Atmospheric Research 297 (2024) 107132

Contents lists available at ScienceDirect

Atmospheric Research

journal homepage: www.elsevier.com/locate/atmosres

Invited review article

Standardized Precipitation Index (SPI) evolution over the Iberian Peninsula during the 21st century

M.N. Lorenzo [a], H. Pereira [b], I. Alvarez [a,b,*], J.M. Dias [b]

[a] Centro de Investigación Mariña (CIM), Universidade de Vigo, Environmental Physics Laboratory (EphysLab), Campus da Auga, 32004 Ourense, Spain
[b] CESAM - Centre for Environmental and Marine Studies, Department of Physics, University of Aveiro, 3810-193 Aveiro, Portugal

ARTICLE INFO

Keywords:
Drought projections
Standardized Precipitation Index
Climate models

ABSTRACT

Droughts are important natural hazards that occur worldwide and can have severe and long-lasting impacts on humans and ecosystems. These phenomena are usually quantified by means of the so-called drought indices, which are indirect indicators based on climatic information. The Standardized Precipitation Index (SPI) is one of the most widely used indexes and this study attempts to characterize the occurrence and spatial variability of this index in the Iberian Peninsula (IP) over the 21st century. The SPI was calculated at two time scales (3 and 12 months), using simulations from the EURO-CORDEX project under two future scenarios (Representative Concentration Pathway (RCP) 4.5 and RCP 8.5) to analyze meteorological and hydrological droughts. Meteorological droughts (SPI-3) are expected to be less frequent but more intense and durable in the eastern IP, intensifying throughout the century and for the RCP 8.5 scenario. In the first decades of the 21st century, hydrological droughts (SPI-12) are projected to be more common and severe in the northwestern region of the IP for the RCP 4.5, and less frequent but more lasting in the other regions of IP for the RCP 8.5. As the century passes, the drought frequency and intensity experience a decrease in the RCP 4.5 scenario, and a slight increase in the RCP 8.5 scenario.

1. Introduction

Drought is one of the most complex and least understood weather phenomena affecting millions of people worldwide with severe impacts on nature and human life. Moreover, it tends to spread irregularly in time and space, and its effects are cumulative and can remain even after the event has ended (Tallaksen and Van Lanen, 2004; Wilhite, 2000; Wilhite et al., 2007). Therefore, understanding the characteristics and occurrences of droughts are major issues aiming to prevent and mitigate the consequences of future occurrences.

Droughts are usually classified into four categories, which include: meteorological, agricultural, hydrological and socio-economic (Mishra and Singh, 2010; Wilhite, 2000; Wilhite and Glantz, 1985). A meteorological drought can be defined as a lack of precipitation over a region for a period of time. An agricultural drought generally refers to a period of reduced soil moisture and consequent crop failure. A hydrological drought can be caused by a deficiency of streamflow and water storage. Finally, a socio-economic drought is associated with the inability of water resources systems to meet water demands, which affects society's productive and consumptive activities.

Over the years, there has been much discussion about which drought indices should be used based on climate applications, drought causes and effects, or the different levels of availability of information for each region. Different variables are commonly involved in drought assessments, such as precipitation, air temperature, or evaporation. Thus, different indices have been developed to investigate droughts in detail, some that use a single variable and others using several parameters.

The Standardized Precipitation Index (SPI), developed to define and monitor droughts (McKee et al., 1993), considers rain as the only variable to determine whether there is a deficit or excess of precipitation in a particular region and period under normal conditions (Hayes et al., 1999; Tadesse et al., 2004). It is one of the most widely-used indexes in Europe to monitor all types of drought (Hayes et al., 2011; Spinoni et al., 2015a), allowing to determine a rare drought or an anomalously wet event at a particular time scale for any location that has a precipitation record (Espinosa et al., 2019; Guttman, 1999; Lloyd-Hughes and Saunders, 2002; Lorenzo et al., 2022; Tošic and Unkaševic, 2014). This index has also been endorsed as the world standard for determining

* Corresponding author at: Centro de Investigación Mariña (CIM), Universidade de Vigo, Environmental Physics Laboratory (EphysLab), Campus da Auga, 32004 Ourense, Spain.

E-mail addresses: nlorenzo@uvigo.es (M.N. Lorenzo), humberto.pereira@ua.pt (H. Pereira), ialvarez@uvigo.es (I. Alvarez), joao.dias@ua.pt (J.M. Dias).

https://doi.org/10.1016/j.atmosres.2023.107132
Received 3 February 2023; Received in revised form 16 November 2023; Accepted 21 November 2023
Available online 25 November 2023

meteorological drought by the World Meteorological Organization (WMO, 2012).

The main advantage of SPI is that it can be calculated for a variety of time scales. This temporal flexibility allows SPI to monitor short-term water supplies, such as meteorological and soil moisture conditions, and long-term water resources, such as streamflow or reservoir levels. Thus, for example, an index of 3 months can be considered for meteorological drought and 12 months or more for hydrological analysis and applications. The main criticism of the SPI is that its calculation is based solely on precipitation data and consequently accounts for drought events induced by a lack of rainfall. The SPI does not consider other variables that may influence drought conditions as, for example, temperature. Nevertheless, this index is still one of the most widely used worldwide. In fact, this index has been used in several recent studies to analyze the different types of drought in the Iberian Peninsula, considering both the whole territory (Torres-Vázquez et al., 2023) and different regions individually (Gomez-Gomez et al., 2022; Ilarri et al., 2022; Lorenzo et al., 2022; Moreno et al., 2022), proving to be a useful tool.

Several recent studies have compared the ability of different drought indices which take temperature into account with indices that do not use this variable in their formulation, to identify impacts in different systems in the Iberian Peninsula (Gaitan et al., 2020; García-Valdecasas et al., 2021b; Páscoa et al., 2021; Vicente-Serrano et al., 2022; Vogel et al., 2021). The results of these studies are diverse, as the best drought index for detecting impacts can vary depending on the system analyzed showing spatial variations. Nevertheless, most of these studies found consistent droughts in time series and spatial patterns among indices, although more severe increases in drought events were detected using temperature.

The Iberian Peninsula (IP), as part of the Mediterranean area, is considered the European drought hotspot (Hoerling et al., 2012; Limones et al., 2022; Spinoni et al., 2015a, 2015b; Vargas and Paneque, 2019). Previous studies have shown that the IP suffered several droughts in the last decades, which have caused economic losses and threats to human survival (Ciais et al., 2005; Coll et al., 2017; Gouveia et al., 2012; Iglesias et al., 2009; Morales Gil et al., 2000; Naumann et al., 2015; Olcina Cantos, 2001; Páscoa et al., 2017; Ribeiro et al., 2019; Vicente-Serrano et al., 2014). These droughts can be considered regional in extent due to each region has specific climatic characteristics since the atmospheric conditions that result in deficiencies of precipitation are climate regime dependent. Thus, differences in drought trends were detected over the territory with a tendency for wet conditions over the northwestern region, while droughts tended to increase in the southern areas.

Future climate projections also suggest a decrease in precipitation and an increase in the frequency of drought events in the IP (Guerreiro et al., 2016, 2017; Heinrich and Gobiet, 2012; Santos et al., 2016; Spinoni et al., 2018, 2020; Stagge et al., 2015). These projections are commonly developed using regional climate models (RCMs), which are valuable tools to estimate the response of regional climates over the 21st century. However, although there is a clear consensus on the increase in future drought conditions, research conducted in this region regarding drought trends, frequency, or severity has shown different behaviors and patterns. Thus, several studies presented mixed results in terms of the intensification of drought conditions, projecting more severe or weaker drought in the same regions (García-Valdecasas et al., 2021a, 2021b; Guerreiro et al., 2017; Jenkins and Warren, 2014; Miró et al., 2021; Moemken et al., 2022; Orlowsky and Seneviratne, 2013; Spinoni et al., 2018, 2020; Stagge et al., 2015).

Possible causes for these differences could be the result of the period analyzed or even the index considered in the study. Previous works have investigated the role of record length on the indices used to identify droughts, founding that results strongly depend on the period selected to calibrate the index (Carbone et al., 2018; García-Valdecasas et al., 2021a; Um et al., 2017; Wu et al., 2005; Zhao and Dai, 2017). Ideally, a minimum of 20 to 30 years of monthly precipitation values are required (Guttman, 1999; McKee et al., 1993). Using different indices to identify droughts could also produce variable results due to the variables involved in calculating the drought indices (Dubrovsky et al., 2009; Loukas et al., 2008; Touma et al., 2015). Drought can be understood from different perspectives since its effects can vary between sectors, and the number of presently used indices in the literature reflects the diverse requirements of users (Lloyd-Hughes and Saunders, 2002; Zargar et al., 2011). Nevertheless, the different indices agreed to some extent indicating that drought events reflected by the different indices are often simultaneous and correlate well (Bouabdelli et al., 2022; Ojha et al., 2021; Tefera et al., 2019). Some drought studies focus on one or two characteristics, such as frequency or intensity (Orlowsky and Seneviratne, 2013; Spinoni et al., 2018, 2020; Stagge et al., 2015). However, considering a wider range of drought characteristics could contribute to a better assessment of drought trends (García-Valdecasas et al., 2021a, 2021b; Jenkins and Warren, 2014).

This study aims to characterize the occurrence and spatial variability of the SPI in the IP over the 21st century. This index can be considered a good indicator of drought and is one of the most widely used indices worldwide because it applies to all climate regimes. Five characteristics of drought shown by the SPI (frequency, duration, percentage of time in drought, intensity, and spatial extent) have been analyzed in parallel. As input data, RCM runs of EURO-CORDEX with a resolution of 0.11° have been used to analyze the historical scenario (1971–2005) and future simulations (2006–2075) of the RCP 4.5 and RCP 8.5 scenarios. The SPI was applied at the 3- and 12-month time scales to assess seasonal and annual drought patterns, evaluating meteorological and hydrological droughts across the region, respectively.

2. Data and methods

2.1. RCM outcomes

Daily near-surface precipitation data from the EURO-CORDEX project (http://www.euro-cordex.net/) were selected to compute the SPI over the IP (Fig. 1). The EURO-CORDEX initiative offers the results of model simulations over Europe considering global climate long-term simulations (up to the year 2100) from the Coupled Model Intercomparison Project Phase 5 (CMIP5) (Jacob et al., 2014; Taylor et al., 2012).

Precipitation outputs were obtained from the fourth version of the Rossby Centre Regional Atmospheric Climate Model (RCA4) driven by five (CNRM-CM5, EC-EARTH-ICHEC, IPSL-CM5A-MR, HadGEM2-ES-MOHC, and MPI-ESM-LR) global climate models (GCMs) over the period 1971–2075 (Table 1). This selection was based on the fact that no other RCM from the EURO-CORDEX project has downscaled any large fraction of the CMIP5 GCMs at 0.11° resolution (around 12.5 Km). In addition, precipitation simulations from this RCM have been previously used in the area under study (Lorenzo and Alvarez, 2020). These authors analyzed different precipitation indices over Spain using the same simulations as this study from the EURO-CORDEX project. They found that the RCA4 model was able to properly represent the spatial distribution of the precipitation over the territory for a control period (1971–2000). They found an acceptable match between model results and observations, stating a clear confidence in using these RCMs to perform future climate simulations over the IP.

