evapotranspiration is becoming crucial to
explain the increased drought severity occurred during the last
three decades in the Iberian Peninsula (Coll 2014).

4 Discussion and conclusions

This study assesses drought variability and trends across the
Iberian Peninsula over more than 100 years extending from
the beginning of the twentieth century till the first decade of
the twenty-first century. The MITPS dataset was used to com-
pute the SPI and SPEI drought indices in a monthly basis in
order to figure out annual and seasonal drought patterns for
the period 1906–2010 (Coll 2014).

Fig. 11 Percentages of stations affected by various categories of drought in annual SPI and SPEI individual stations in the Iberian Peninsula from 1906 to 2010
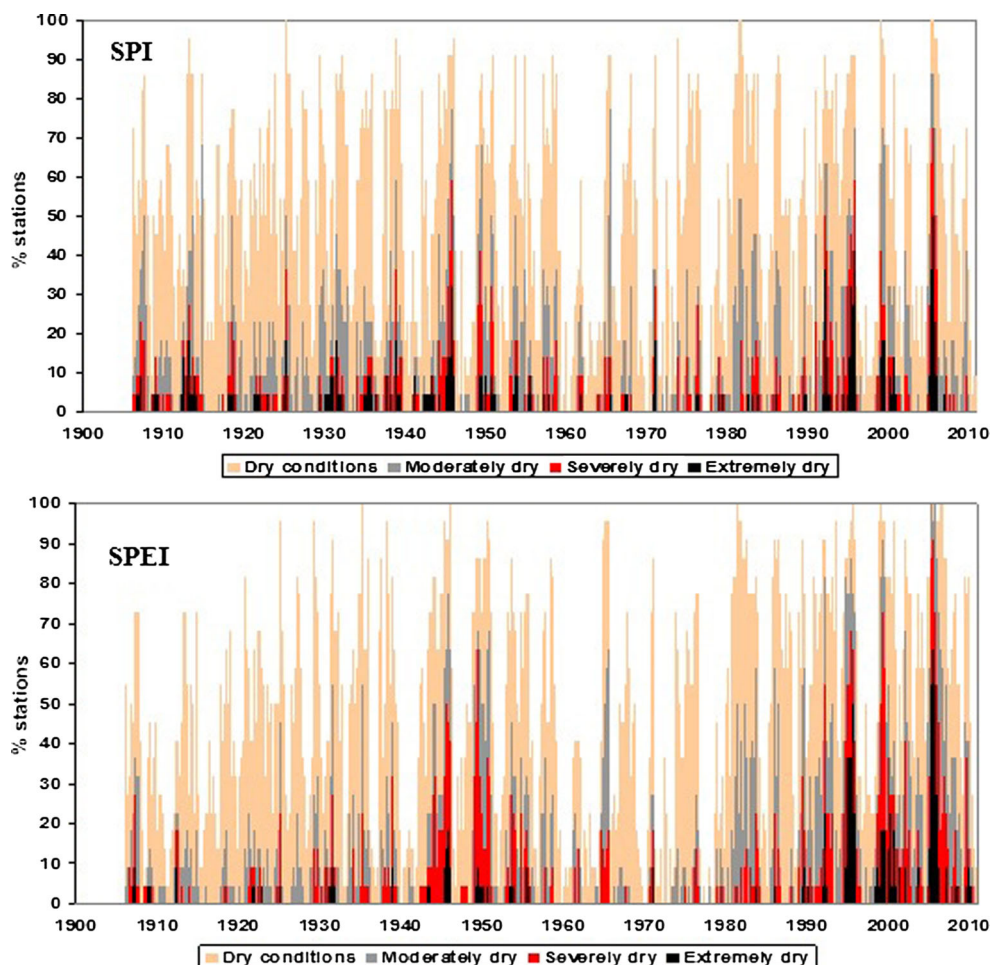
From the results, a clear temperature increase was found for the whole Iberian Peninsula at annual and seasonal scale reaching maximum rates of change in south, south-eastern and central Iberia especially during spring and summer. Brunet et al. 2006 also identified similar temperature increase for the period 1850–2003 while other regional studies found similar temperature patterns (e.g. for the interior of Valencia, Miró et al. 2006; Castilla-León, del Río et al. 2005; Andalucía, Castro-Díez et al. 2007 and Catalonia, Martínez et al. 2009). However, precipitation evolution showed a high inter-annual variability but non-significant trends were detected across the Iberian Peninsula. Slightly non-significant wet conditions were found in the western area and also non-significant drier conditions were identified in the southern Iberia especially in spring. Trenberth (2007) also found a non-significant precipitation decrease in the Mediterranean basin from a global analysis and other studies did not show significant changes in annual precipitation across the twentieth century (Lana and Burgueño 2000; Llasat and Quintas 2004; Saladié 2004; Barrera-Escoda 2008; CLIVAR 2010).

