Long-term variability and trends in meteorological droughts in Western Europe (1851-2018)

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This article has been accepted for publication and undergone full peer review but has not been through the copyediting, typesetting, pagination and proofreading process which may lead to differences between this version and the Version of Record. Please cite this article as doi: 10.1002/joc.6719

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Abstract: We analyzed long-term variability and trends in meteorological droughts across Western Europe using the Standardized Precipitation Index (SPI). Precipitation data from 199 stations spanning the period 1851-2018 were employed, following homogenisation, to derive SPI-3 and SPI-12 series for each station, together with indices on drought duration and severity. Results reveal a general absence of statistically significant long-term trends in the study domain, with the exception of significant trends at some stations, generally covering short periods. The largest decreasing trends in SPI-3 (i.e. increasing drought conditions) were found for summer in the British and Irish Isles. In general, drought episodes experienced in the last two or three decades have precedents during the last 170 years, emphasising the importance of long records for assessing change. The main characteristic of drought variability in Western Europe is its strong spatial diversity, with regions exhibiting a homogeneous temporal evolution. Notably, the temporal variability of drought in Western Europe is more dominant than long-term trends. This suggests that long-term drought trends cannot be confirmed in Western Europe using precipitation records alone. This study provides a long-term regional assessment of drought variability in Western Europe, which can contribute to better understanding of regional climate change during the past two centuries.

Keywords: Standardized Precipitation Index; Drought; Precipitation; Instrumental Period; Trends; Western Europe; Mediterranean.

1. Introduction

Many studies have analyzed droughts across Europe (e.g. Bordi *et al.*, 2009; Brázdil *et al.*, 2015; Potop *et al.*, 2014; Todd *et al.*, 2013; van der Schrier *et al.*, 2006). Drying trends have been suggested over the Mediterranean region (e.g. Hoerling *et al.*, 2012; Sousa *et al.*, 2011; Stagge *et al.*, 2017; Vicente-Serrano *et al.*, 2014c), particularly due to anthropogenic influences (Gudmundsson *et al.*, 2017; Gudmundsson and Seneviratne, 2016; Hoerling *et al.*, 2012). These trends have been supported by several studies based on paleo-climatic reconstructions and modelling approaches (e.g. Briffa *et al.*, 2009; Hanel *et al.*, 2018; Marvel *et al.*, 2019; Nicault *et al.*, 2008). However, other investigations that have employed precipitation-based drought indices have not found significant trends across Europe (e.g. Lloyd-Hughes and Saunders, 2002; Spinoni *et al.*, 2017, 2019), including the Mediterranean (e.g. Di Lena *et al.*, 2014; Domínguez-Castro *et al.*, 2019; Martins *et al.*, 2012; Merino *et al.*, 2015). The findings of these studies stress the difficulty in finding consensus on drought trends given the complexity of defining (Lloyd-Hughes, 2014) and quantifying (Vicente-Serrano, 2016; Wilhite and Pulwarty, 2017) drought. Furthermore, uncertainty in drought trends in Europe is linked to the use of different periods of analysis (Hannaford *et al.*, 2013) and deployment of a wide spectrum of possible drought metrics. The latter employ several hydroclimatic variables including, precipitation (Lloyd-Hughes and Saunders, 2002; Vicente-Serrano, 2006a), atmospheric evaporative demand (Spinoni *et al.*, 2015; Stagge *et al.*, 2017; Vicente-Serrano *et al.*, 2014b), streamflow (Hannaford *et al.*, 2013; Hisdal *et al.*, 2001; Lorenzo-Lacruz *et al.*, 2013; Parry *et al.*, 2012), groundwater (Lorenzo-Lacruz *et al.*, 2017; Marchant and Bloomfield, 2018) and soil moisture simulations (Hanel *et al.*, 2018; Moravec *et al.*, 2019).

In this context, the observed increase in atmospheric evaporative demand (AED), as revealed by Robinson *et al.* (2017), Stagge *et al.* (2017) and Vicente-Serrano *et al.* (2014a) could be seen as a key driver of drought severity in Europe over recent decades, particularly in the Mediterranean region (García-Herrera *et al.*, 2019; Stagge *et al.*, 2017; Vicente-Serrano *et al.*, 2014b). This may explain the decrease of soil moisture in land-atmosphere model outputs (e.g. Hanel *et al.*, 2018). Despite the significant role of AED, precipitation remains the dominant climatic variable contributing to recent drought severity and variability (Briffa *et al.*, 2009; Lloyd-Hughes and Saunders, 2002). This dependency is valid from a hydroclimatic perspective, given the stronger response of streamflow to precipitation, compared to AED (Yang *et al.*, 2018), which has been empirically verified for Western Europe (see Vicente-Serrano, *et al.*, 2019).

Future climate projections, based on different drought metrics, suggest that vast areas of Europe are likely to be impacted by severe drought events by the end of the 21st Century in response to anthropogenic forcing (e.g. Beniston *et al.*, 2007; Forzieri *et al.*, 2014; Samaniego *et al.*, 2018; Sheffield and Wood, 2008; Spinoni *et al.*, 2018). These events could be seen as an extension of observed drought episodes in Europe over the past two decades, including, for example: the 2011/2012 (Trigo *et al.*, 2013) and 2004/2005 (García-Herrera *et al.*, 2007; Santos *et al.*, 2007) droughts in Iberia, the 2003/2004 (Mihajlović, 2006) and 2012 (Cindrić *et al.*, 2016) in Croatia, the 2011/2012 (Zahradníček *et al.*, 2015) drought in the Czech Republic, the 2015 drought (Hoy *et al.*, 2017; Ionita *et al.*, 2017; Laaha *et al.*, 2017) in central Europe, and the 2017 drought (García-Herrera *et al.*, 2019) in Western Europe. However, a considerable number of intense drought events took place in Europe in the first half of the 20th century, but have not received a similar level of attention as those mentioned above (e.g. the 1944-45 Iberian drought or the widespread 1921-22 European drought). In fact, a long-term assessment of drought variability and changes in Western Europe remains lacking. Such an assessment is necessary to test whether present drought characteristics are unusual in the context of available instrumental observations.

Therefore, the main objectives of this study are: i) to analyse long-term (1851-2018) variability and trends in meteorological droughts over Western Europe, ii) to define the spatial patterns of these trends, and iii) to determine changes in the duration, magnitude and spatial extent of droughts. To realise these objectives we assess drought characteristics using the standardized precipitation index (SPI) applied to a newly developed precipitation dataset (199 long-term stations) covering Western Europe.

2. Data

Precipitation data were collected from different sources, including national meteorological agencies in different countries (e.g. Spain, Portugal, Germany, Netherlands, France, and the United Kingdom), the Global Historical Climatology Network (GHCN) dataset (https://www.ncdc.noaa.gov/data-access/land-based-station-data/land-based-datasets/global-historical-climatology-network-ghcn), the European Climate Assessment & Dataset (ECA&D) project (https://www.ecad.eu//dailydata/index.php), in addition to a set of long-term precipitation series presented in earlier works by Murphy *et al.* (2019), Noone *et al.* 2017 and Todd *et al.* (2015). Overall, we collected monthly precipitation data from 1871 locations across Western Europe covering the period from 1851 to 2018. Amongst them, data from only 206 observatories were retained, as they have short gaps (less than 5% of the total record missing).

The selected time series were subjected to rigorous quality control and homogeneity testing. The quality control was mainly based on a comparison of the anomaly of precipitation at each candidate station with the closest five neighbouring stations. Herein, the anomalies were computed with respect to the base period 1871-2018 and compared for each month independently. This statistical testing was also supported by a careful visual assessment to compare data from each station with the closest reference stations. The aim was to trim suspicious values, while keeping 'real' extreme values. This procedure is important, given that some parts of the Mediterranean can experience exceptional local wet events during summertime. Following this procedure, data for 798 months (0.2% of the total dataset) were removed and assigned as "missing values". At the station level, the number of trimmed values was generally less than 5 data points over the whole study period (1851-2018) (Figure 1a).

To perform homogeneity testing, HOMER (HOMogenization software in R) was employed. HOMER is a semi-automated tool in the R platform, which combines a fully automated joint segmentation with a partly subjective pairwise comparison. This tool allows for identification of breaks in monthly precipitation series by means of a wide range of relative homogeneity tests. These tests are highly recommended for testing homogeneity of climate data (Venema *et al.*, 2012). According to the relative homogeneity tests, data from each candidate series were compared with data from a number of reference series (the best 5 correlated series) at both seasonal and annual scales (Mestre *et al.*, 2013; Noone *et al.*, 2016). When a statistically significant break is detected in a series, a correction factor was applied following Mestre *et al.* (2013). Figure 1b illustrates the frequency of inhomogeneities found in the dataset. As depicted, most of the series (*N=138*) were free from the presence of inhomogeneities, while the frequency of stations with two or more breaks was low. The dataset did not show a particular concentration of inhomogeneities over specific periods, which gives confidence in the overall high quality of the data (Figure 1c). Following homogeneity testing, only three stations were discarded due to the presence of a high number of inhomogeneities in the data and their weak correlation with neighbouring reference series. Figure 2 illustrates the spatial distribution of the final dataset following the results of the quality control and homogeneity testing. According to the data availability, the final dataset includes 115, 171 and 199 stations whose records date back to 1851, 1861 and 1871, respectively. It should be noted that the few missing values present in the series, due to quality control checks, were filled by HOMER after the homogeneity testing following the procedure detailed by Mestre *et al.* (2013).

3. Methods

The SPI is a standardized drought index that allows direct comparison over space and time, irrespective of precipitation magnitude and climatic conditions. Originally proposed by Mckee *et al.* (1993), SPI is one of the most widely-used drought metrics and is also recommended for drought monitoring by the WMO (Hayes *et al.*, 2011; WMO, 2012). To quantify drought, we computed SPI at two timescales (3- and 12-month) using precipitation data from 199 stations. 3-month allows identifying seasonal dryness and 12-month to determine the annual conditions. To ensure comparability of SPI series derived for different lengths (1851-2018, 1861-2018 and 1871-2018) the reference period used to calculate the distribution parameters in fitting SPI was 1871-2018 for all stations. SPI was derived using the SPEI package within the R platform (Beguería *et al.*, 2014) using the Gamma distribution following the guidelines of the World Meteorological Organization (WMO).

Drought characteristics were defined for each precipitation series in the study domain using the calculated SPI series. A drought event was simply defined using an SPI threshold comparable over space and time (Tallaksen *et al.*, 1997; 2009). A value equal to -0.84 represents the 20th percentile of the SPI cumulative probability distribution and return period of one in five years, thus ensuring a sufficient sample size for reliable trend detection. Drought duration was defined as the number of consecutive and uninterrupted months with SPI below -0.84, while the accumulated precipitation deficit was defined as the sum of SPI values over consecutive months with SPI values lower than -0.84.