These precipitation results were evaluated considering a multi-model ensemble with the same model weight (García-Valdecasas et al., 2021a; Moemken et al., 2022). We analyzed the models' historical period (1971–2005) and the future simulations for 2006–2075 under the emission scenarios RCP 4.5 and RCP 8.5. The future period was divided into two periods of 35 years (2006–2040 and 2041–2075) for comparison with the historical one. Climate projections for RCP 4.5 and RCP 8.5 scenarios are based on greenhouse gas emission scenarios corresponding to the stabilization of radiative forcing after the 21st century at 4.5 W/m^2 (RCP4.5) and 8.5 W/m^2 (RCP8.5) (Moss et al., 2010).

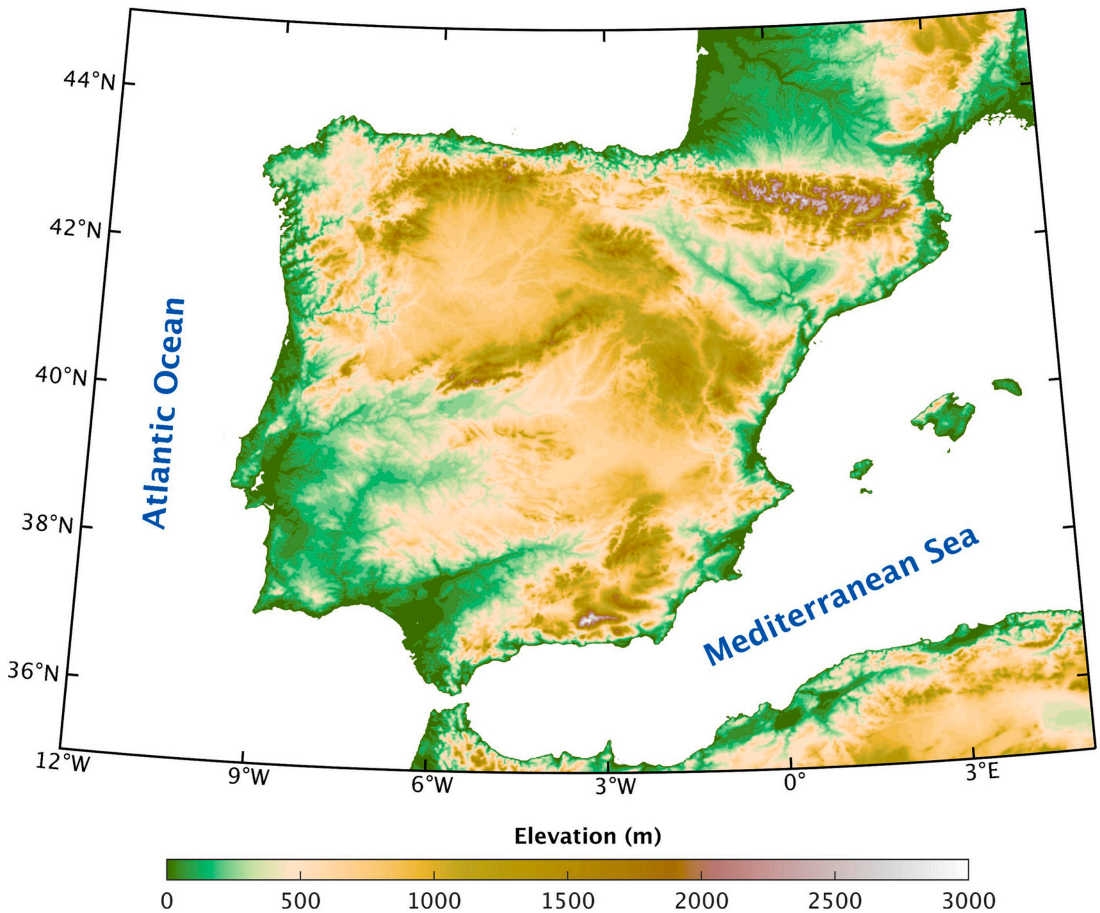

Fig. 1. Map of the study area.

Table 1
Models used in this study.

GCM	RCM
CNRM-CM5 EC-EARTH ICHEC IPSL-CM5A-MR HadGEM2-ES-MOHC MPI-ESM-LR	RCA4

2.2. Standardized Precipitation Index (SPI)

The SPI was used to characterize drought (McKee et al., 1993). This index evaluates drought conditions based only on precipitation and has proven to be effective for analyzing wet and dry periods (Espinosa et al., 2019; Guttman,1999; Lloyd-Hughes and Saunders, 2002; Lorenzo et al., 2022; Tošic and Unkaševic, 2014). The SPI method stands out for its speed, great approximation in drought analysis, simplicity, and minimal data requirement (Guttman, 1999; Ji and Peters, 2003; Keyantash and Dracup, 2002).

Two different time scales of 3- (SPI-3) and 12- months (SPI-12) were analyzed to detect drought episodes at relatively short timescale and long-term patterns for the study of episodes related to meteorological and hydrological droughts respectively (Mishra and Singh, 2010; Spinoni et al., 2015a). The SPI for the recent past (1971–2005) and future periods (2006–2040 and 2041–2075) was estimated separately (García-Valdecasas et al., 2021a). The period 1971–2005 was used as a reference period, and future scenarios were compared to this historical period.

A drought event was defined as the sum of consecutive months in which the SPI falls below a certain threshold for at least two consecutive months. In this study, a drought event starts when the SPI is equal to or below −1.0 and ends with the first positive SPI. After calculating the SPI and defining a drought event, drought metrics were analyzed using five characteristics: frequency, duration, percent time, intensity, and spatial extent. Drought frequency was calculated as the number of events in a given period. The duration reflects the average length (in months) of drought events in this period, and the percent time in drought was defined as the fraction of the time in drought over the same period. Intensity corresponds to the cumulative SPI from all events. Thus, the more negative the value, the more intense the drought. Finally, the spatial extent was calculated by the percentage of grid points under drought related to the total number of grid points covering the whole IP.

The Mann-Kendall test (Kendall, 1975; Mann, 1945) is a non-parametric statistical method frequently used to quantify the significance of trends in a data series. It is widely used in hydrological and meteorological variables and is recommended by the WMO to analyze environmental datasets (Irannezhad et al., 2016; Nashwan and Shahid, 2019). In addition, this test was previously applied to analyze future SPI projections in different areas (Chim et al., 2021; Li et al., 2022; Zarch et al., 2015). Thus, this test was applied to identify trends in the increase and decrease of drought conditions at the two different time scales (2006–2040 and 2041–2075).

3. Results

3.1. SPI drought metrics for the recent past

Drought indicators in terms of frequency, duration, percent time, and intensity for the historical period (1971–2005) are presented in Fig. 2. White color in the scale represents the average value of each indicator

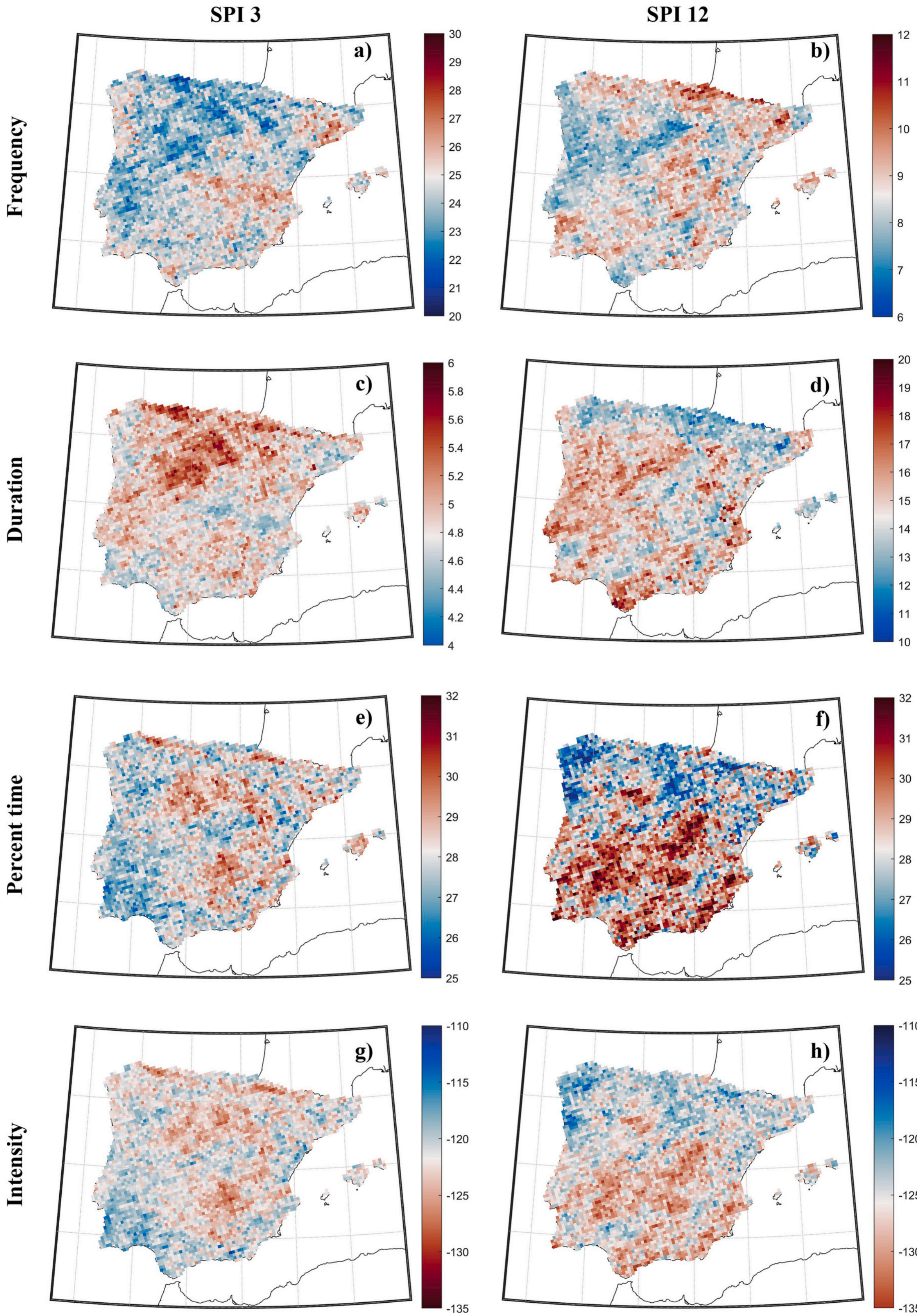

Fig. 2. Spatial distribution of SPI drought frequency (events), duration (months), percent time in drought (%), and intensity (no unit) across the study area computed at the 3-month and 12-month time scales for the historical period (1971–2005). The white color represents the average value of each indicator, and the red (blue) color represents the areas that are higher (lower) than the mean values. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

calculated for this period over the whole peninsula. Thus, red color is shown on the areas exceeding these mean values, indicating worse drought conditions in relation to these values.

Drought frequency showed a scattered spatial pattern for the SPI-3 and SPI-12, with fewer events in the last. At the 3-month time scale, drought events were found with a higher frequency all over the IP, showing an average value (white color) of around 25 events. The maximum occurrence (close to 30 events) was observed over the southeastern and northeastern areas (Fig. 2(a)). For events computed at the 12-month time scale (Fig. 2(b)), simulations revealed fewer events across the IP with an average value between 8 and 9 events. These events were longer than at the 3-month time scale. Thus, SPI-3 presented events with a duration ranging from 4 to 6 months, with the longest events (6 months) over the northern plateau and in different regions along the northern part of the IP (Fig. 2(c)), while SPI-12 showed events of longer duration, ranging from 10 to 20 months, with the highest values (20 months) in the southernmost tip of the peninsula (Fig. 2(d)).