Otherwise, the results provided by the computation of the SPI and SPEI drought indices showed similar drought variability across time indicating dry conditions mainly in the 1920s, 1940s and 1950s, while wet conditions were focused in the 1910s, 1930s, 1960s and 1970s in all time scales. Both drought indices also attributed the driest conditions in terms of drought severity and surface area affected by drought to the years 1945, 1995 and 2005, when severe and extreme dry conditions affected large areas of the Iberian Peninsula, especially in October 1995 and August 2005. But, from the 1980s to 2010, the SPEI experienced greater drought severity and also larger surface area affected by drought than the SPI, mainly due to the major role of atmospheric evaporative demand (included only in the SPEI algorithm) related to the clear increase in temperatures during the last decades with slightly lower precipitation than normal. These results are supported by the findings from Vicente-Serrano et al. (2014a) who concluded that the increase in drought severity experienced in the Iberian Peninsula for the last decades was caused by greater atmospheric evaporative demand derived from temperature increase after comparing the evolution of the SPI and SPEI drought indices.

At the same time, trends analysis revealed a no clear signal in the SPI evolution at annual and seasonal time scale for the

Fig. 12 Magnitude of change in annual and seasonal SPI and SPEI (in z-units/decade) for the period 1906–2010. *Plus marks* are referred to statistical significance at the 95 % level. Spatial interpolation is applied by using the Kriging method.
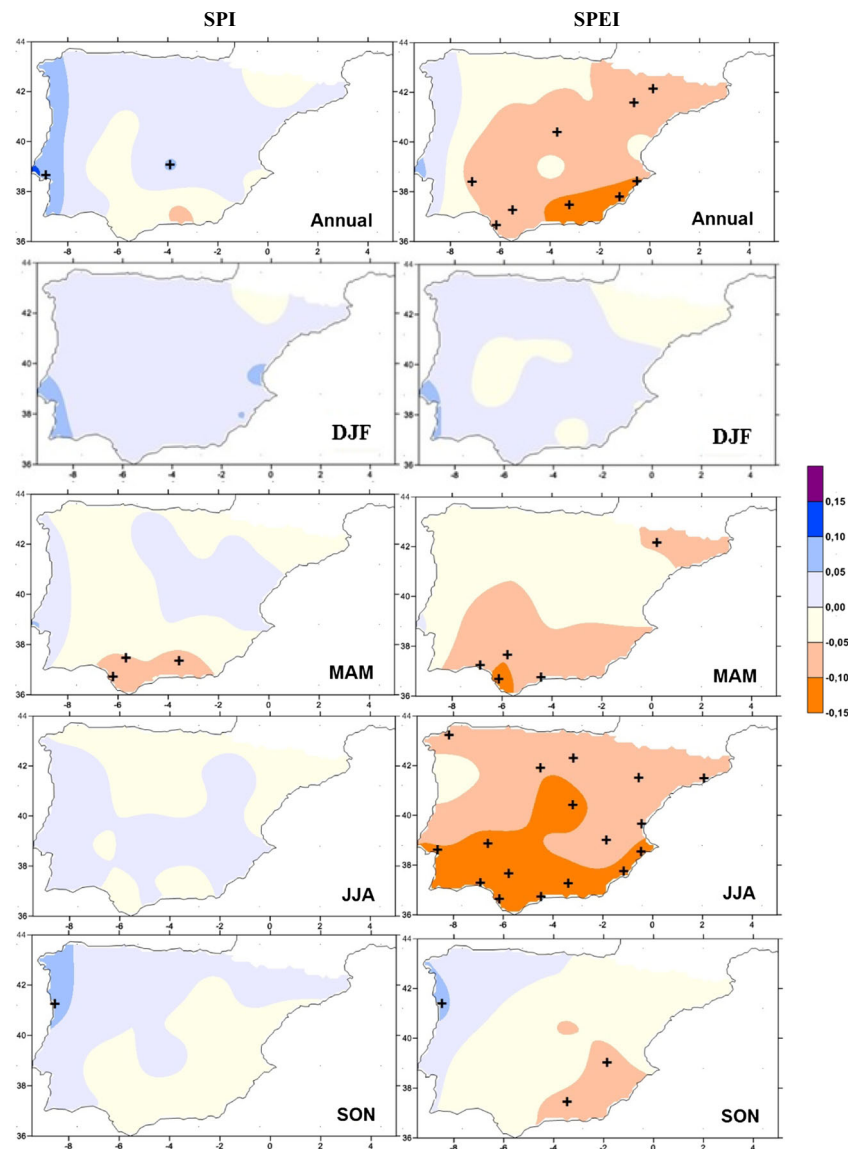
period 1906–2010, although slightly wetter conditions were found in western Iberia, meanwhile slightly drier conditions were focused in southern Iberia especially for spring. This statement is in good agreement with the non-significant trend in precipitation found and mentioned above since the SPI evolution is only driven by precipitation. Otherwise, the trends computed from the SPEI series showed a clear drying trend for most of the Iberian Peninsula with maximum rates of change in the south, south-eastern and central Iberia as well as in the Ebro basin at the annual scale and also for spring, but with largest drying trends for summer. Despite drought is considered as a regional phenomenon, the low density of stations integrated in the MITPS dataset could imply some uncertainties related to the accuracy of the spatial drought analysis in the Iberian Peninsula.