In addition, the spatial extent of drought was defined to represent the total area impacted by drought. Given the uneven distribution of meteorological stations, a Thiessen polygon method was applied to approximate the representative area of each station. This method gives weights to individual stations according to the area represented by each (Jones and Hulme, 1996). The total surface area impacted by drought was calculated for Western Europe as a whole and for regions, including; central, south and north West Europe (Supplementary Figure 1). The total area impacted by drought was calculated for three different drought categories: mild drought: SPI = -0.84: return period of one in five years; moderate drought: SPI = -1.28: return period of one in 10 years; and severe drought: SPI = -1.65: return period of one in twenty years).

Trends in the SPI series, drought duration, magnitude and total surface area were assessed using least squares regression. For the SPI and drought area series, trends were calculated using SPI-3 at 3-month intervals in February, May, August and November, which represent SPI-3 drought conditions during winter, spring, summer and autumn, respectively. SPI-12 in December was used to characterize drought at the annual scale. Trend significance was assessed using a modified version of the nonparametric Mann–

Kendall statistic which limits the possible impact of serial autocorrelation on trend significance (Hamed and Ramachandra Rao, 1998). Significance was assessed at the 95% level ($p<0.05$).

Principal Component Analysis (PCA) was used to determine homogeneous regions in terms of drought variability. We applied an S-mode PCA using the SPI-12 series for each of the 199 stations. In the S-mode, stations are the variables and the time observations refer to the cases (Serrano *et al.*, 1999). As PCA is sensitive to missing values, we restricted our analysis to 1871-2018 when all 199 stations have complete records. The areas represented by each mode were identified by mapping the factorial loadings (i.e. the highest correlation found between each original variable and the extracted principal components). The loadings were interpolated by means of a method of splines with tension (Mitášová and Mitáš, 1993). The number of components was selected according to the criterion of eigenvalue > 1, before applying the Varimax rotation method to the original data. (White *et al.*, 1991). Once the components were rotated we retained those that grouped more than 75% of the total variance.

To extend the temporal analysis in each region, we identified the most representative station of each component (based on factorial loadings). The aim was to analyse the interannual variability of drought characteristics corresponding to each retained component from 1851 or 1861 onwards, according to data availability. Heat maps were plotted for each representative series based on the magnitude of change in drought series, based on linear regression. Trends were computed for running periods with a minimum of 30 and a maximum of 168 years, using annual (12-month) and seasonal (3-month) SPI values, as well as drought duration and magnitude series. Trend magnitude and significance in the heat maps correspond to the beginning of the period of analysis.

4. Results

4.1. Trend detection

Figure 3 illustrates the magnitude of change in long-term SPI series calculated at the annual scale (December SPI-12) and the corresponding statistical significance for our three time periods. Statistically significant positive trends (wetter conditions) are evident over the British and Irish Isles and central Europe from 1851. On the contrary, albeit with fewer stations, negative trends (drier conditions) predominate over Italy and the Balkans. The negative trends in the Balkans are more pronounced from 1871 onwards, while the positive trends recorded from 1851 in northwest Europe are less consistent. In other regions like the Iberian Peninsula and southern France, no consistent patterns of change are evident, although negative trends prevail in western and southern Iberia since 1871 (Figure 3), albeit mostly non-significant at the 95% level ($p<0.05$). The percentage of stations with positive trends exceeds those with negative trends, irrespective of the season or the study period (Table 1).

Trends show important seasonal differences, analysed using SPI-3 (Supplementary Figures 2 to 5). Specifically, trends are mostly positive in winter, with largest change in central areas of west Europe. Exceptionally few stations exhibit statistically significant negative trends for winter. In spring, the spatial distribution of trends is more heterogeneous, with positive trends dominating in the British and Irish Isles, northern France and Germany and negative trends in the southwest of the Iberian Peninsula, Italy and the Balkans. However, in most cases (76.9% for the period 1871-2018), these trends were statistically non-significant at the 95% level ($p<0.05$).

Summer shows the largest percentage of negative trends, though statistically non-significant at the majority of stations. Significant negative trends are found mainly over the British and Irish Isles, particularly Ireland for the period 1871-2018. Trends are generally non-significant in autumn, however, we note a consistent positive trend in Ireland, and conversely a negative trend over northern parts of the Balkans.

Similar to SPI values, changes in drought duration and magnitude do not show consistent long-term trends across Western Europe (Figures 4 to 7 and Table 2). In a few instances, statistically significant positive or negative trends are observed at the seasonal scale (i.e. SPI-3, Figures 4 and 6). In contrast, no significant changes are noted for long-term droughts (i.e. SPI-12, Figures 5 and 7). For SPI-3, no coherent spatial patterns of drought trends are observed, with no clear differences even between northern and southern regions. As an indication of this high spatial variability in drought trends, using SPI-3 a significant positive trend in the duration and magnitude of droughts (i.e. a tendency towards longer/greater drought duration/magnitude) is observed for some stations in the Iberian Peninsula, the Balkans, Italy and the south of the British and Irish Isles. Conversely, a negative trend (i.e. less severe droughts) is noted in southern Germany, Switzerland, eastern France, northern Ireland, Scotland and the Netherlands. Similarly, SPI-12 trends exhibit high spatial variability, even for neighbouring stations. Notably, few stations exhibit statistically significant trends (Figures 5 and 7).

The surface area impacted by drought does not show significant changes, at 3 and 12 month time scales (Figure 8). Changes are statistically significant only in winter, with a reduction of almost 3.6% in the area impacted by severe drought (SPI-3 < -1.28) between 1871 and 2018 (Table 3). The temporal evolution of the area impacted by drought reveals that the most extensive drought events were recorded in the 1870s, 1920s, 1940s, 1950s, 1970s and 2010s. This also suggests that interannual temporal variability clearly dominates over long-term trends. Focusing on northern and south west Europe, results indicate no clear significant trends (Supplementary Figures 6 and 7). In south west Europe, the most extensive droughts were recorded in the 1940s and 1950s, with severe droughts (SPI <-1.28) prevailing over more than 50% of the study domain. Severe drought was also extensive during the 1870s, 1890s, 2000s and 2010s, but with less of a spatial fingerprint by comparison with the 1940s and 1950s.

4.2. Spatial and temporal components of droughts

Given the spatial diversity of long-term SPI at the seasonal and annual time scale, we applied a PCA in an S-mode to delineate the main patterns of SPI-12 values from 1871-2018. Results suggest coherent spatial patterns, with clear linkages to the diversity of climate conditions across Western Europe (Figure 9). We retained 23 components, which together contribute more than 75.2% of the total variance. To illustrate the temporal variability corresponding to each component we selected the series with the highest correlation with each component as representative. The temporal evolution of SPI-12 for each representative series was explored for the period 1871-2018, and for the period 1851-2018 or 1861-2018 based on data availability.

Component 1 is representative of drought variability over Ireland (Figure 10), showing no clear long-term trend, with the exception of the summer SPI. While drought events are common over the whole series, the most severe droughts were observed during the 1850s, 1920s, 1930s, 1950s and 1970s. As illustrated in Figure 10, statistically significant trends are mainly placed close to the diagonal of the heat maps, which represent the results of the analysis over short periods of 30 years in duration. This suggests that only few significant trends are observed for long periods, and accordingly that short-term variability dominates over long-term trends. The only exception corresponds to SPI-3 in summer, with a significant negative trend (the area in the plot framed by the dotted lines) noted for the periods of different duration (but in all cases for record lengths greater than 100 years) that start between 1880 and 1990 (in the X-axis) and finish between 2000 and 2018 (the Y-axis). This is depicted by the representative time series for this component (Cappoquinn station in Ireland).

Component 2 reveals the temporal variability of droughts in southern Germany, eastern France and most of Switzerland (Figure 11). This component is well-represented by the station of Karlsruhe in Germany, with the most severe droughts recorded in the 1850s, 1860s, 1900s, 1960s and 1970s. Significant trends are only found for winter from 1851 to 2018. Annual SPI exhibits a significant positive trend from 1860 to 2000. The duration and magnitude of droughts based on SPI-3 show a significant reduction from 1851 to 2018. This seems to be due to drought behaviour at the beginning of the series. These patterns are not defined using SPI-12, for which no significant trends are identified.

The third component is mostly representative of the temporal evolution of drought in southern England, best represented by the Althorp Park series. Major drought episodes are recorded in the 1850s, 1900s, 1920s, 1970s, 1990s and 2010s (Figure 12). Similar to the first and second components, no significant long-term trend is observed in this region. Significant trends are only found for short periods close to the diagonal of the heat maps for all the SPI, duration and magnitude series.

Component 4 captures the temporal variability of drought in northern Germany and the Netherlands (Figure 13), with the temporal evolution of drought illustrated using the series at Göttingen in Germany for the period 1861-2018. The most severe drought events are evident during the 1910s and 1930s. Again, this region does not show long-term trends in the various drought metrics examined. Significant trends are only found for short time spans (e.g. a negative trend from 1950 to 2000 during summer), but in spring it seems that there is a longer positive trend starting almost in 1900.

Component 5 represents drought variability over eastern Europe, including Hungary, eastern Austria, Slovakia and eastern Croatia. This is the only region which exhibits long-term changes in drought with two contrasting periods: a humid period from 1890 to 1930 and a persistent drought period from the 1960s onwards (Figure 14). Correspondingly, negative trends in the annual, winter and spring SPI, as well as in the drought duration and magnitude series, are evident from the beginning of the 20th century to present.

Component 6 summarizes drought variability in the majority of Italy and the western Balkans. This region experienced its main drought episodes during the 1920s and 1940s (Figure 15). In contrast, humid conditions dominate from the 1960s, especially in the past decade. Other drought metrics do not exhibit a significant long-term trend over this region. A similar temporal pattern is also noted for component 7 (Figure 16). In Iberia, the dominant role of natural variability is also noted, with drought conditions prevailing during the 1870s, 1880s, 1950s, 1990s and 2000s. Significant trends are restricted to summer SPI from the 1950s. However, the decrease in SPI values has no influence on the trends in drought duration and magnitude. In the northwestern UK, no long-term trends in the SPI series are observed. As illustrated in Figure 17, drought conditions predominated for the periods 1850-1900 and 1930-1980. On the other hand, humid conditions were more pronounced between 1900 and 1930 and from 1990 to 2018. Significant trends are recorded for different periods of 50-60 years, suggesting the influence of important long-term climate cycles.

Running trends in the SPI and drought indices for the components 9 to 23 are shown in Supplementary Figures 8 to 22. A quick inspection of these figures demonstrates that there are no clear long-term trends. This finding is evident for all components, including those corresponding to the Mediterranean region (e.g. Component 9 in Italy, Component 13 in northeastern Spain and southwestern France). In Barcelona, which is a representative of Component 13, dry conditions dominate from 2008, with no precedents since 1910. Nevertheless, more severe drought events were recorded between 1870 and 1905. In northern Spain (Component 14), no dominant long-term trends are observed, albeit with severe drought events between 1890 and 1920 and between 1980 and 2005. Exceptionally, a long term drying trend is recorded in southeastern Spain (Component 12). This trend is mostly impacted by the dominant humid conditions between 1880 and 1900. Thus, the recent dry periods recorded in the 1990s and 2010s can be seen as comparable to those recorded between 1910 and 1945 (Supplementary Figure 11). In other Mediterranean regions (e.g. Component 18, southern France), the last decades are mainly characterized by humid conditions. Conversely, the most severe droughts were recorded between 1915 and 1955 (Supplementary Figure 17). In Slovenia (Component 17), dominant dry conditions were mainly recorded in the past four decades, and earlier in the series between 1850 and 1940 (Supplementary Figure 16).