The percentage of time spent in drought presented a similar average value for both time scales, around 28% (Fig. 2(e, f)). At the 3-month time scale (Fig. 2(e)), the northern and southern plateaus showed drought conditions for longer than the average value over the historical period. On the other hand, the 12-month time scale (Fig. 2(f)) showed more clear drought conditions. The whole southern area of the peninsula was affected by drought conditions for >30% of the time.

Regarding intensity, the spatial patterns for both time scales were similar to the ones corresponding to the percent time, showing the maximum intensities over the areas with a higher percentage of time spent in drought. Note that for this indicator, the red color corresponds to more negative values indicating higher intensity levels than the average situation. At SPI-3 (Fig. 2(g)), the events were more moderate than at SPI-12 (Fig. 2(h)), with a maximum intensity of −130 along the northern and southern plateau and some areas over the northern coast. At the 12-month time scale, the maximum values were observed over the southern region, reaching intensity levels more negative than −130.

3.2. SPI drought metrics for the future

3.2.1. Trends

The increasing or decreasing trends in the SPI and drought indicators were analyzed for future scenarios (RCP 4.5 and RCP 8.5) to assess drought distribution over the IP. Trends were analyzed over the period for which the models provide future predictions considering two future periods of 35 years each, 2006–2040 and 2041–2075.

For the first decades of the century, the trends for SPI-3 and drought metrics are presented as positive (red color) and negative (blue color) in Fig. 3. In general, a significant decreasing trend in the SPI-3 was observed throughout the IP for both scenarios (Fig. 3(a, b)), indicating an increase in drying conditions over the period. The drought frequency, duration, and percent time trends were positive for both scenarios (Fig. 3 (c-h)), although the RCP 4.5 presented a smaller number of grid points with significant positive trends. These significant trends were located mostly over the southern and northern IP. On the other hand, positive trends projected by the RCP 8.5 scenario were more homogeneous across the territory. The trends in the intensity were negative for both scenarios (Fig. 3(i, j)), covering almost the whole peninsula for the RCP 8.5 scenario and showing that drought could be aggravated. Note that, according to the definition of this indicator, the more negative the value, the more intense the drought.

Regarding SPI-12, Fig. 4 shows the trends for the first decades of the century for both scenarios. Significant trends were also observed at this time scale, with a spatial occurrence of positive/negative trends similar to the one observed for SPI-3 at each indicator. The area of significant trends also increased for the RCP 8.5 scenario for all indicators.

Trends over the period 2041–2075 for SPI-3 and SPI-12 are depicted in Figs. 5 and 6, respectively. Both time scales presented a slightly different spatial pattern compared to the 2006–2040 maps. Trends for SPI-3 under the RCP 4.5 scenario (Fig. 5 (a)) showed significant positive values spread in the northern area, mainly concentrated in the northeastern region. Significant negative values were also detected in a small southern region. For the RCP 8.5 scenario (Fig. 5 (b)), large areas of negative trends were present across the territory, indicating increased drying conditions. The spatial pattern corresponding to frequency, duration, and percent time showed scarce significant positive trends dispersed across the peninsula for both scenarios (Fig. 5(c-h)). The trends obtained for intensity also presented a similar spatial occurrence to previous indicators, although in this case, with a negative sign (Fig. 5 (i, j)).

The spatial patterns obtained for SPI-12 (Fig. 6) were in good accordance with the corresponding spatial patterns for the SPI-3 (Fig. 5), although more significant points were found all over the territory for both scenarios. Trends of SPI-12 for the RCP 4.5 scenario (Fig. 6(a)) presented significant negative values in the southern area and positive ones located in the northwestern and northeastern regions, pointing to wetting conditions over the north. The RCP 8.5 scenario (Fig. 6(b)) presented more significant points, mostly negative all over the peninsula, except in a small part of the northeastern region. Trends obtained for frequency, duration, and percent time were positive (Fig. 6(c-h)). These significant trends were located mainly over the southern IP, although some areas of positive trends were also found in smaller regions scattered across the territory. As previously mentioned, the area with significant trends is larger for the RCP 8.5 scenario, with positive values mainly concentrated over the southeastern region. On the other hand, the spatial pattern of intensity trends (Fig. 6(i, j) also followed the other indicators, although the sign of the trends was negative here. The generalized trends in the SPI at the meteorological and hydrological scales indicated a clear intensification of drought conditions in a large part of the IP during 2006–2040, more pronounced in the RCP 8.5. Trends for 2041–2075 presented a different behavior showing a significant increase in drought conditions, mainly in the southeastern area.

3.2.2. Future changes

To better identify future changes in drought conditions over the 21st century, changes relative to a baseline were analyzed, considering 1971–2005 as the reference period and two future periods of 35 years each, 2006–2040 and 2041–2075. Changes in drought metrics at the SPI-3 for the first decades of the century are shown in Fig. 7. The models' simulations projected increases and decreases (between −20% to 20%) in the number of events throughout the territory for the two RCP scenarios (Fig. 7(a, b)). For RCP 4.5, the higher frequency was observed mainly at the western IP and some scattered regions over the northern area. A reduction in events was detected over larger areas, with maximum decreases in the southeastern region. The RCP 8.5 scenario also showed a similar pattern with maximum values over the northern plateau. A widespread reduction in the frequency was observed over several areas.

Changes in the duration showed increases and decreases for both scenarios between −25% and 25% (Fig. 7(c, d)). Events lasted longer over the southern and eastern IP, whereas shorter events were predicted in northwestern regions. These spatial changes in frequency and duration suggest that a smaller number of longer drought episodes could occur over the eastern part of the IP, while drought in the western area would be more frequent but shorter. In addition, results for the RCP8.5 scenario indicate that the duration of meteorological droughts will increase over almost the entire region.

In general, changes in the percentage of time spent in drought ranged from −10% to 10% (Fig. 7(e, f)). For the RCP 4.5 scenario, negative changes were observed mainly over the northwestern area, meaning a lower percentage of time in drought conditions. On the other hand, although the RCP 8.5 showed scattered negative changes over most of the region, it revealed positive changes of >10% in the southwestern area. This spatial pattern was similar to the one corresponding to the intensity maps (Fig. 7(g, h)) for both scenarios. Thus, drought in the RCP

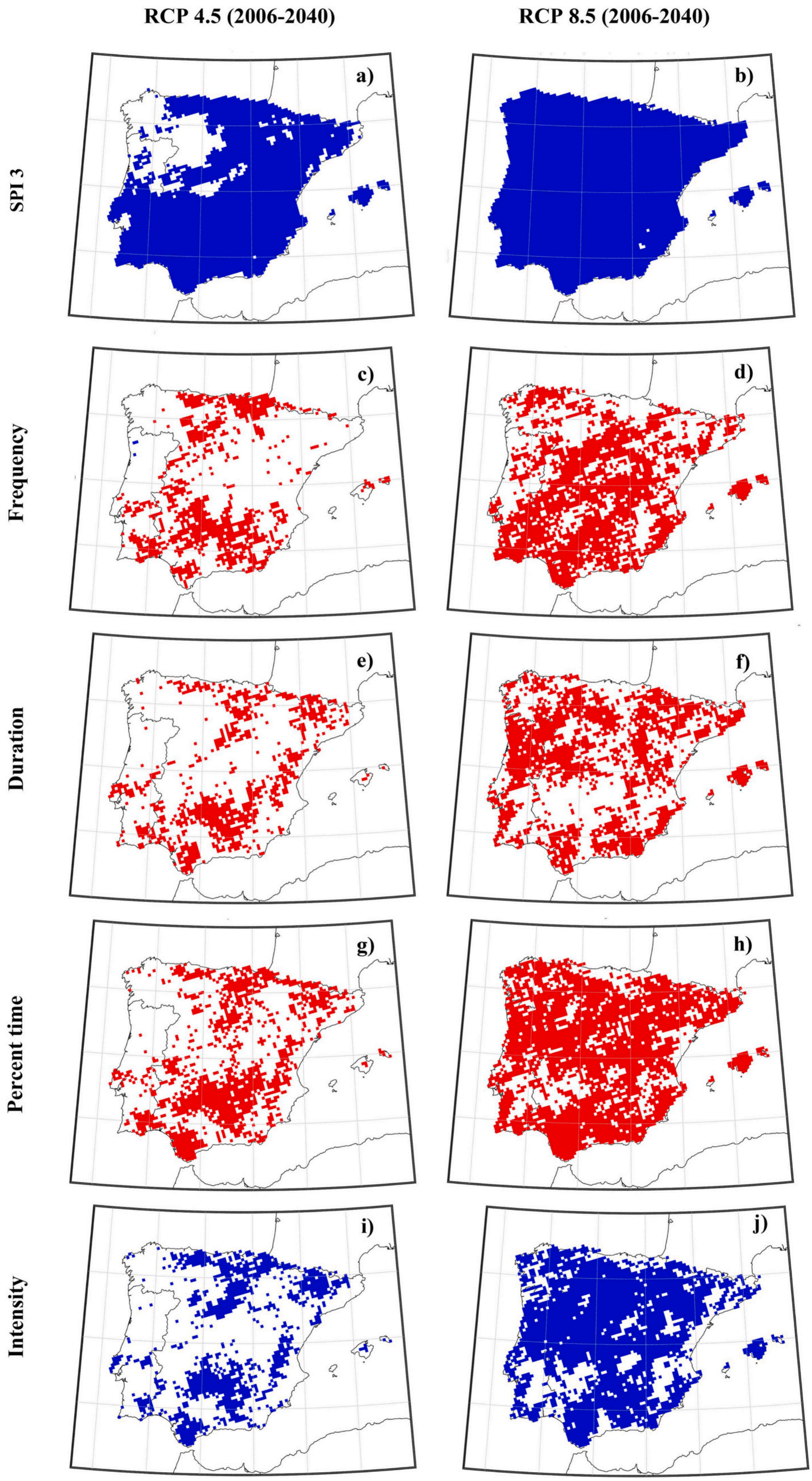

Fig. 3. Significant trends in SPI-3 (a, b), frequency (c, d), duration (e, f), percent time (g, h), and intensity (i, j) in the period 2006–2040 under RCP4.5 and RCP8.5. Positive (negative) trends are shown in red (blue). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