These results are in good agreement with the studies done by Sousa et al. (2011), Vicente-Serrano et al. (2011) using also

the SPI and SPEI indices, and Lorenzo-Lacruz et al. (2012) using streamflow data for the Iberian Peninsula. Other studies also show drier conditions across southern Europe (Sheffield et al. 2012; Dai 2012) and especially in the Mediterranean basin (van der Schrier et al. 2013). Despite the substantial coincidences in results comparing the SPI and SPEI drought indices computed in this study, trends were larger in the SPEI than in SPI mainly due to the inclusion of the atmospheric evaporative demand in the algorithm, which increased significantly during last decades (Vicente-Serrano et al. 2014a).

There is general agreement about precipitation as the main driver in explaining drought variability, but the observed and predicted global warming by IPCC AR5 has and will have important implications for evapotranspiration processes (Vicente-Serrano et al. 2010). From the results, the increased drought severity experienced during the last four decades in the Iberian Peninsula was mainly caused by the increased

reference evapotranspiration strongly related with temperature increase in a climate change context. Nevertheless, the use of Thornthwaite ET_0 estimation could have added some uncertainties in drying trends found from the SPEI results since this method is less physically realistic than others such as the Penman-Monteith parameterization. However, Vicente-Serrano et al. (2014a) found a dominant drying trend for the Iberian Peninsula streamflows for the period 1961–2011 independent of the ET_0 approaches applied (which Penman-Monteith and Thornthwaite methods were included in the study). Moreover, other studies tested the effect of the ET_0 on drought indices (van der Schrier et al. 2011; Dai 2011, 2012) showing similar results in global drought trends by using different ET_0 estimation methods, although Sheffield et al. (2012) showed that Thornthwaite ET_0 estimation produced higher rates of ET_0 than other parameterizations as Penman-Monteith at global scale. Despite the possible shortcomings derived from the computation of the Thornthwaite ET_0 estimation, it was the only method able to be applied for the whole study period (1906–2010). Poor quality and relatively short length of datasets for other climatic variables made other more physically realistic ET_0 unfeasible.

Future drought projections are pointing toward an increase of drought conditions in most of the Iberian Peninsula along the twenty-first century (Kirtman et al. 2013). The observed and projected drying trend could compromise the availability of water resources to maintain natural ecosystems and for the development of actual and future human activities. Nevertheless, a general consensus about saving water derived from the application of an appropriate water policies related to water management should be a priority to minimize the impact of future droughts across the Iberian Peninsula (Coll 2014).

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