5. Discussion

This study presents the first comprehensive assessment of long-term variability and trends in drought over Western Europe, providing new perspectives on the severity of drought episodes over the instrumental period. Specifically, our assessment covers almost the whole of Western Europe and uses data from a relatively dense network of precipitation stations, which extend back to the mid 19th century. Previous studies have assessed long-term drought trends for specific regions in Europe (e.g. Noone *et al.*, 2017; Paulo *et al.*, 2016; Spraggs *et al.*, 2015; Todd *et al.*, 2013), or employed reconstruction approaches (e.g. Hanel *et al.*, 2018; Marvel *et al.*, 2019).

Our study stresses that from the long-term (1851-2018) perspective there are no generally consistent trends in droughts across Western Europe. This finding concurs with Lloyd-Hughes and Saunders (2002) and van der Schrier *et al.* (2006) who analyzed drought and moisture variability over Europe during the 20th century using gridded datasets. Exceptionally, long-term trends were detected in a few regions, mainly in eastern Europe and in Ireland during summer. In the remaining regions, the identified trends were only observed for short periods, suggesting high interdecadal variability of drought. This also indicates that anomalous drought episodes observed in Western Europe in the past two or three decades have several precedents, at least since 1850. This finding holds despite different climatic conditions prevailing in the region. For example, the increase of SPI values was generally the dominant pattern in some regions of northern Europe, with less frequent and severe drought events. In southern Europe, although the tendency towards more humid conditions was less evident, the long-term trend analysis did not suggest any tendency towards more severe droughts.

This finding seems to contradict previous studies that suggest an increase in drought severity over southern Europe in recent decades (e.g. Gudmundsson and Seneviratne, 2016; Hoerling *et al.*, 2012; Stagge *et al.*, 2017; Vicente-Serrano *et al.*, 2014c). These differences might be simply explained by differences in study period. This issue is of particular importance in trend detection, given that the magnitude and significance of the observed trends can vary considerably, as a function of the length of the series and the selected study period (Hannaford *et al.*, 2013; Murphy *et al.*, 2013). The possible effect of the selection of the study period is particularly evident for Component 13, represented by the observatory of Barcelona, where no significant climate signal was observed due to the presence of longer and more severe droughts in the earlier decades of the series. This highlights the importance of conducting trend assessments using long-term data and the importance of ongoing national and international data rescue initiatives (Brunet and Jones, 2011; Ryan *et al.*, 2018).

We emphasise that our findings should be seen in the context of the drought metric applied. Our assessment of drought characteristics is based on SPI, which is a precipitation-based metric. For a long-term assessment of drought in the region, it is not possible to use metrics that employ other important variables (e.g. streamflow, soil moisture or AED). This is simply due to data scarcity of these variables. For example, streamflow data are available, with adequate density, only for the last few decades (Blöschl *et al.*, 2019; Vicente-Serrano *et al.*, 2019). This is also the case for the large number of meteorological variables necessary to quantify AED (e.g. wind speed, relative humidity and solar radiation). Studies that have analyzed long-term drought trends using hydrological metrics, are based on reconstructions and model simulations (Hanel *et al.*, 2018), which have large uncertainty (Cheng *et al.*, 2017; Stegehuis *et al.*, 2013). Thus, the lack of trends presented in our study, should be seen within the context of our study design.

It is necessary to stress that this study may be affected by some limitations. For example, Murphy *et al.*, (2019, 2020) have shown that pre 1870 winter precipitation in north West Europe is likely too low due to undercatch of snow. Such changes that affect multiple stations simultaneously may not be detected using relative homogenisation methods and they could affect winter and annual SPI trends for stations in the British and Irish Isles. Moreover, the unequal distribution of gauges could affect the obtained drought patterns, mostly for southern Europe in which spatial differences in the drought evolution are stronger. In any case, the unequal station coverage would not affect the intended application of the PCA in this study, which was not intended to represent the main patterns of drought variability but to identify regions with homogeneous behavior allowing for a more straightforward analysis of the long-term variability and trends.

Our findings do not necessarily contradict several recent works that have indicated an increase in the frequency, severity and duration of droughts in Western Europe in recent decades. For example, according to Robinson *et al.* (2017), AED has significantly increased in northern West Europe over the last decades. A similar finding has also been confirmed by Vicente-Serrano *et al.* (2014a) for southern Europe, being mostly associated with an increase in air temperature and decline in relative humidity. Some studies indicate that streamflow variability has been generally less impacted by the increase in AED (Vicente-Serrano *et al.*, 2019), mainly due to the stronger response of streamflow to precipitation than to AED (Yang *et al.*, 2018). Nonetheless, changes in AED could have more influence on drought in regions impacted by strong land cover changes (e.g. southern Europe). In such environments, natural revegetation in humid headwaters and the generation of new irrigated lands (García-Ruiz *et al.*, 2011) could favour higher evapotranspiration under enhanced AED and accordingly increase hydrological drought conditions downstream (Vicente-Serrano *et al.*, 2017). In addition, increased AED would enhance the severity of droughts associated with precipitation deficit. Recently, this dependency has been confirmed by García-Herrera *et al.* (2019) for the 2016/2017 drought event in Europe. Several ecological studies have reported an enhancement of drought impacts during recent decades in some European regions, albeit with no significant precipitation changes (e.g. Carnicer *et al.*, 2011; Peñuelas *et al.*, 2018; Vicente-Serrano *et al.*, 2012). Enhanced AED serves to increase vegetation stress during periods of negative soil moisture anomalies, irrespective of the vapor pressure deficit control on stomatal conductance (Zhang *et al.*, 2019). This situation would reduce biomass production and increase the risk of forest mortality (Allen *et al.*, 2015; Vicente-Serrano *et al.*, 2019a and c). In this context, the findings of this study stress that although the increase of drought severity and its environmental and/or hydrological impacts cannot be supported by the decrease in precipitation; it is likely they are more linked to human transformations (e.g. irrigation, land cover changes, etc.) or to observed increases in AED under global warming (Vicente-Serrano *et al.*, 2020a). The thermodynamic processes associated with an AED enhancement in recent decades are intense in the region (Hirschi *et al.*, 2011; Seneviratne *et al.*, 2010; Teuling *et al.*, 2013). Herein, what are termed "global-change-type-droughts" by Breshears *et al.* (2005) to refer to drought episodes under global warming, seems to be representative of possible drought intensification in Western Europe in recent decades, associated with warming conditions and related thermodynamic processes and feedbacks. Thus, it can be concluded that drought intensification in Western Europe cannot be attributed to precipitation deficit, at least in the last 170 years.

With respect to those studies that usually classify Europe into large domains (e.g. northern vs. southern Europe) in order to characterize drought variability and trends, our study indicates that this approach has a degree of uncertainty, recalling the strong spatial variability of drought. The principal component analysis showed consistent spatial patterns of drought, whose temporal variability was homogenous. However, the temporal variability of drought showed considerable differences amongst neighbouring regions. This strong spatial and temporal variability was identified at the regional scale in Europe, including Spain (e.g. Vicente-Serrano, 2006b; Vicente-Serrano *et al.*, 2004), Portugal (e.g. Santos *et al.*, 2010), Italy (e.g. Bonaccorso *et al.*, 2003) and Serbia (e.g. Gocic and Trajkovic, 2014), amongst others. This strong variability is mainly attributed to the complex atmospheric configurations that control climate in the region. In this context, although the North Atlantic Oscillation (NAO) is the dominant circulation pattern controlling drought variability in Europe (López-Moreno *et al.*, 2008), other large-scale circulation patterns also contribute to climate variability in specific European regions (Kingston *et al.*, 2015; Manzano *et al.*, 2019; Trigo *et al.*, 2009; Vicente-Serrano *et al.*, 2016). This is more pronounced in the Mediterranean, where the influence of local/regional circulation variability induces more heterogeneous drought patterns, even for small areas (Vicente-Serrano and López-Moreno, 2006).

6. Conclusions

This study stresses the following findings:

- Spatial differences were observed in the SPI12 magnitude trend, where a positive trend was found in the British and Irish Isles, northern France and Germany, and a negative trend in the southeast of the Iberian Peninsula, Italy and Balkans. In addition, this great spatial variability is reflected in the 23 components of the PCA to obtain 75.2% of the variance explained.
- Seasonal differences were found in the SPI3 magnitude trend, where a negative trend in summer was detected, especially in the British and Irish Isles. In addition, a reduction in the area affected by severe drought was detected, especially in winter.
- With few exceptions, trends in droughts over Western Europe are statistically non-significant from a long-term perspective.
- Changes in droughts are spatially variable, especially on a seasonal basis. Therefore detailed local and regional assessment of drought variability should be of high priority in Western Europe. Such assessments would provide local

policy and decision-makers with the most appropriate and reliable information for understanding drought change and management.

Acknowledgements

This work was supported by the research projects PCIN-2015-220 and CGL2017-82216-R financed by the Spanish Commission of Science and Technology and FEDER, IMDROFLOOD financed by the WaterWorks 2014 co-funded call of the European Commission, CROSSDRO financed by the AXIS (Assessment of Cross(X) - sectorial climate Impacts and pathways for Sustainable transformation) JPI-Climate co-funded call of the European Commission, INDECIS, which is part of ERA4CS, an ERA-NET initiated by JPI Climate, and funded by FORMAS (SE), DLR (DE), BMWFW (AT), IFD (DK), MINECO (ES), ANR (FR), FCT (PT) with co-funding by the European Union (Grant 690462), Irish Research Council COALESCE grant (COALESCE/2019/43). Dhais Peña-Angulo received a "Juan de la Cierva" postdoctoral contract (FJCI-2017-33652 Spanish Ministry of Economy and Competitiveness, MEC), Marco Turco has received funding from the Spanish Ministry of Science, Innovation and Universities through the project PREDFIRE (RTI2018-099711-J-I00). Our grateful thanks extend to Instituto Português do Mar e da Atmosfera-(IPMA), Portugal, Agencia Estatal de Meteorología (AEMET), Spain, Deutscher Wetterdienst (Germany), Meteofrance (France), Met Office (UK), Koninklijk Nederlands Meteorologisch Instituut (KNMI), Netherlands, the Global Historical Climatology Network (GHCN), and the European Climate Assessment & Dataset (ECAD) for providing precipitation data used in this study.

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Table 1: Percentage of series showing positive and negative SPI trends at seasonal (SPI-3) and annual (SPI-12) scales during the periods 1851-2018, 1861-2018 and 1871-2018.

Table2: Percentage of stations showing positive and negative trends in drought duration and magnitude obtained from SPI-3- and SPI-12 series for the periods 1851-2018, 1861 -2018 and 1871 to 2018.

Table 3: Trends in the total area (%) impacted by different drought categories during the period 1851-2018. Percentage change is expressed for the whole study period. Significant at $p < 0.05$.

Table 1: Percentage of series showing positive and negative SPI trends at seasonal (SPI-3) and annual (SPI-12) scales during the periods 1851-2018, 1861-2018 and 1871-2018.