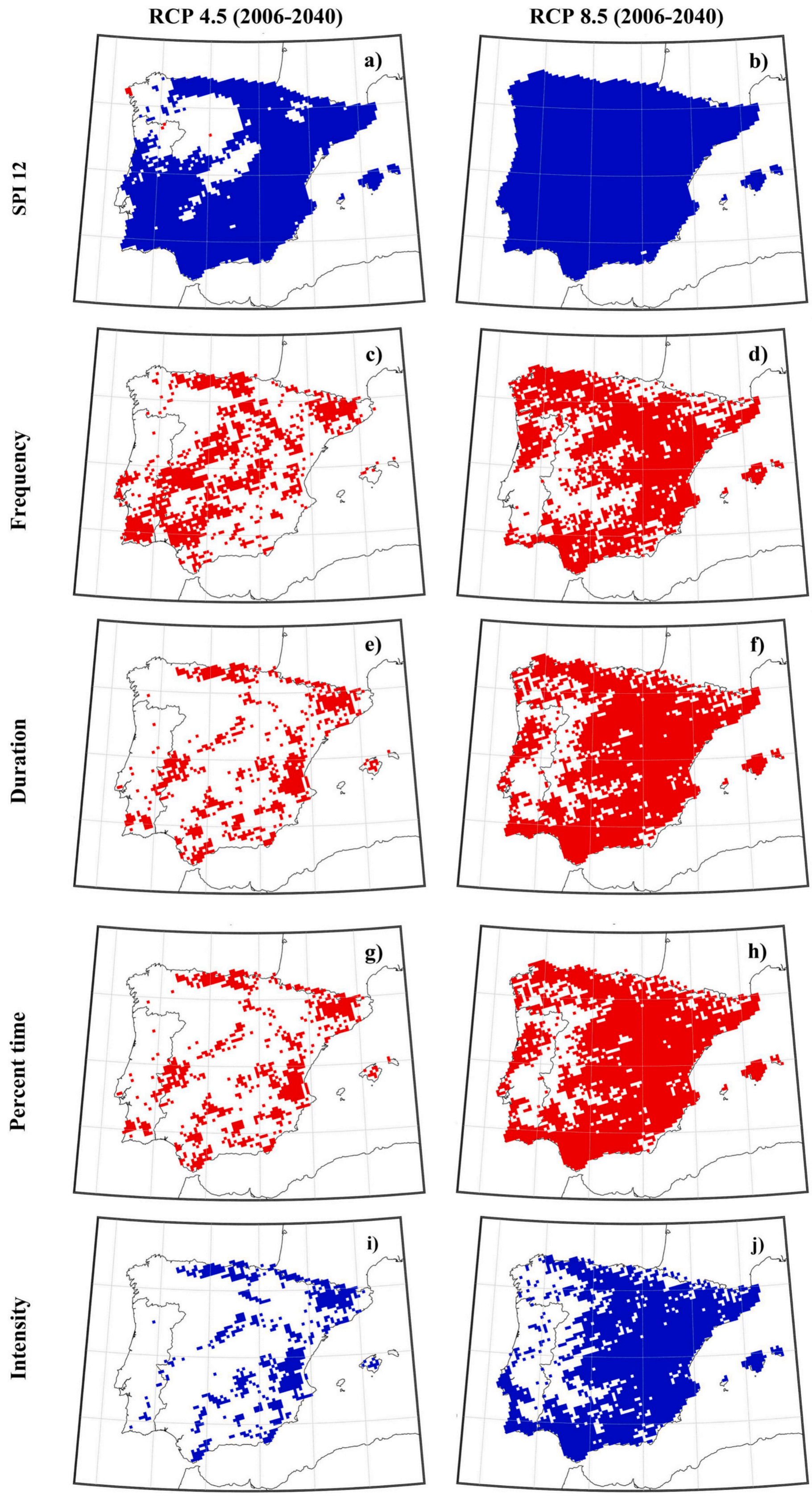

Fig. 4. Significant trends in SPI-12 (a, b), frequency (c, d), duration (e, f), percent time (g, h), and intensity (i, j) in the period 2006–2040 under RCP4.5 and RCP8.5. Positive (negative) trends are shown in red (blue). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

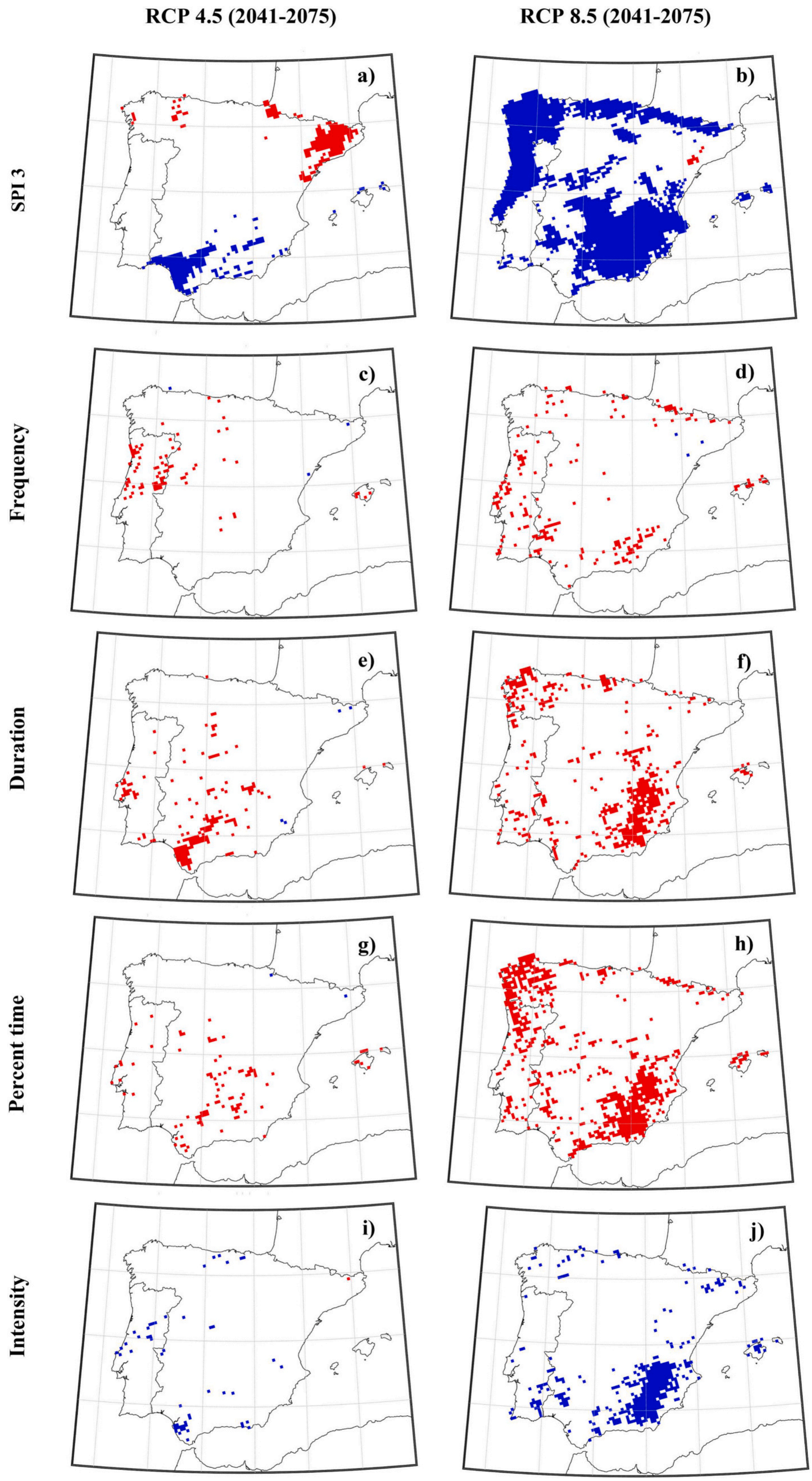

Fig. 5. Significant trends in SPI-3 (a, b), frequency (c, d), duration (e, f), percent time (g, h), and intensity (i, j) in the period 2041–2075 under RCP4.5 and RCP8.5. Positive (negative) trends are shown in red (blue). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

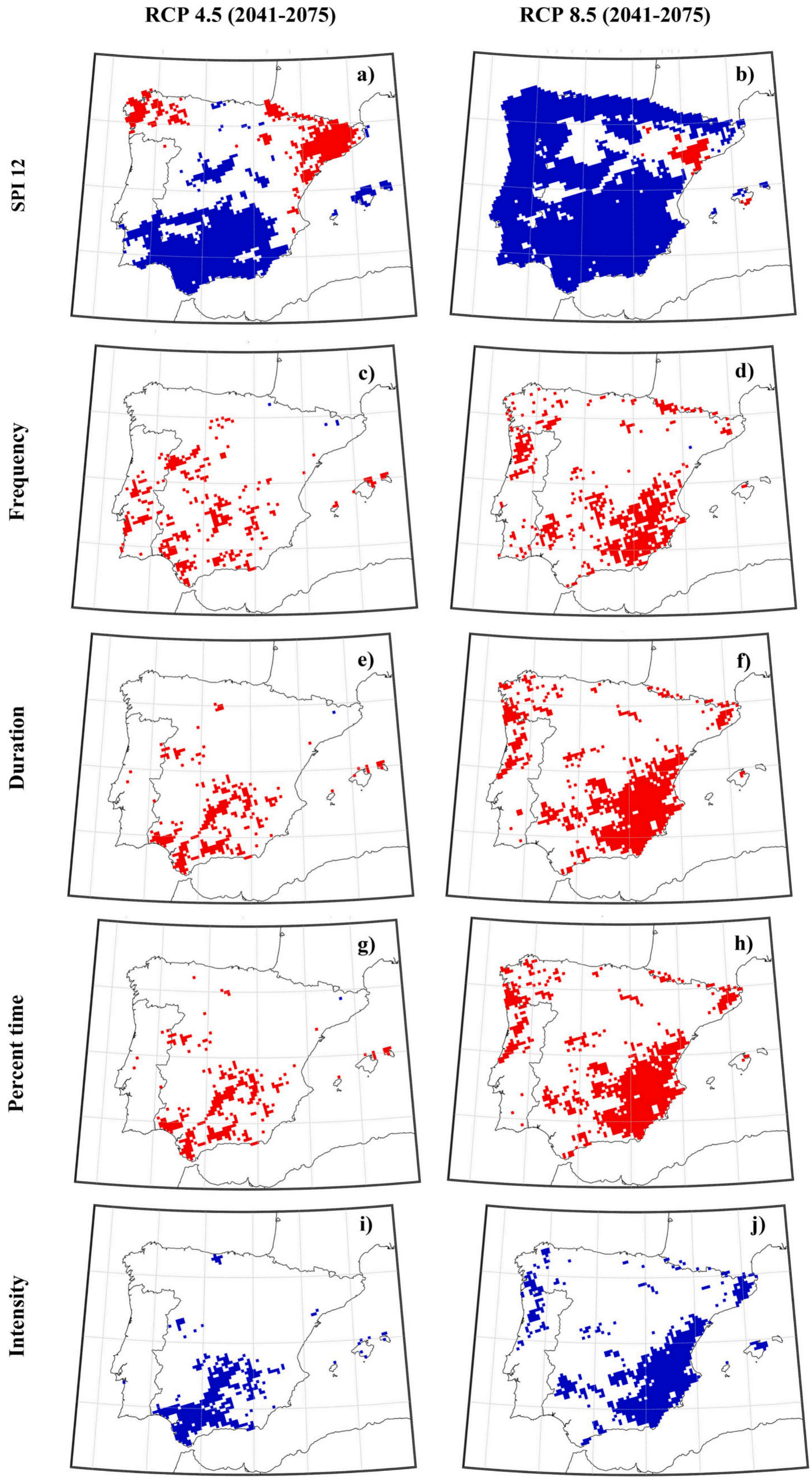

Fig. 6. Significant trends in SPI-12 (a, b), frequency (c, d), duration (e, f), percent time (g, h), and intensity (i, j) in the period 2041–2075 under RCP4.5 and RCP8.5. Positive (negative) trends are shown in red (blue). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

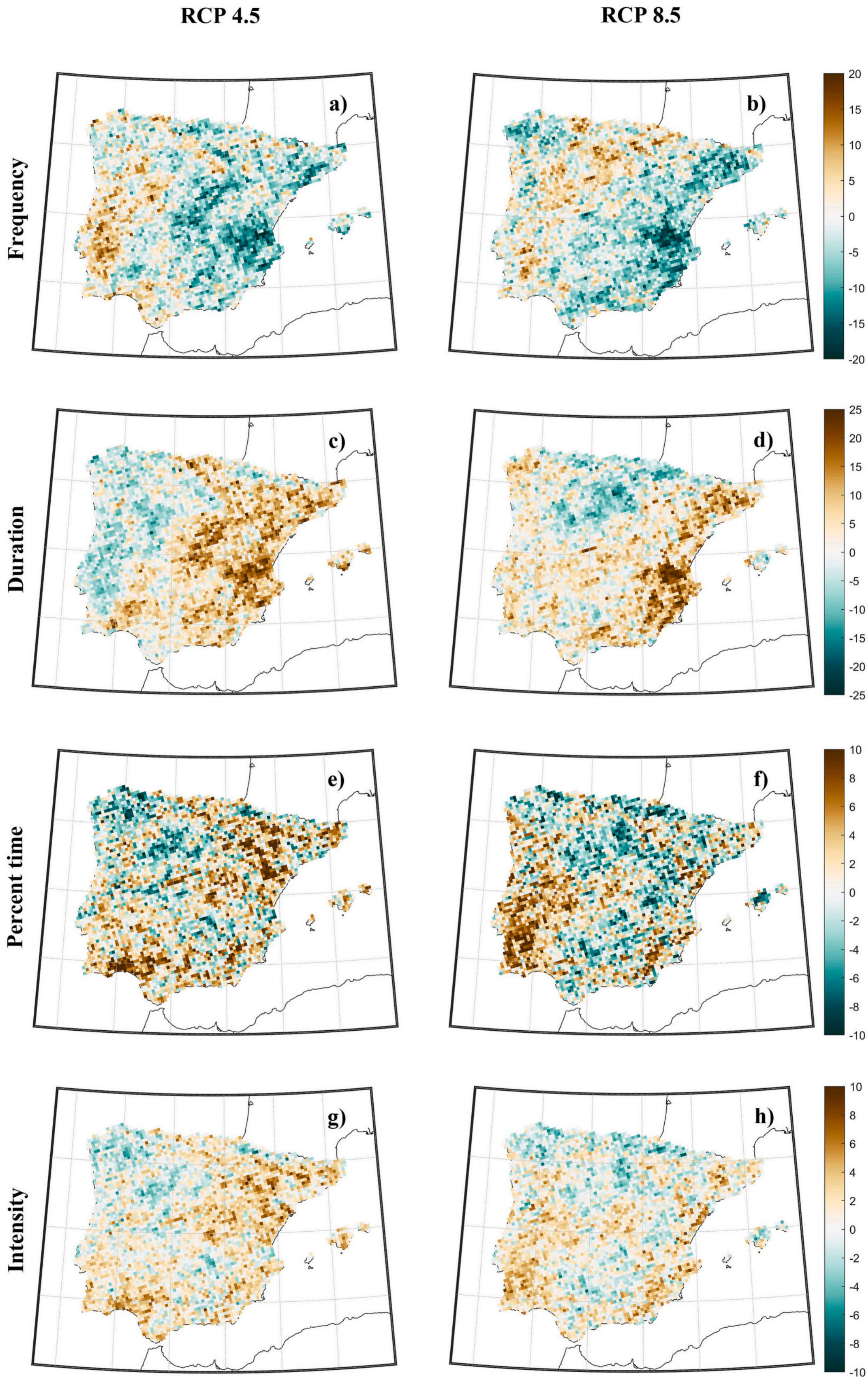

Fig. 7. Projected changes (in percent) relative to the reference period (1971–2005) of SPI-3 drought frequency (a, b), duration (c, d), percent time (e, f), and intensity (g, h) in the period (2006–2040) under RCP4.5 and RCP8.5.

4.5 scenario will intensify mainly in the southwestern and northeastern regions, with increases that may exceed 10%. For the RCP 8.5 scenario, this intensification appears to be concentrated in the southwestern part of the IP.

Fig. 8 shows the changes in drought metrics for the century's first decades at SPI-12, which correspond to hydrological drought. The RCP 4.5 scenario showed more frequent drought events in a large part of the IP with maximum increases of about 25% (Fig. 8(a)). On the contrary, RCP 8.5 scenario presented a generalized decline in frequency, except over some northwestern regions, with an increase in the number of events of 20–25% (Fig. 8(b)).

Changes in the duration were more marked than for the SPI-3 (meteorological drought) in a range of −30% to 30% (Fig. 8(c, d)). For the RCP 8.5 scenario, longer events than in the recent past will be observed in most IP, whereas the RCP 4.5 scenario indicated scattered decreases all over the IP. The analysis of the SPI-12 also revealed an opposite pattern for frequency and duration. Thus, the regions where a decrease in duration was observed agreed with those presenting more frequent drought events. As for SPI-3 (Fig. 7), these maps showed that more drought events with shorter duration could occur over different regions.

Changes in the percentage of time spent in drought presented a similar pattern for both scenarios (Fig. 8(e, f)). These changes were also more pronounced than for SPI-3, ranging from −20% to 20%. A large area over the northern part of the IP will be affected by drought conditions, while, on average, the southern area will present the opposite. The intensity maps (Fig. 8(g, h)) also presented similar spatial distributions for both scenarios, with more marked changes in the SPI-12 than in SPI-3. This spatial pattern was also very similar to the percent time maps, and the results showed that drought will be aggravated mainly over the northern area of the territory.

Overall, these results for the first decades of the 21st century revealed increases and decreases in the frequency of droughts at seasonal and annual scales for both scenarios (Figs. 7 and 8). In addition, the projected changes in frequency and duration suggested that shorter events will occur more frequently while longer events will be less numerous. Drought's characteristics also showed that the meteorological drought will intensify in the southwestern and northeastern regions and that more severe hydrological droughts will occur mainly in the northern area.

Regarding differences between RCP scenarios, similar patterns were obtained at the 3-month time scale with more frequent but shorter events in the western parts of the IP during the first decades of the century (Fig. 7(a-d)). Nevertheless, at the 12-month time scale, both scenarios showed an entirely different pattern with a sharp decline in frequency for the RCP 8.5 scenario (Fig. 8(a, b)). Thus, the number of droughts for this scenario could be much lower than the RCP 4.5 scenario, although these events may show an increase in duration (Fig. 8(c, d)). Changes for 2041–2075 at the 3-month time scale are presented in Fig. 9. Frequency maps (Fig. 9(a, b)) showed a similar pattern compared to 2006–2040 maps (Fig. 7(a, b)). A northwest-southeast gradient for both scenarios is obtained with the projected increases and decreases in the drought frequency. An increase in drought events was observed in the northwest, and a decline was detected in the southeast. The maximum values were found over the northern plateau, while the minimum ones were obtained over the southern plateau. The RCP 8.5 scenario revealed more pronounced changes than the RCP 4.5.

The duration maps (Fig. 9(c, d)) also showed a similar spatial pattern compared with the 2006–2040 period, with increases and decreases for both scenarios between −25% to 25%. These results revealed an increase in the duration over the southern and eastern regions, indicating marked increases over the southern plateau and the northeastern area for both scenarios. As for 2006–2040, the spatial distribution of the duration followed a pattern opposite to that of the frequency, indicating that shorter events could occur more frequently.

The percentage of time spent in drought increased and decreased all over the IP (Fig. 9(e, f)). The maps were similar, with changes between −10% and 10%. Both scenarios presented positive changes over most IP, but the RCP 8.5 map showed more marked changes. In terms of intensity, a pronounced increase throughout the IP was predicted, indicating that drought will be more severe (Fig. 9(g, h)). Overall, the results indicated that drought events at the 3-month time scale throughout the century (Fig. 7 and Fig. 9) are less frequent but longer-lasting over the eastern area.

Drought events at the 12-month time scale for the period 2041–2075 are shown in Fig. 10. Changes in frequency (Fig. 10(a, b)) presented a generalized decline for the RCP 4.5 scenario over the IP, except for the northern plateau where an increase in drought events was detected. This pattern contrasts with the one observed in Fig. 8(a), where SPI-12 showed a general increase in drought events over a large part of the IP. In addition, RCP 8.5 showed an increase in drought events in the northwestern area.

In terms of duration, decreases and increases ranging from −30% to 30% were found over the region (Fig. 10(c, d)). As in the previous cases (Figs. 7, 8, and 9), the duration maps showed an opposite pattern compared with the frequency maps, indicating that the frequency decreases when the duration increases. The RCP 4.5 scenario showed increases in many parts of the IP, with the highest values concentrated mainly along the Mediterranean and Atlantic coasts. This pattern also contrasts with the 2006–2040 map (Fig. 8(c)), with widespread decreases in the mean duration in almost the entire IP. On the other hand, the RCP 8.5 scenario projected longer events over the eastern areas following a similar pattern to the one observed in Fig. 8(d), although with less pronounced changes.

Changes in the percentage of time spent in drought presented a similar pattern to 2006–2040 (Fig. 8(e, f)), with the northern region under drought for a longer time (Fig. 10(e, f)). Yet, central and southern areas presented negative changes more prominent in the RCP 4.5 scenario. This result contrasts with the SPI-3 for 2041–2075 (Fig. 9), where the percentage of time spent in drought showed a generalized increase in most of the territory for both scenarios. Considerable increases in intensity were also found over the northern areas as occurred for the first decades of the century (Fig. 8(g, h)), indicating that drought will be aggravated in these regions (Fig. 10(g, h)).

In summary, droughts' conditions at the 12-month time scale presented a slightly different behavior along the century (Fig. 8 and Fig. 10), particularly for the RCP 4.5 scenario. Thus, under the moderate emission scenario RCP 4.5, less frequent events with an increase in duration over large parts of the IP were projected towards the end of the century. Moreover, the RCP 8.5 scenario presented a frequency increase over the century in agreement with the SPI-3 result (Fig. 7 and Fig. 9). The average annual spatial extent of drought was also analyzed over the territory to better estimate spatial and temporal changes in projection (Fig. 11). Drought extent from the SPI-3 during the first decades of the century (Fig. 11(a)) showed a positive increasing trend at the annual scale with a value around 4.6% per decade and 6.6% per decade for the RCP 4.5 and RCP 8.5 scenarios respectively. Drought covered a large part of the territory exceeding 50% of the extent for all years. For the period 2041–2075 (Fig. 11(b)) the increase in the average extent reached a similar value for both scenarios (2.3% per decade), lower than the observed for the first decades of the century. In addition, the SPI-3 indicated an area under drought higher than 60% for the whole period. The spatial distribution of drought from the SPI-12 also showed a positive trend for both scenarios all over the century. For the first decades of the century (Fig. 11(c)) the increase in the average extent reached 7.0% per decade and 8.2% per decade for the RCP 4.5 and RCP 8.5 scenarios respectively. Drought extensions showed an important increase during these years with values rising from 10% to almost 70% of the spatial extent. For the period 2041–2075 (Fig. 11(d)) trend values are lower but positive, reaching a value around 3.5% per decade for both scenarios. Changes in spatial extent followed a similar pattern to the first decades.