	Negative ($p < 0.05$)	Negative ($p > 0.05$)	Positive ($p > 0.05$)	Positive ($p < 0.05$)
Winter (1851)	0.0	8.7	47.0	44.3
Winter (1861)	1.2	15.2	53.8	29.8
Winter (1871)	1.0	15.6	51.3	32.2
Spring (1851)	4.4	25.4	56.1	14.0
Spring (1861)	5.8	31.0	45.6	17.5
Spring (1871)	9.5	30.2	46.7	13.6
Summer (1851)	12.2	67.0	20.9	0.0
Summer (1861)	8.8	61.4	29.2	0.6
Summer (1871)	16.6	61.8	21.6	0.0
Autumn (1851)	3.5	38.3	47.8	10.4
Autumn (1861)	2.3	48.5	46.8	2.3
Autumn (1871)	4.5	54.3	37.7	3.5
Annual (1851)	6.1	19.1	40.0	34.8
Annual (1861)	7.6	26.9	41.5	24.0
Annual (1871)	9.0	35.2	34.7	21.1

Table2: Percentage of stations showing positive and negative trends in drought duration and magnitude obtained from SPI-3- and SPI-12 series for the periods 1851-2018, 1861-2018 and 1871 to 2018.

	Negative ($p < 0.05$)	Negative ($p > 0.05$)	Positive ($p > 0.05$)	Positive ($p < 0.05$)
Magnitude 3 months (1851)	13.0	58.3	22.6	6.1
Magnitude 3 months (1861)	11.1	48.0	35.7	5.3
Magnitude 3 months (1871)	10.6	42.2	36.2	11.1
Duration 3 months (1851)	11.3	63.5	19.1	6.1
Duration 3 months (1861)	11.7	48.0	34.5	5.8
Duration 3 months (1871)	9.5	43.7	38.7	8.0
Magnitude 12 months (1851)	0.0	75.7	24.3	0.0
Magnitude 12 months (1861)	0.6	63.7	35.7	0.0
Magnitude 12 months (1871)	1.0	54.3	44.2	0.5
Duration 12 months (1851)	1.7	72.2	26.1	0.0
Duration 12 months (1861)	0.6	62.0	37.4	0.0
Duration 12 months (1871)	2.5	52.8	43.7	1.0

Table 3: Trends in the total area (%) impacted by different drought categories during the period 1851-2018. Percentage change is expressed for the whole study period. Significant at $p < 0.05$.

	Winter	Spring	Summer	Autumn	Annual
Mild (whole Europe)	-9.2	3.0	6.4	2.5	0.9
Moderate (whole Europe)	-5.5	1.5	4.8	2.9	1.5
Severe (whole Europe)	**-3.6***	1.4	2.8	1.7	1.4
Mild (Northern Europe)	**-12.6***	-0.5	6.9	0.3	-4.0
Moderate (Northern Europe)	**-9.0***	-0.3	5.3	1.1	-3.5
Severe (Northern Europe)	**-6.3***	0.0	3.0	0.3	-0.8
Mild (Southern Europe)	-3.9	5.8	4.6	4.1	1.8
Moderate (Southern Europe)	-0.8	3.1	3.2	4.0	1.0
Severe (Southern Europe)	-0.1	2.4	2.1	2.8	1.2

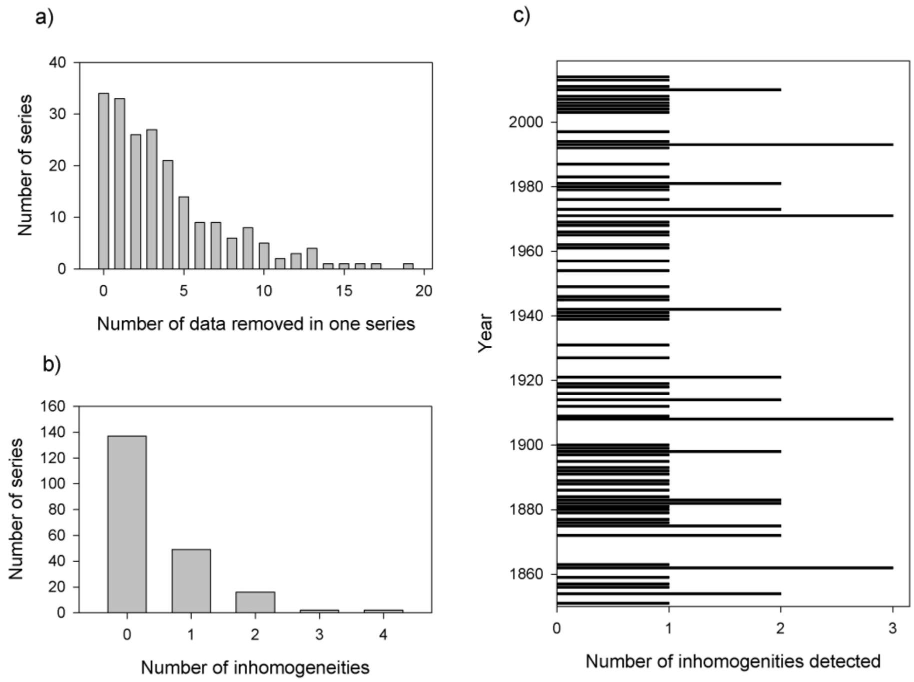

Figure 1: a) Frequency of the number of cases (months) removed from each series after quality control checks, b) the number of inhomogeneities detected in the series, and c) distribution of detected inhomogeneities as a function of time.

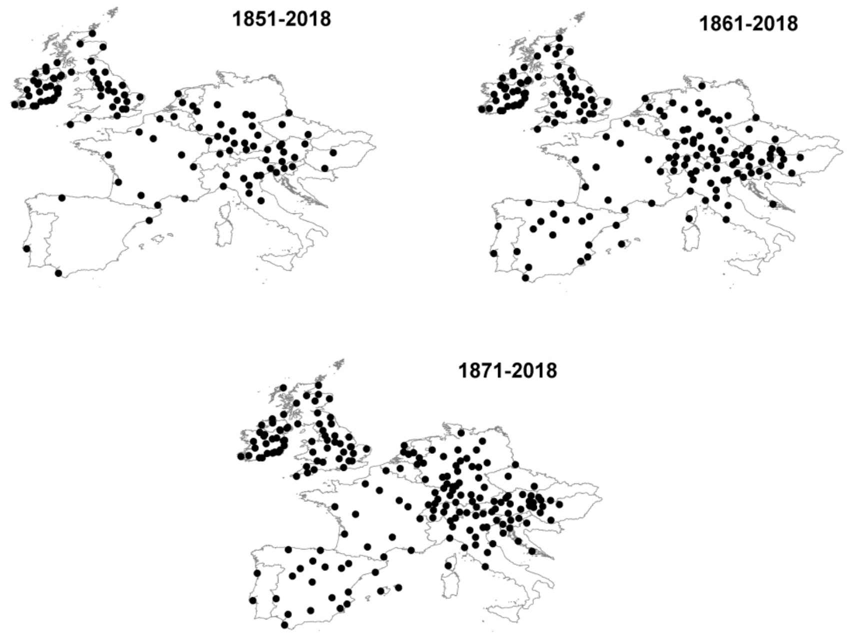

Figure 2. Spatial distribution of the available precipitation stations employed for different analysis periods.

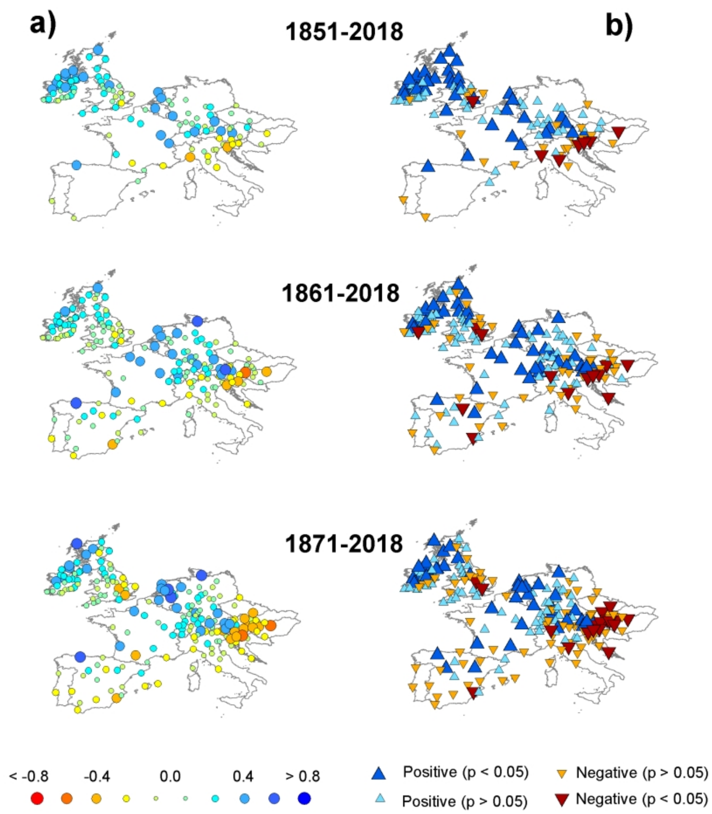

Figure 3. Spatial distribution of (a) the magnitude of change in annual SPI series (December SPI-12) and (b) their statistical significance. The magnitude of change is expressed in z units/decade.

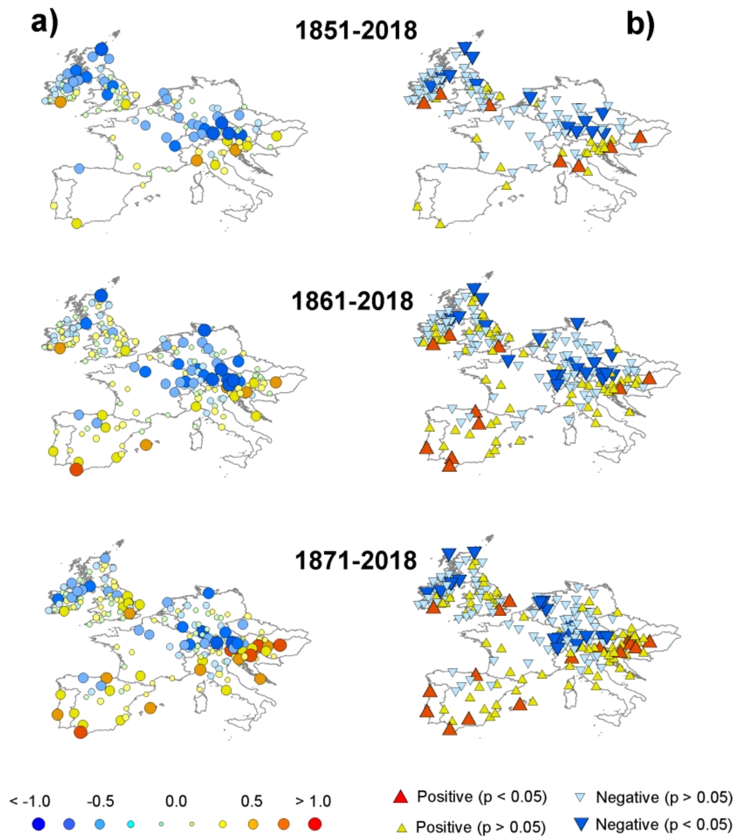

Figure 4. Spatial distribution of changes in the duration of drought events based on SPI-3 series (a) and (b) their statistical significance. Changes are expressed in months/decade.