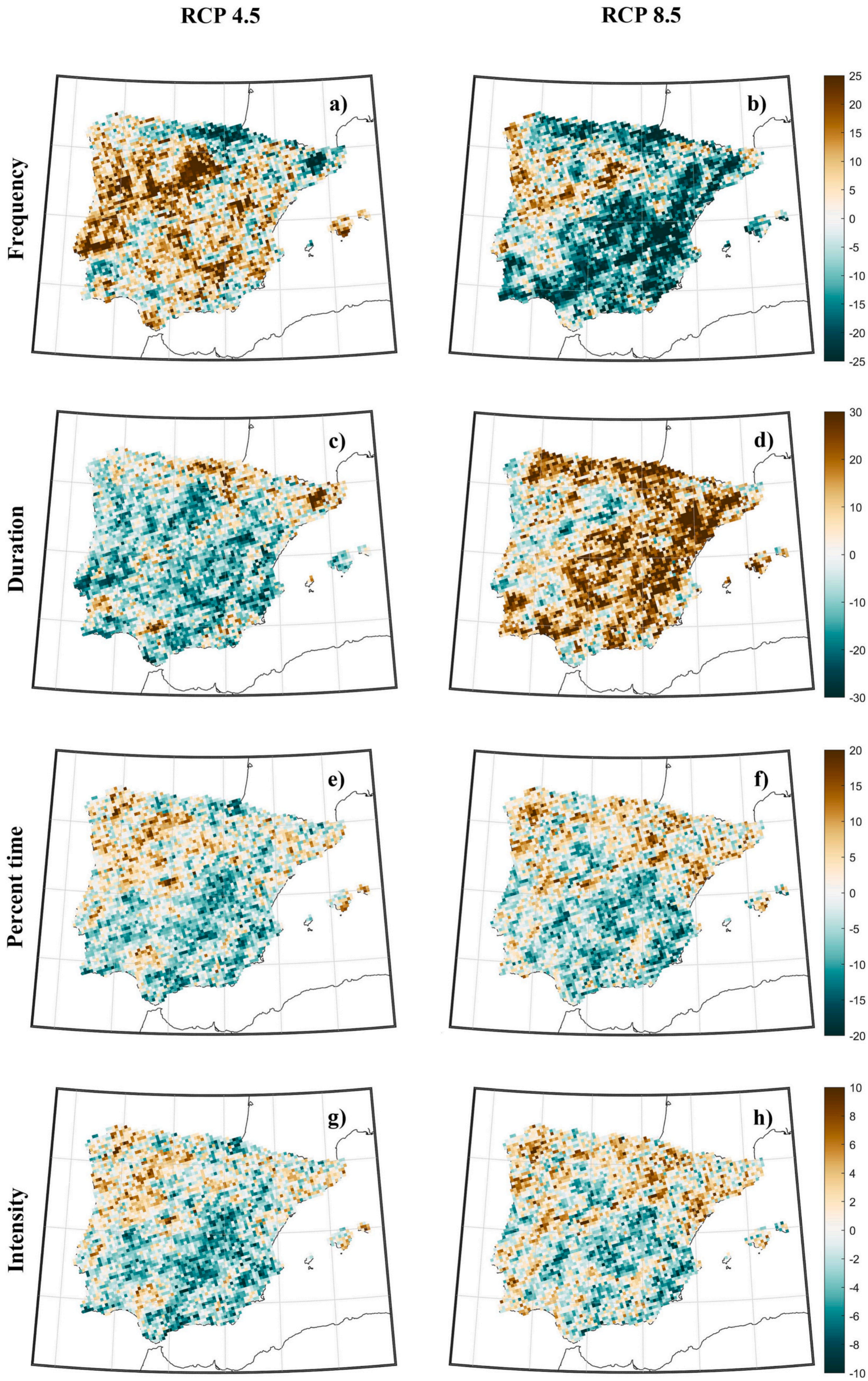

Fig. 8. Projected changes (in percent) relative to the reference period (1971–2005) of SPI-12 drought frequency (a, b), duration (c, d), percent time (e, f), and intensity (g, h) in the period (2006–2040) under RCP4.5 and RCP8.5.

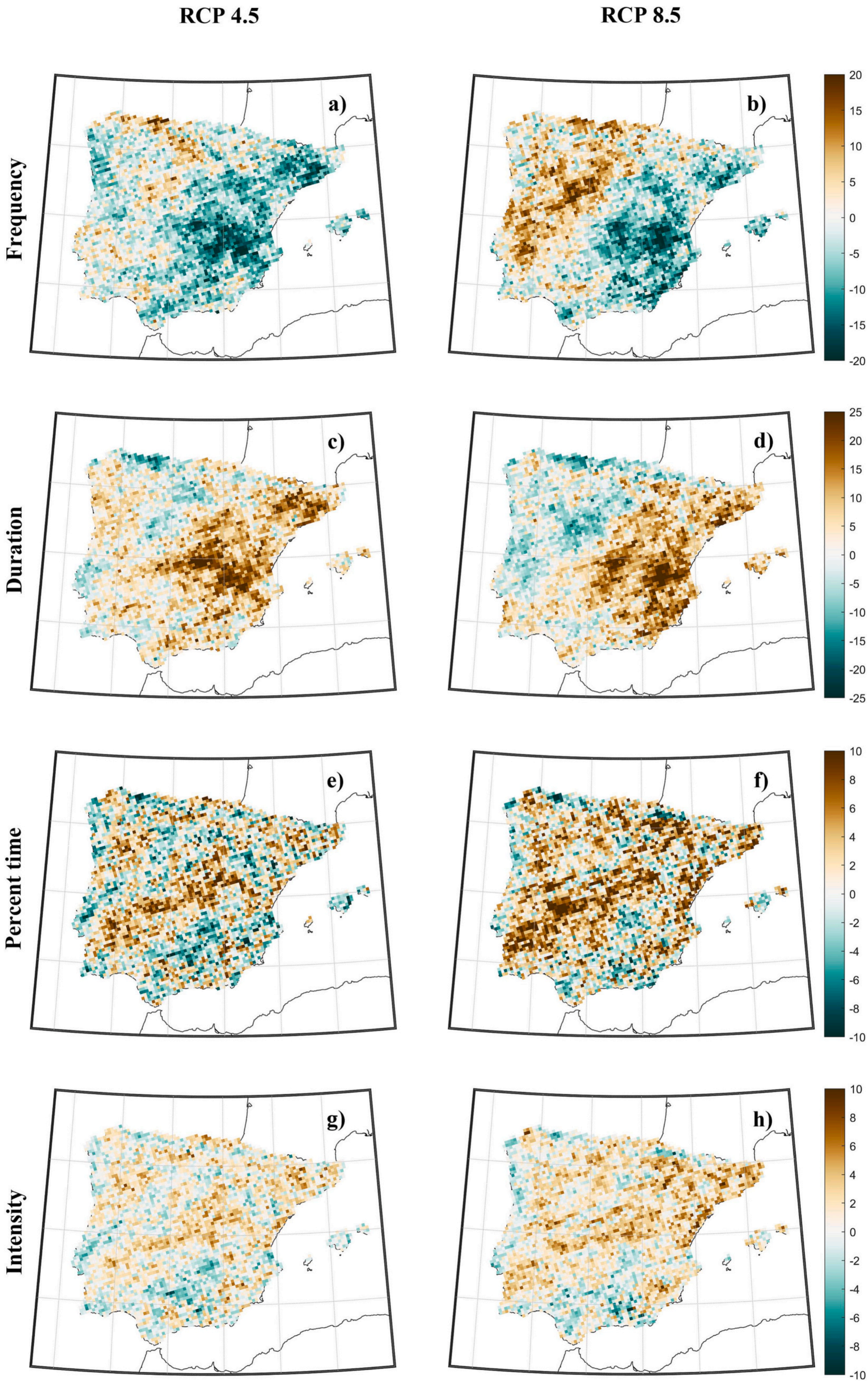

Fig. 9. Projected changes (in percent) relative to the reference period (1971–2005) of SPI-3 drought frequency (a, b), duration (c, d), percent time (e, f), and intensity (g, h) in the period (2041–2075) under RCP4.5 and RCP8.5.

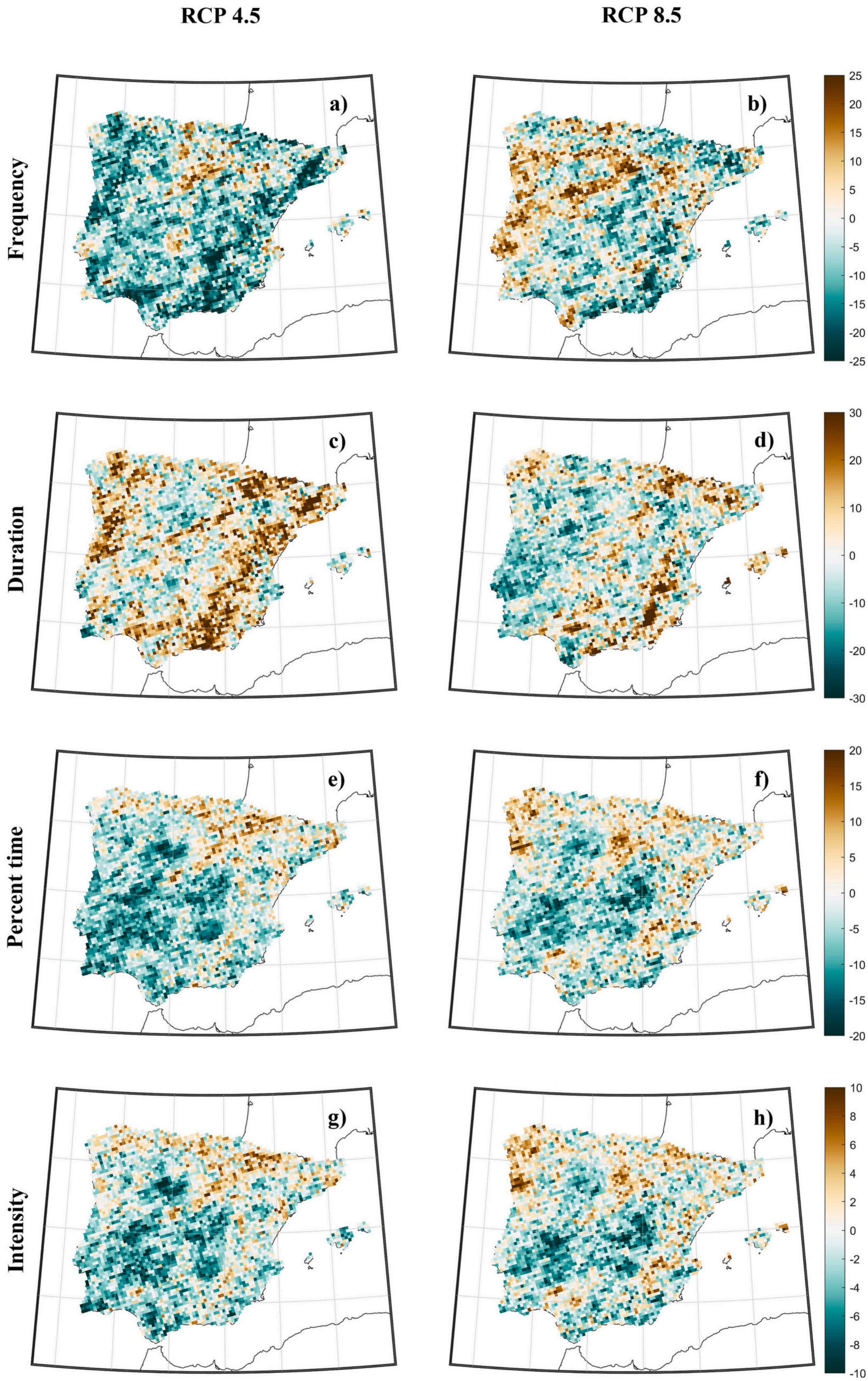

Fig. 10. Projected changes (in percent) relative to the reference period (1971–2005) of SPI-12 drought frequency (a, b), duration (c, d), percent time (e, f), and intensity (g, h) in the period (2041–2075) under RCP4.5 and RCP8.5.

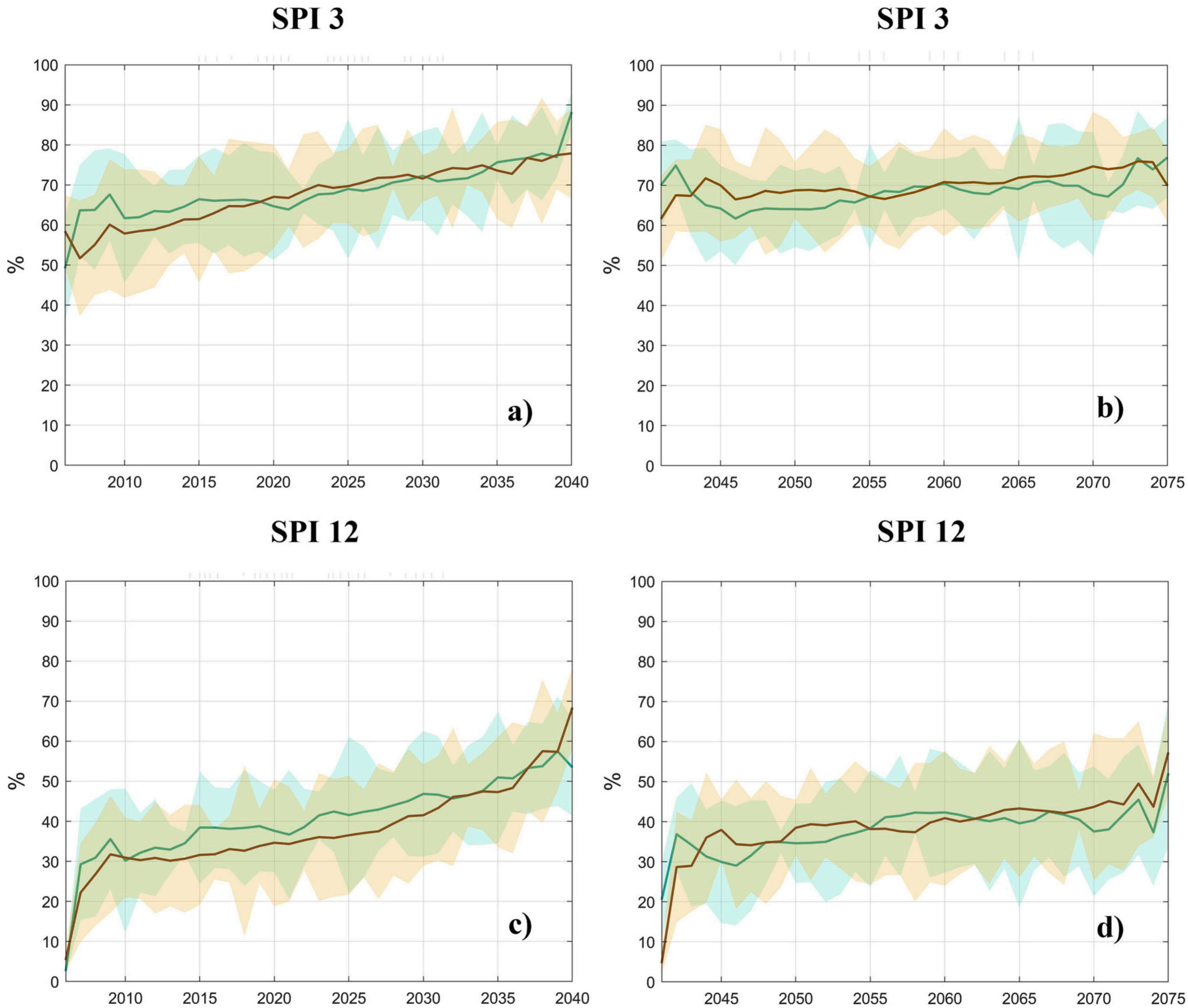

Fig. 11. Mean drought extent distribution per year on the Iberian Peninsula for SPI-3 (a, b) and SPI-12 (c, d) in the period (2006–2040) and (2041–2075) under RCP4.5 and RCP8.5. Green/Brown lines correspond to the RCP 4.5/RCP 8.5 scenario. The wide solid line represents the average of the five models, and the shaded region represents the dispersion through the standard error of the average. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

4. Discussion

4.1. Historical droughts

Model outcomes (Fig. 2) suggest frequent droughts over the entire IP territory in recent decades. These results follow several studies showing recurrent droughts at the IP using different model simulations and drought indices (García-Valdecasas et al., 2021a, 2021b; Guerreiro et al., 2017; Russo et al., 2017; Spinoni et al., 2018). Most of these studies analyzed multi-model ensembles calculated using global climate models outcomes from the CMIP5 or high-resolution simulations from RCMs provided by the EURO-CORDEX project. In general, recurrent droughts over the IP were found in the recent past showing fewer and longer events on larger time scales. Nevertheless, some discrepancies among drought events characteristics were observed in the different studies. Thus, simulations can indicate longer or shorter events over the same region. Some of these discrepancies could result from the different periods analyzed to calculate the drought indices, which could influence drought characteristics (Um et al., 2017; Wu et al., 2005).

The pattern observed in Fig. 2 is also concordant with several studies focused on data measured in different meteorological stations and gridded datasets. These studies showed increasing drought conditions in most of the territory, although a high spatial variability in the duration, intensity, and frequency of droughts was observed (Coll et al., 2017; Domínguez-Castro et al., 2019; Gallego et al., 2011; Moemken and Pinto, 2022; Páscoa et al., 2017, 2021; Vicente-Serrano, 2006a, 2006b). In general, an increase in the mean duration and magnitude of the drought was observed in the southern regions of the IP, while a wetting trend was identified in the northwestern region (Coll et al., 2017; Garcia-Barron et al., 2011; Lorenzo et al., 2022; Sousa et al., 2011; Vicente-Serrano et al., 2004, 2011). The number of drought events in recent decades also showed variable results, as it may rely on the dataset selection, i.e., larger datasets may have a higher number of events. This high variability reveals the importance of drought analysis at a local level, showing that RCMs are useful tools to provide future drought scenarios.

4.2. Projections for drought events

The generalized trends in the SPI at the meteorological and hydrological scales indicated a clear intensification of drought conditions in a large part of the IP during 2006–2040 (Fig. 3 and Fig. 4), more pronounced in the RCP 8.5. These results follow the pattern described by different works on the IP for the last decades of the 20th century. Several studies agreed on an increase in drought frequency and intensity, showing a significant tendency towards more arid conditions in most of the territory over the past century (Coll et al., 2017; Páscoa et al., 2017, 2021; Spinoni et al., 2017). Trends for 2041–2075 (Fig. 5 and Fig. 6) presented a different behavior showing a significant increase in drought conditions, mainly in the southeastern area. This contrast with previous studies indicating more frequent and severe droughts all over southern Europe as the century passes (Moemken et al., 2022; Santos et al., 2016; Spinoni et al., 2018, 2020; Stagge et al., 2015). Changes in drought characteristics for the first decades of the 21st century (Figs. 7 and Fig. 8) indicated that shorter events will occur more frequently while longer events will be less numerous. In addition, meteorological drought will intensify in the southwestern and northeastern regions and more severe hydrological droughts will occur mainly in the northern area.

These results contrast with previous works which investigated future drought occurrence in Europe, finding a general increase in the frequency of droughts over southern Europe and the IP for the first half of the century (Guerreiro et al., 2017; Jenkins and Warren, 2014; Moemken et al., 2022; Orlowsky and Seneviratne, 2013; Stagge et al., 2015). Some of these studies also showed an increase in the duration and intensity of droughts for large parts of the IP, indicating that droughts will become more severe and longer-lasting over most of the territory. However, it should be noted that these studies have relied on different datasets and indices to identify drought events, which could lead to contrasting results on drought characteristics (Dubrovsky et al., 2009; Loukas et al., 2008; Touma et al., 2015). Furthermore, results also depend on the period selected to calculate the drought indices, which could explain some discrepancies (Dubrovsky et al., 2009; Um et al., 2017; Wu et al., 2005; Zhao and Dai, 2017). In fact, most of these studies are focused on periods from 2020 onwards, which makes it difficult to compare with our results.

Analyzing differences between RCP scenarios, similar patterns were obtained at the 3-month time scale with more frequent but shorter events in the western IP (Fig. 7(a-d)). At the 12-month time scale, both scenarios showed a decline in frequency for the RCP 8.5 scenario (Fig. 8 (a, b)), although these events may show an increase in duration (Fig. 8(c, d)).

These results partially coincide with those reported by García-Valdecasas et al. (2021b). The authors found longer droughts, but less frequent, for 2021–2050 over most of the IP territory at the 12-month time scale under the RCP 8.5 scenario. On the contrary, several studies in Europe showed significant increases in drought frequency for the Mediterranean area under the extreme emission scenario RCP 8.5 at the beginning of the century (Guerreiro et al., 2017; Jenkins and Warren, 2014; Moemken et al., 2022; Orlowsky and Seneviratne, 2013; Stagge et al., 2015). These studies found that emissions will affect droughts, with the highest emission scenario having the greatest impact on drought conditions. Thus, drought severity, frequency, and duration were projected to increase over the Iberian Peninsula under the RCP 8.5 scenario, intensifying by the end of the century.

Considering the results over the whole 21st century, drought events at the 3-month time scale throughout the century (Fig. 7 and Fig. 9) are less frequent but longer-lasting over the eastern area. In addition, these changing patterns were more evident in the last decades, following previous studies investigating changes in drought conditions in Europe under future climate conditions (Moemken et al., 2022; Spinoni et al., 2018, 2020; Stagge et al., 2015). These works showed agreement on the intensification of changes in southern Europe towards the end of the 21st century. Nevertheless, as previously mentioned, most of these studies indicated more frequent and severe events as the century passes, with the high-emissions scenario agreeing with the stronger changes.

To summarize, droughts' conditions at the 12-month time scale (Fig. 8 and Fig. 10), presented less frequent events with an increase in duration over large parts of the IP. Whereas, the RCP 8.5 scenario presented a frequency increase over the century in agreement with the SPI-3 result (Fig. 7 and Fig. 9). However, changes were found to be more moderate in terms of duration, with substantial decreases compared to the first decades. As previously mentioned, these results contrast with past studies predicting a general increase in the number and duration of drought events for the Mediterranean region under both emission scenarios. The most extreme emission scenario, RCP 8.5, produced more severe drought responses with an increase in drought severity throughout the century (Guerreiro et al., 2017; Naumann et al., 2018; Spinoni et al., 2018, 2020; Stagge et al., 2015).