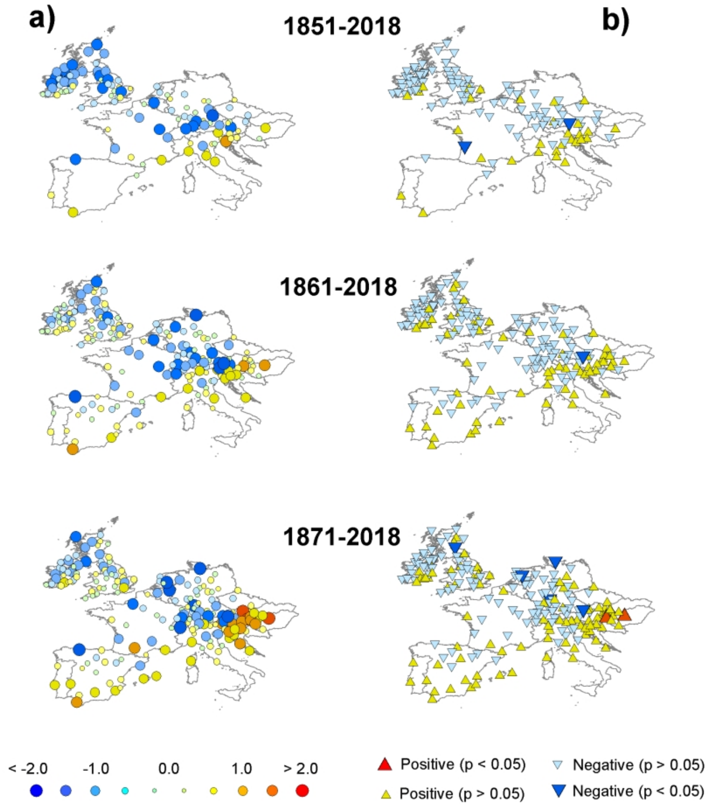

Figure 5. Spatial distribution of changes in the duration of drought events based on SPI-12 series (a) and (b) their statistical significance. Changes are expressed in months/decade.

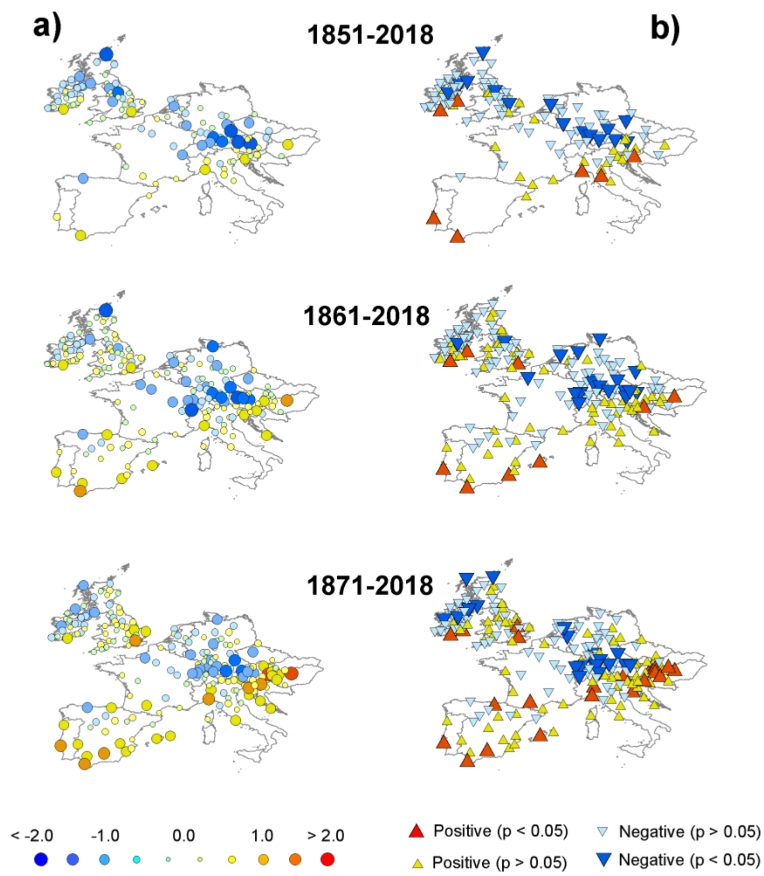

Figure 6. Spatial distribution of changes in the magnitude of drought events based on SPI-3 series (a) and (b) their statistical significance. Changes are expressed in cumulative z-units/decade.

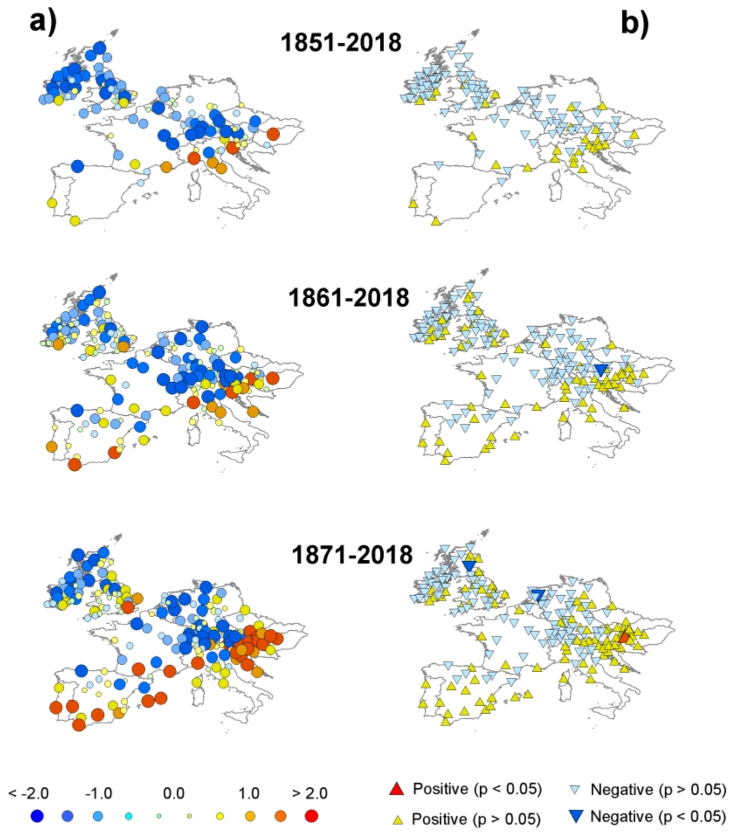

Figure 7. Spatial distribution of changes in the magnitude of drought events based on the SPI-12 series (a) and (b) their statistical significance. Changes are expressed in cummulative z-units/decade.

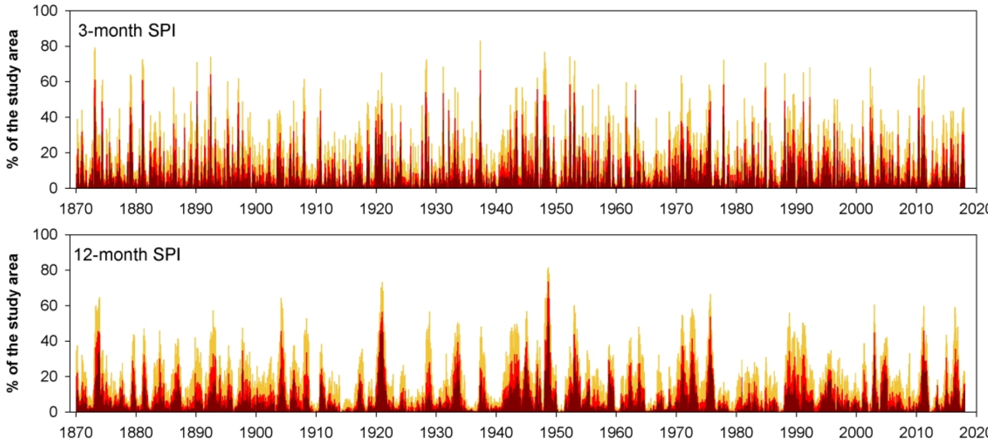

Figure 8: Evolution of the European land area impacted by mild (orange), moderate (red) and severe droughts (dark read) from 1871 to 2018.

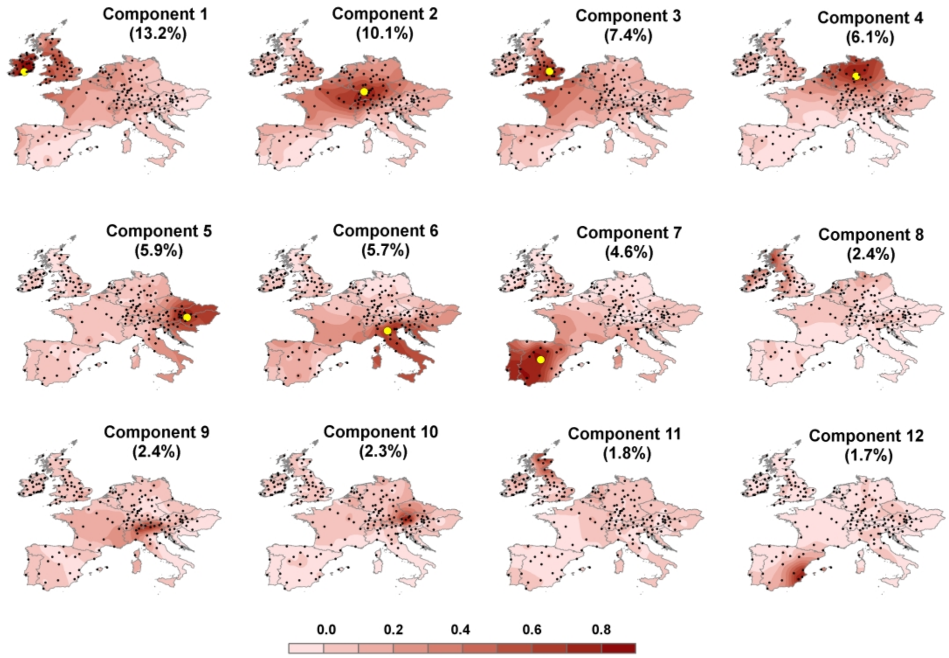

Figure 9: Spatial distribution of the loadings from PCA using SPI-12 series for the period 1871-2018. Components 1 to 12 are shown. The proportion of variance explained by each component is also included. Yellow points represent the location of the most representative meteorological station.

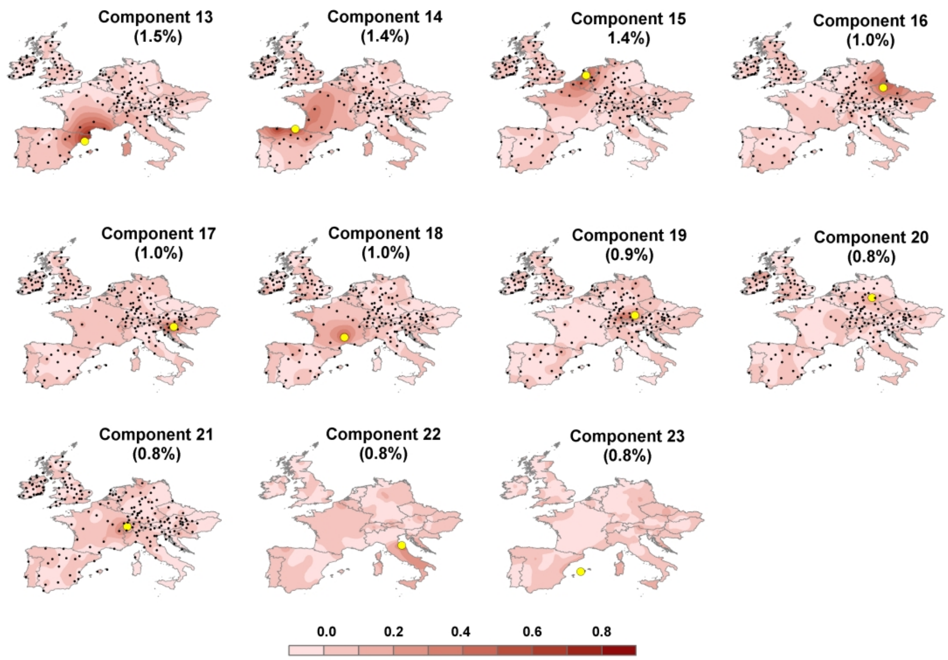

Figure 9 cont.: Spatial distribution of the loadings from PCA using SPI-12 series for the period 1871-2018. Components 13 to 23 are shown. The proportion of variance explained by each component is also included. Yellow points represent the location of the most representative meteorological station.

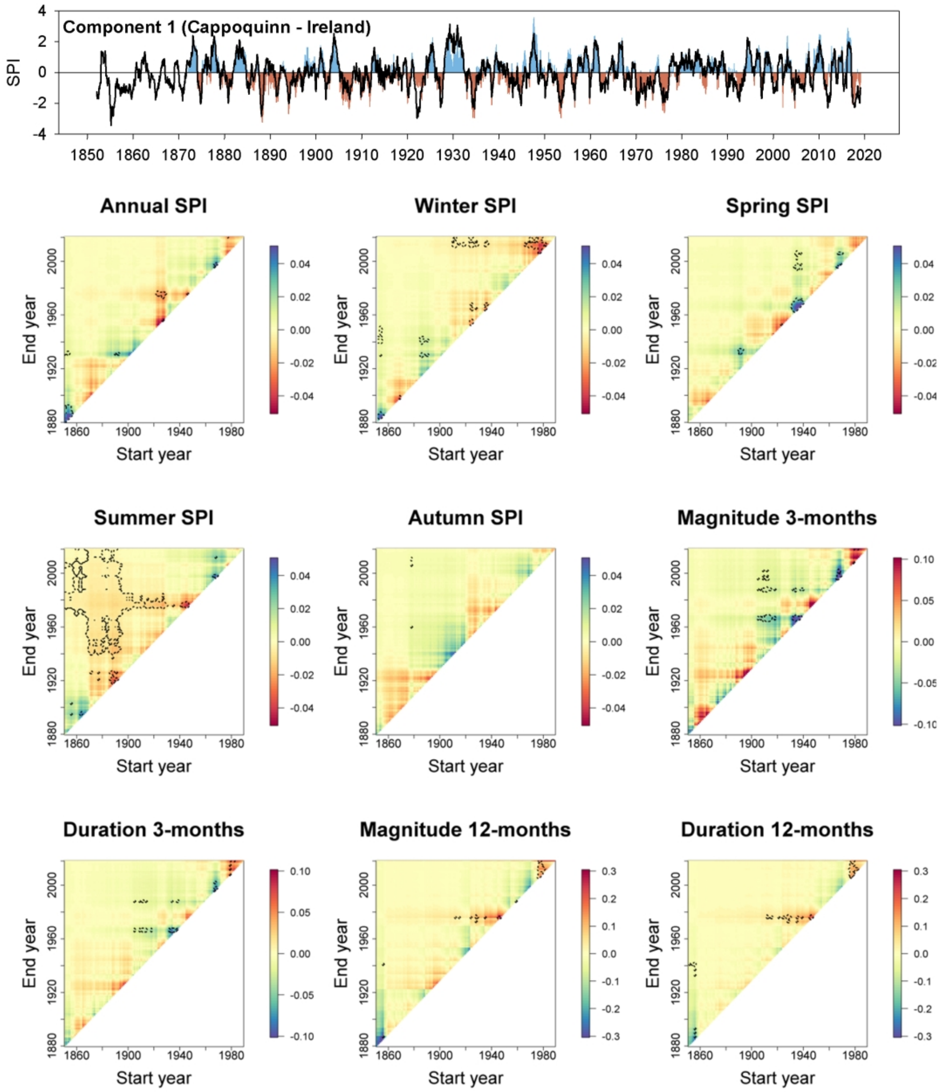

Figure 10: Temporal evolution of the SPI-12 series of component 1 in color and the series of the most representative station (black line). The correlation between the series of the component and the series of the station is r = 0.85. Also shown are heat maps of 30-year running trends in annual and seasonal SPI and 3- and 12-month SPI drought duration and magnitude for the station of Cappoquin (Ireland). X and Y-axes indicate the start and end years, respectively, of the time slices for the running trend analysis. The scale indicates the magnitude of the trend based on the slope of the linear regression analysis. Dotted lines indicate periods with a significant trend ($p<0.05$).

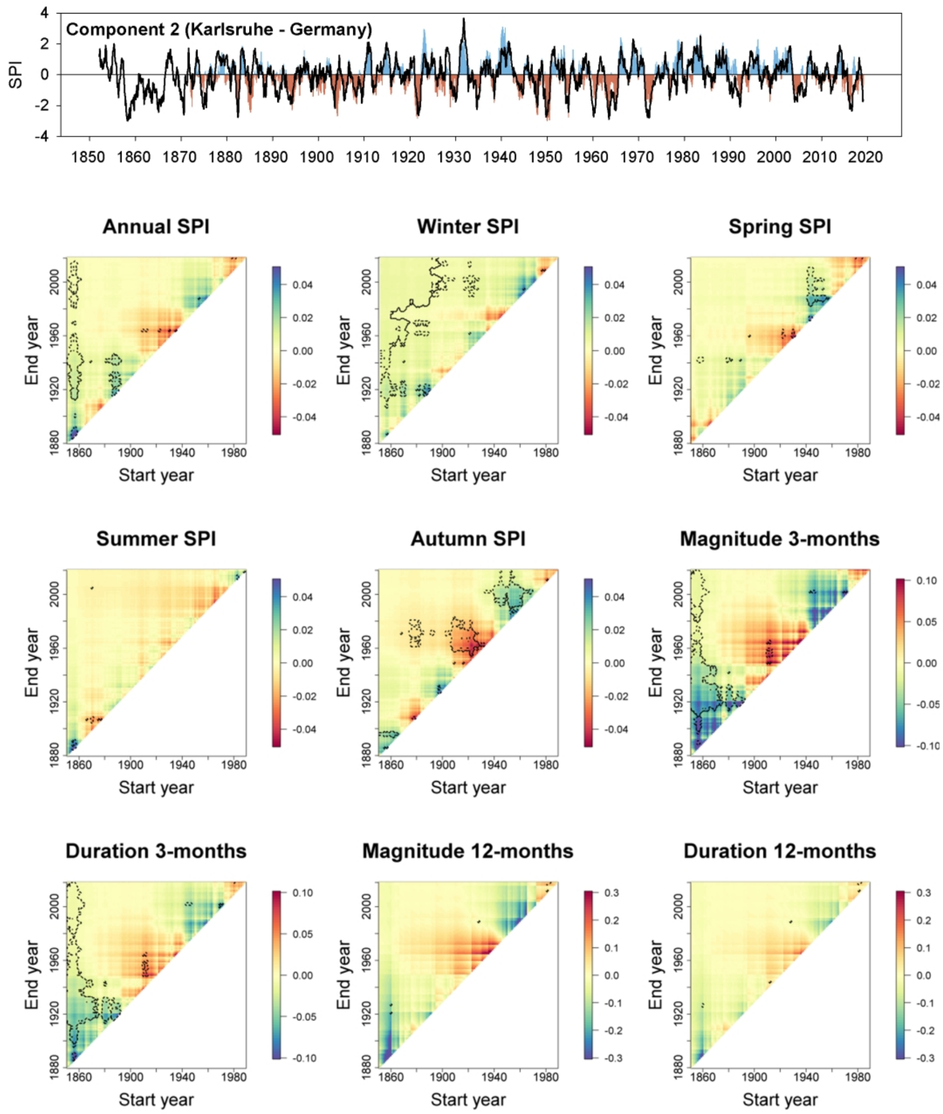

Figure 11: Temporal evolution of the SPI-12 series of component 2 in color and the series of the most representative station (black line). The correlation between the series of the component and the series of the station is r = 0.75. Also shown are heat maps of 30-year running trends in annual and seasonal SPI and 3- and 12-month SPI drought duration and magnitude for the station of Karlsruhe (Germany). X and Y-axes indicate the start and end years, respectively, of the time slices for the running trend analysis. The scale indicates the magnitude of the trend based on the slope of the linear regression analysis. Dotted lines indicate periods with a significant trend ($p<0.05$).

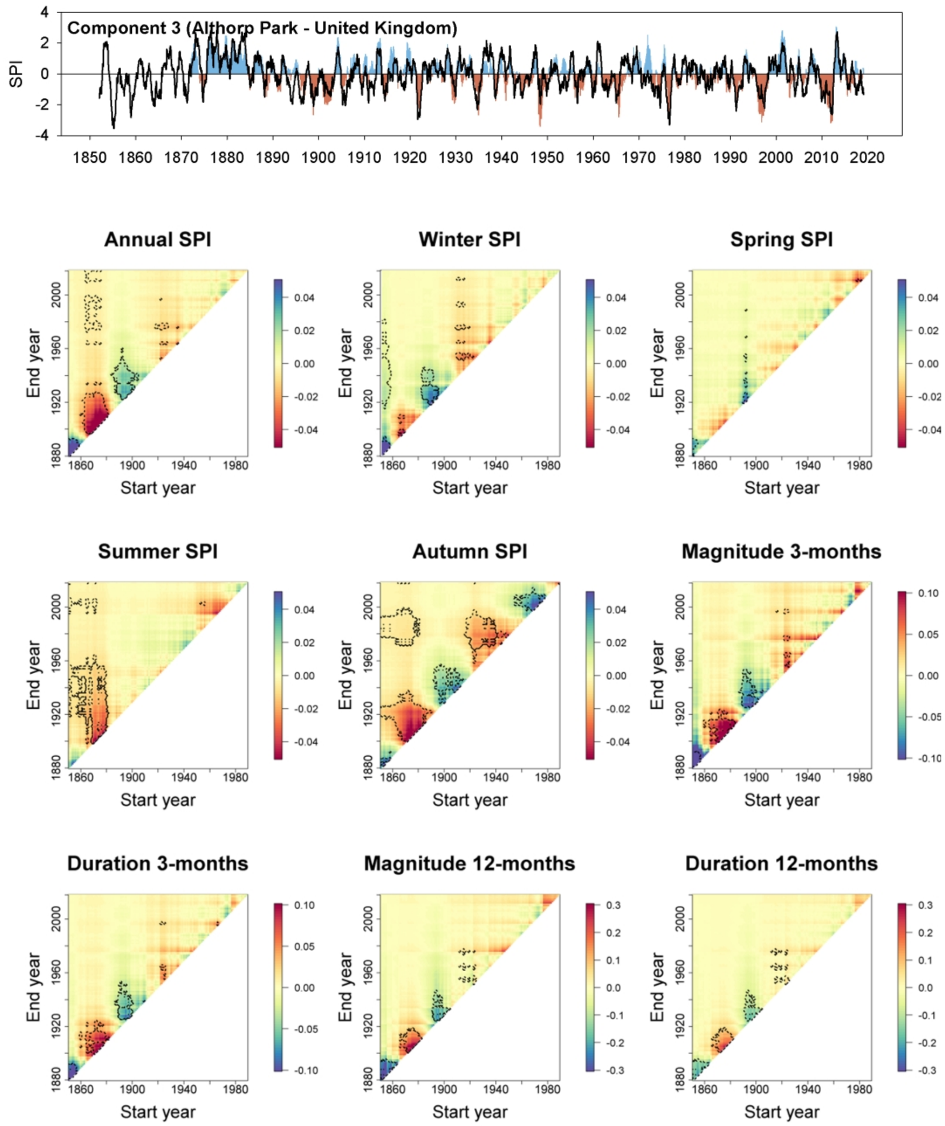

Figure 12: Temporal evolution of the SPI-12 series of component 3 in color and the series of the most representative station (black line). The correlation between the series of the component and the series of the station is r = 0.76. Also shown are heat maps of 30-year running trends in annual and seasonal SPI and 3- and 12-month SPI drought duration and magnitude for the station of Althorp Park (United Kingdom). X and Y-axes indicate the start and end years, respectively, of the time slices for the running trend analysis. The scale indicates the magnitude of the trend based on the slope of the linear regression analysis. Dotted lines indicate periods with a significant trend ($p<0.05$).

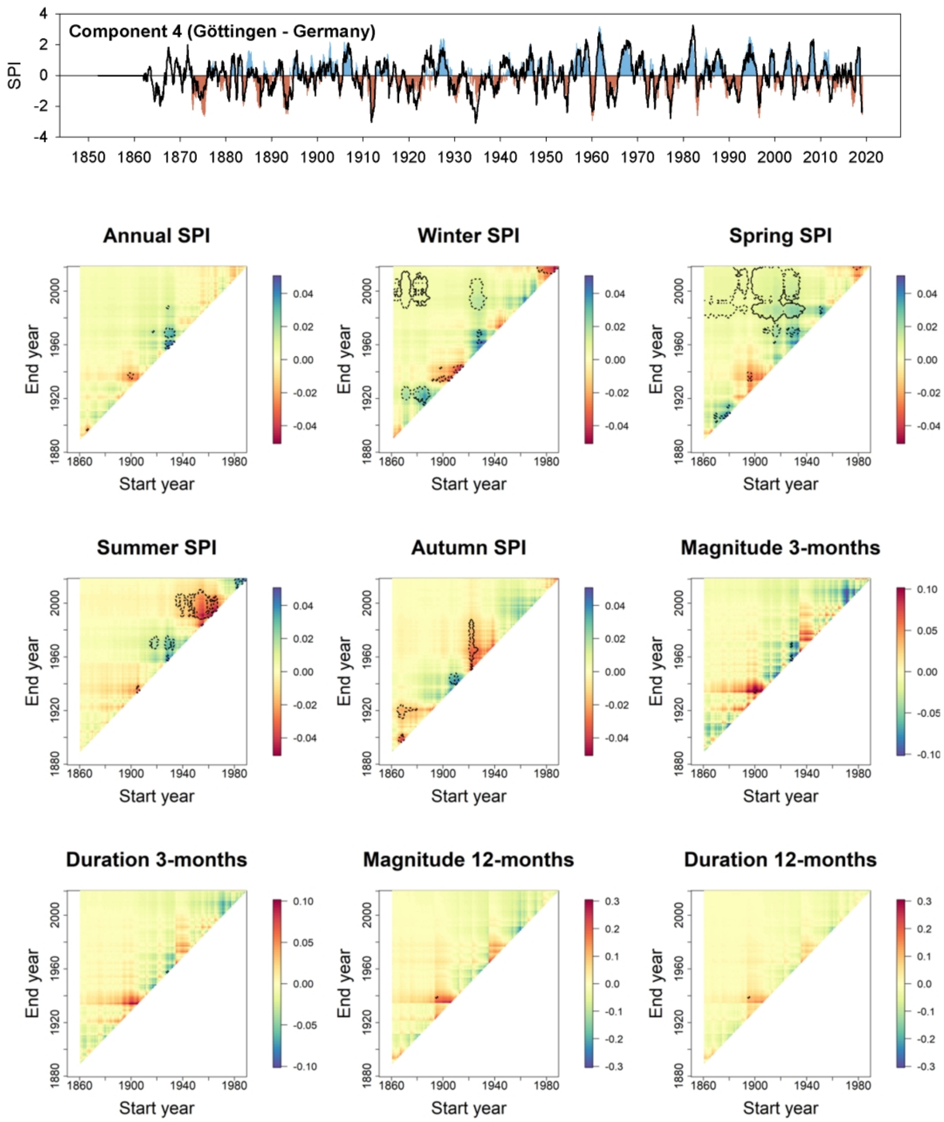

Figure 13: Temporal evolution of the SPI-12 series of component 4 in color and the series of the most representative station (black line). The correlation between the series of the component and the series of the station is r = 0.80. Also shown are heat maps of 30-year running trends in annual and seasonal SPI and 3- and 12-month SPI drought duration and magnitude for the station of Göttingen (Germany). X and Y-axes indicate the start and end years, respectively, of the time slices for the running trend analysis. The scale indicates the magnitude of the trend based on the slope of the linear regression analysis. Dotted lines indicate periods with a significant trend (p<0.05).

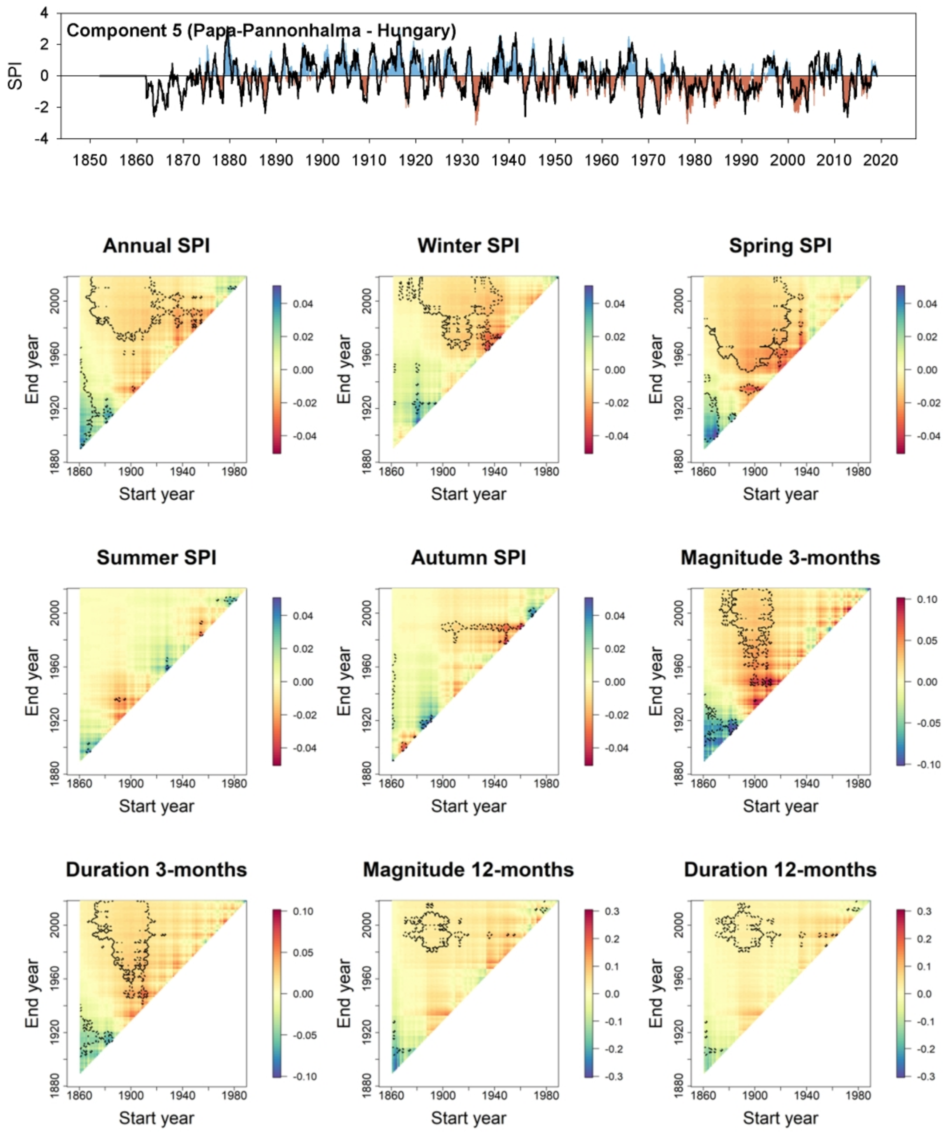

Figure 14: Temporal evolution of the SPI-12 series of component 5 in color and the series of the most representative station (black line). The correlation between the series of the component and the series of the station is r = 0.84. Also shown are heat maps of 30-year running trends in annual and seasonal SPI and 3- and 12-month SPI drought duration and magnitude for the station of Papa-Pannonhalma (Hungary). X and Y-axes indicate the start and end years, respectively, of the time slices for the running trend analysis. The scale indicates the magnitude of the trend based on the slope of the linear regression analysis. Dotted lines indicate periods with a significant trend ($p<0.05$).

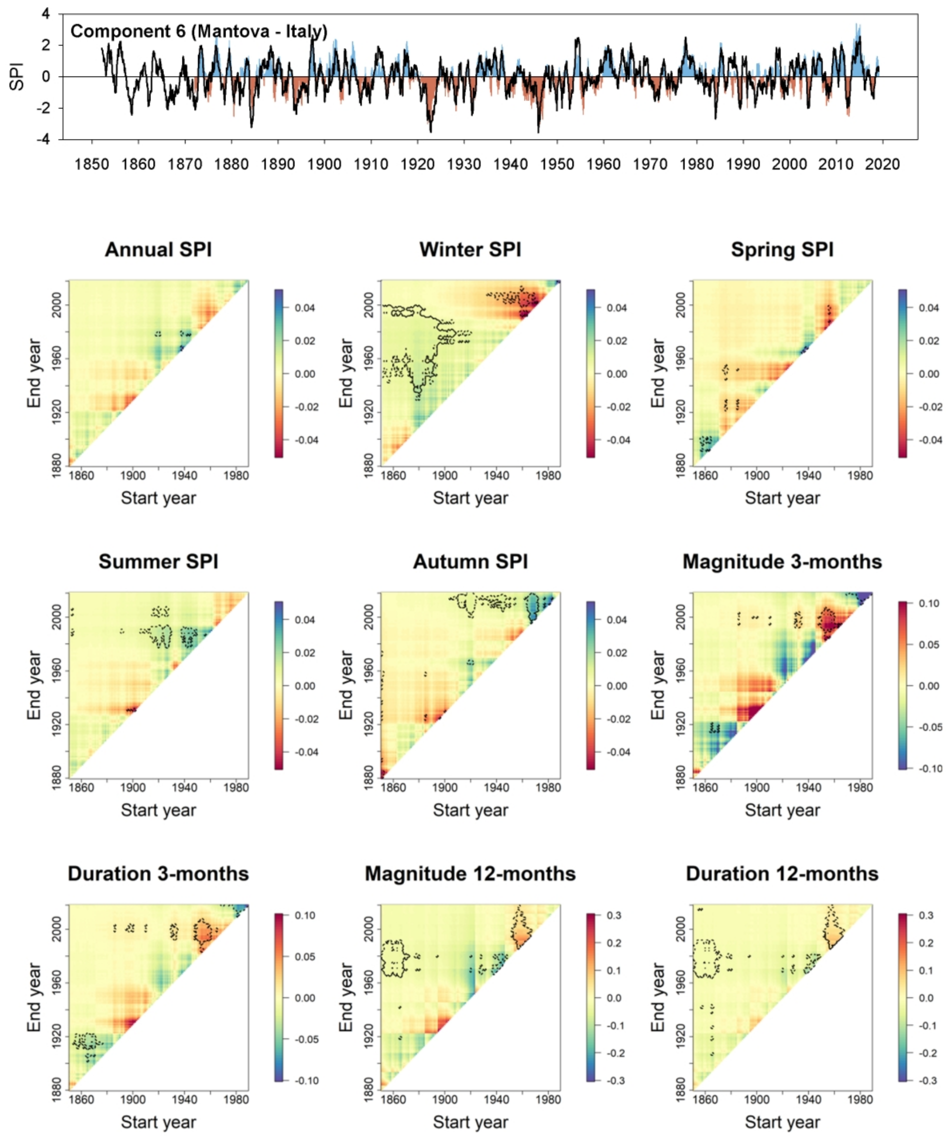

Figure 15: Temporal evolution of the SPI-12 series of component 6 in color and the series of the most representative station (black line). The correlation between the series of the component and the series of the station is r = 0.78. Also shown are heat maps of 30-year running trends in annual and seasonal SPI and 3- and 12-month SPI drought duration and magnitude for the station of Mantova (Italy). X and Y-axes indicate the start and end years, respectively, of the time slices for the running trend analysis. The scale indicates the magnitude of the trend based on the slope of the linear regression analysis. Dotted lines indicate periods with a significant trend (p<0.05).

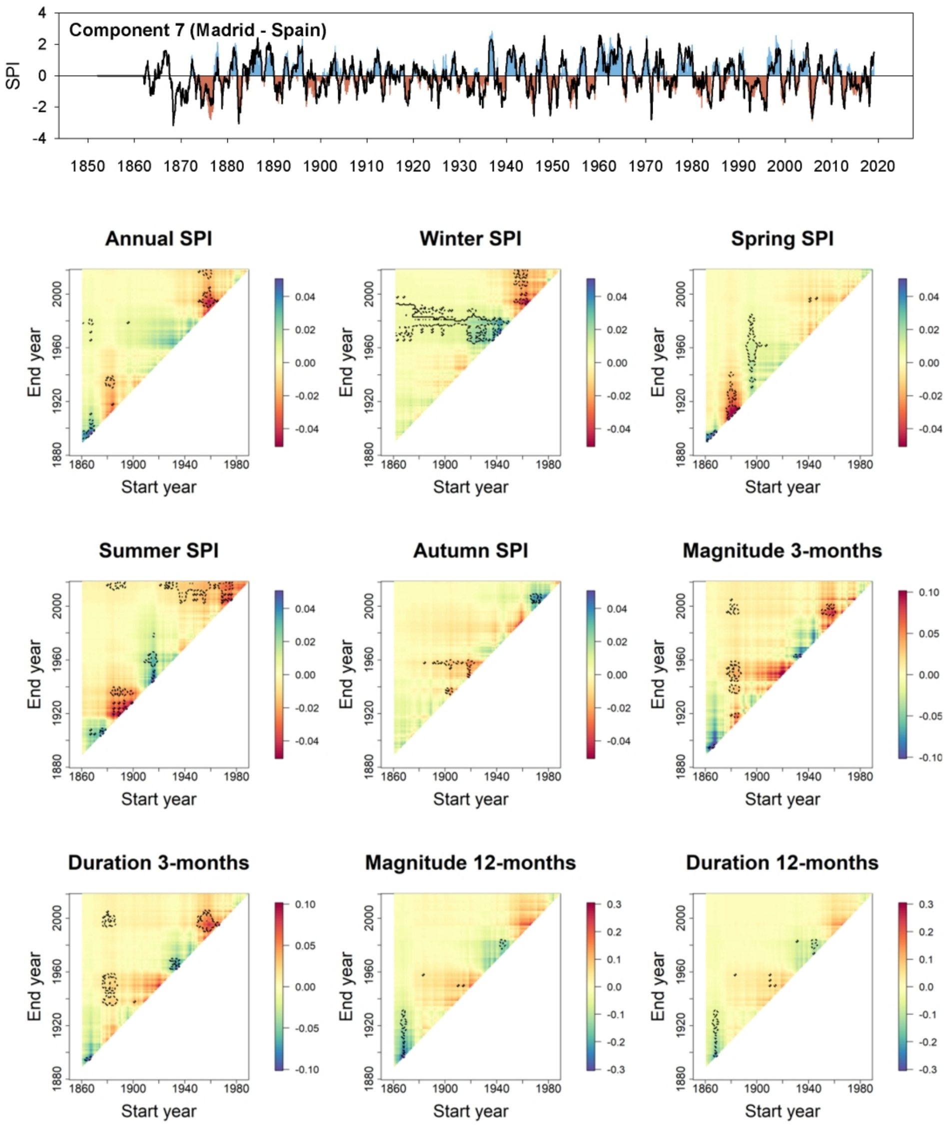

Figure 16: Temporal evolution of the SPI-12 series of component 7 in color and the series of the most representative station (black line). The correlation between the series of the component and the series of the station is r = 0.86. Also shown are heat maps of 30-year running trends in annual and seasonal SPI and 3- and 12-month SPI drought duration and magnitude for the station of Madrid (Spain). X and Y-axes indicate the start and end years, respectively, of the time slices for the running trend analysis. The scale indicates the magnitude of the trend based on the slope of the linear regression analysis. Dotted lines indicate periods with a significant trend (p<0.05).

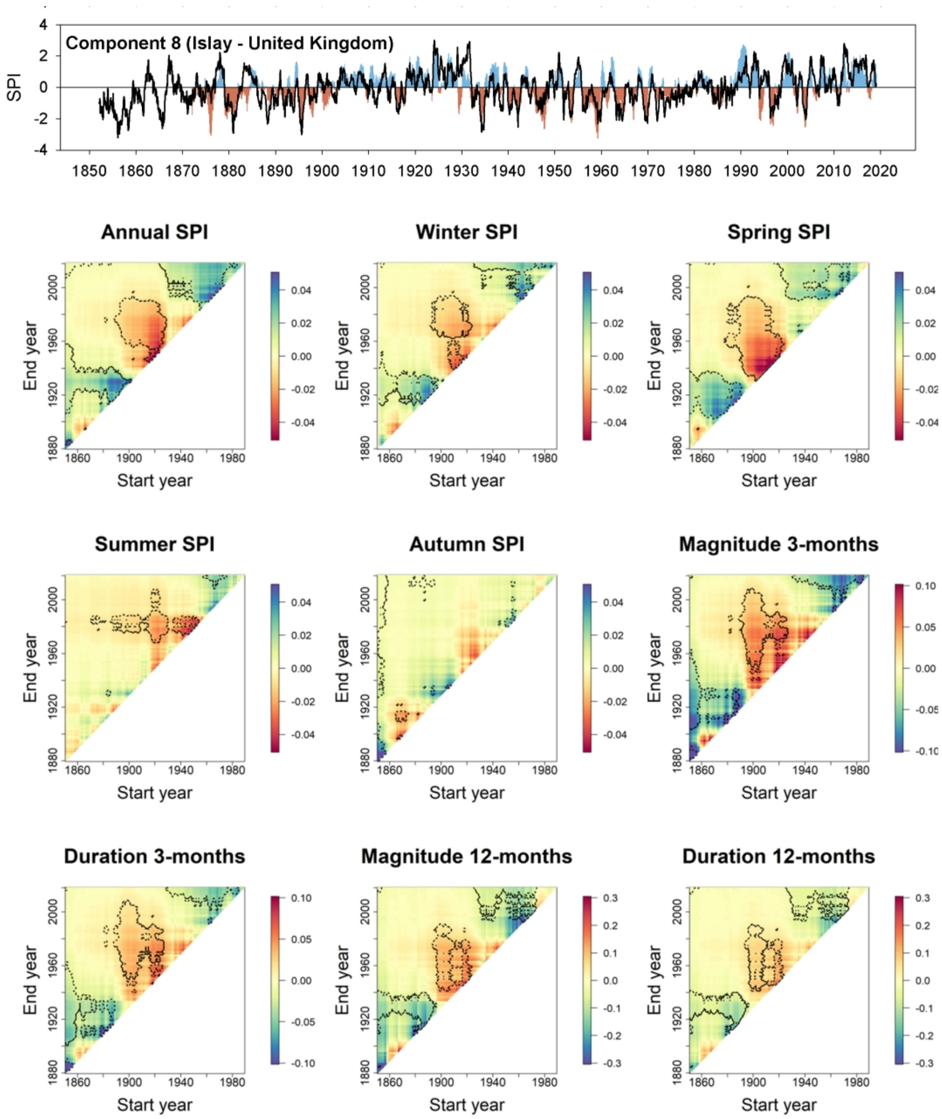

Figure 17: Temporal evolution of the SPI-12 series of component 8 in color and the series of the most representative station (black line). The correlation between the series of the component and the series of the station is r = 0.70. Also shown are heat maps of 30-year running trends in annual and seasonal SPI and 3- and 12-month SPI drought duration and magnitude for the station of Islay (United Kingdom). X and Y-axes indicate the start and end years, respectively, of the time slices for the running trend analysis. The scale indicates the magnitude of the trend based on the slope of the linear regression analysis. Dotted lines indicate periods with a significant trend (p<0.05).