It is important to keep in mind that these results were obtained using the SPI, which is solely based on precipitation. It is well-known that drought events can be influenced by several factors such as precipitation, temperature, seasonality and even terrain characteristics leading to a complex characterization and prediction of these phenomena. Most of the published studies indicated that precipitation has a major role in explaining the occurrence of droughts. Even recently, new indices considering precipitation as input have been introduced to analyze past and future droughts over the Iberian Peninsula (Moemken and Pinto, 2022; Moemken and Pinto, 2022). On the other hand, several works suggested that the warming trend in temperature is an important factor that can aggravate drought conditions. In fact, some recent studies in the Iberian Peninsula (Gaitan et al., 2020; García-Valdecasas et al., 2021b; Páscoa et al., 2021; Vicente-Serrano et al., 2022; Vogel et al., 2021) indicated that the influence of temperature is not negligible and that increasing temperatures can reinforce the severity of drought events.

It should be noted that the use of drought indices which include temperature data could produce different results to the ones presented in this work. Nevertheless, several studies analyzing the performance of different indices which take or don't take into account temperature, found that, in most cases, drought events reflected by the different indices are often simultaneous and correlate well (Bouabdelli et al., 2022; Ojha et al., 2021; Tefera et al., 2019). The main differences were found in their severity.

All indices have certain limitations. The applicability of the SPI in dry seasons can be questioned because during these seasons, periods without rainfall are the norm and can make drought analysis more difficult. On the other hand, indices which consider temperature data in their formulation are highly correlated with this variable, and could therefore be considered, to a certain degree, as indicators of compound events.

Drought can be understood from different perspectives since its effects can vary between sectors, and the number of presently used indices in the literature reflects the diverse requirements of users. Due to the complex nature of drought events, the use of multi-variate indicators helps to study these extreme phenomena (Spinoni et al., 2018). Orography, season, land use and many other factors can affect the suitability of the most appropriate index for the study of a particular area. Thus, the analysis of a simple index as the SPI could be completed with the study of, for example, the concurrence of other extreme phenomena such as heat waves or heat stress, depending on the different systems to be analyzed.

Understanding the spatial and temporal characteristics of future droughts is crucial for mitigating ecosystems impacts and reducing risks. Thus, although far from the aim of this paper, further research should focus on exploring the links between drought trends and climate anomalies. The increase in droughts could be related to anomalies in anti-cyclonic circulation, moisture transport, or atmospheric blocking in mid-latitudes. In fact, over the last decade, there has been a growing interest among the scientific community in studying links between atmospheric processes and surface climate. Some studies have investigated the frequency of the different circulation types using future projections over Europe, founding a general increase in the anticyclonic types (Breton et al., 2022; Lorenzo et al., 2011; Schaller et al., 2018; Ullmann et al., 2014). These results indicate that dryer conditions could be expected in southwest Europe in the future. This behavior is in agreement with the increase in the NAO positive conditions also expected towards the end of the 21st century, leading to lower precipitation and higher risk of droughts over the Mediterranean region. Consequently, the analysis of changes in atmospheric circulation could help to understand the synoptic causes of droughts.

5. Conclusions

Previous studies have suggested that the Iberian Peninsula suffered several droughts in the last decades and will encounter more severe and intense droughts in the future. As a result, these future changes may impact the society and the economy, making the identification and quantification of future drought events an important task. This work investigated projected changes in meteorological and hydrological droughts in the IP through the SPI index using simulations from the EURO-CORDEX project. Projections of SPI-3 and SPI-12 from 2006 to 2075 were explored under two concentration scenarios, RCP 4.5 and RCP 8.5, trying to contribute to the knowledge of droughts in one of Europe's drought hotspots.

In the future, RCPs scenarios forecast shorter drought events more frequently and longer events less numerous. In the first decades of the century, meteorological droughts might be less frequent but longer, and the number of hydrological droughts for the RCP 8.5 could be lower than for the RCP 4.5, showing an increase in duration. By the end of the century, both RCPs projected less frequent events with an increase in the duration over the east side of IP for meteorological droughts. Hydrological droughts are expected to be less frequent and durable over large parts of the IP for the RCP 4.5 scenario, while the RCP 8.5 scenario presented a frequency increase.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgments

The presented work was performed in context of the Horizon Europe project SARIL which is funded by the European Union under grant agreement ID 101103978. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Climate, Infrastructure and Environment Executive Agency. Neither the European Union nor the granting authority can be held responsible for them. This study forms part of the Marine Science programme (ThinkInAzul) supported by Ministerio de Ciencia e Innovación and Xunta de Galicia with funding from European Union NextGenerationEU (PRTR-C17·I1) and European Maritime and Fisheries Fund. This work was also partially supported by Xunta de Galicia, Consellería de Cultura, Educación y Universidad under project ED431C 2021/44 (Programa de Consolidación e Estructuración de Unidades de Investigación Competitivas). H. Pereira was funded by FCT (Fundação para a Ciência e a Tecnologia) with grant number SFRH/BD/138755/2018. H. Pereira, I. Alvarez and J.M. Dias acknowledge financial support to CESAM by FCT/MCTES (UIDP/50017/2020 + UIDB/50017/2020 + LA/P/0094/2020), through national funds.

References

Bouabdelli, S., Zeroual, A., Meddi, M., Assani, A., 2022. Impact of temperature on agricultural drought occurrence under the effects of climate change. Theor. Appl. Climatol. 148, 191–209. https://doi.org/10.1007/s00704-022-03935-7.

Breton, F., Vrac, M., Yiou, P., Vaittinada Ayar, P., Jézéquel, A., 2022. Seasonal circulation regimes in the North Atlantic: towards a new seasonality. Int. J. Climatol. 42, 5848–5870. https://doi.org/10.1002/joc.7565.

Carbone, G.J., Lu, J., Brunetti, M., 2018. Estimating uncertainty associated with the standardized precipitation index. Int. J. Climatol. 38, e607–e616. https://doi.org/10.1002/joc.5393.

Chim, K., Tunnicliffe, J., Shamseldin, A., Chan, K., 2021. Identifying future climate change and drought detection using CanESM2 in the upper Siem Reap River, Cambodia. Dyn. Atmos. Oceans 94, 101182. https://doi.org/10.1016/j.dynatmoce.2020.101182.

Ciais, P.H., Reichstein, M., Viovy, N., Granier, A., Ogée, J., Allard, V., Aubinet, M., Buchmann, N., Bernhofer, Chr, Carrara, A., Chevalier, F., De Noblet, N., Friend, A.D., Friedlingstein, P., Grunwald, T., Heinesch, B., Keronen, P., Knohl, A., Krinner, G., Loustau, D., Manca, G., Matteuci, G., Miglietta, F., Ourcival, J.M., Papale, D., Pilegaards, K., Rambal, S., Sufert, G., Spussana, J.F., Sanz, M.J., Schulze, E.D., Vesala, T., Valentini, R., 2005. Europe-wide reduction in primary productivity caused by the heat and drought in 2003. Nature 437, 529–533. https://doi.org/10.1038/nature03972.

Coll, J.R., Aguilar, E., Ashcroft, L., 2017. Drought variability and change across the Iberian Peninsula. Theor. Appl. Climatol. 130, 901–916. https://doi.org/10.1007/s00704-016-1926-3.

Domínguez-Castro, F., Vicente-Serrano, S.M., Tomás-Burguera, M., Peña-Gallardo, M., Beguería, S., El Kenawy, A., Luna, Y., Morata, A., 2019. High-spatial-resolution probability maps of drought duration and magnitude across Spain. Nat. Hazards Earth Syst. Sci. 19, 611–628. https://doi.org/10.5194/nhess-19-611-2019.

Dubrovsky, M., Svoboda, M.D., Trnka, M., Hayes, M.J., Wilhite, D.A., Zalud, Z., Hlavinka, P., 2009. Application of relative drought indices in assessing climate-change impacts on drought conditions in Czechia. Theor. Appl. Climatol. 96, 155–171. https://doi.org/10.1007/s00704-008-0020-x.

Espinosa, L.A., Portela, M.M., Rodrigues, R., 2019. Spatio-temporal variability of droughts over past 80 years in Madeira Island. J. Hydrol. Reg. Stud. 25, 100623 https://doi.org/10.1016/j.ejrh.2019.100623.

Gaitan, E., Monjo, R., Portoles, J., Pino-Otin, M., 2020. Impact of climate change on drought in Aragon (NE Spain). Sci. Total Environ. 740, 140094 https://doi.org/10.1016/j.scitotenv.2020.140094.

Gallego, M.C., Trigo, R.M., Vaquero, J.M., Brunet, M., Garcia, J.A., Sigro, J., Valente, M. A., 2011. Trends in frequency indices of daily precipitation over the Iberian Peninsula during the last century. J. Geophys. Res. 116, D02109. https://doi.org/10.1029/2010JD014255.

Garcia-Barron, L., Aguilar, M., Sousa, A., 2011. Evolution of annual rainfall irregularity in the southwest of the Iberian Peninsula. Theor. Appl. Climatol. 103, 13–26. https://doi.org/10.1007/s00704-010-0280-0.

García-Valdecasas, M., Romero-Jiménez, E., Rosa-Cánovas, J.J., Yeste, P., Castro-Díez, Y., Esteban-Parra, M.J., Vicente-Serrano, S.M., Gámiz-Fortis, S.R., 2021a. Assessing future drought conditions over the Iberian Peninsula: the Impact of using different periods to Compute the SPEI. Atmosphere 12, 980. https://doi.org/10.3390/atmos12080980.

García-Valdecasas, M., Gámiz-Fortis, S., Romero-Jiménez, E., Rosa-Cánovas, J.J., Yeste, P., Castro-Díez, Y., Esteban-Parra, M.J., 2021b. Projected changes in the Iberian Peninsula drought characteristics. Sci. Total Environ. 757, 143702 https://doi.org/10.1016/j.scitotenv.2020.143702.

Gomez-Gomez, J., Pulido-Velazquez, D., Collados-Lara, A., Fernandez-Chacon, F., 2022. The impact of climate change scenarios on droughts and their propagation in an arid Mediterranean basin. A useful approach for planning adaptation strategies. Sci. Total Environ. 820, 153128 https://doi.org/10.1016/j.scitotenv.2022.153128.

Gouveia, C.M., Bastos, A., Trigo, R.M., Dacamara, C.C., 2012. Drought impacts on vegetation in the pre- and post-fire events over Iberian Peninsula. Nat. Hazards Earth Syst. Sci. 12, 3123–3137. https://doi.org/10.5194/nhess-12-3123-2012.

Guerreiro, S.B., Kilsby, C.G., Fowler, H.J., 2016. Rainfall in Iberian transnational basins: a drier future for the Douro, Tagus and Guadiana? Clim. Chang. 135, 467–480. https://doi.org/10.1007/s10584-015-1575-z.

Guerreiro, S.B., Kilsby, C., Fowler, H.J., 2017. Assessing the threat of future mega drought in Iberia. Int. J. Climatol. 37, 5024–5034. https://doi.org/10.1002/joc.5140.

Guttman, N.B., 1999. Accepting the standardized precipitation index: a calculation algorithm. JAWRA J. Am. Water Resourc. Assoc. 35, 311–322. https://doi.org/10.1111/j.1752-1688.1999.tb03592.x.

Hayes, M., Svoboda, M.D., Wilhite, D.A., 1999. Monitoring the 1996 drought using the standardized Precipitation Index. Bull. Am. Meteorol. Soc. 80, 29–438. https://doi.org/10.1175/1520-0477(1999)080<0429:MTDUTS>2.0.CO;2.

Hayes, M., Svoboda, M., Wall, N., Widhalm, M., 2011. The Lincoln declaration on drought indices. Bull. Am. Meteorol. Soc. 92, 485–488. https://doi.org/10.1175/2010BAMS3103.1.

Heinrich, G., Gobiet, A., 2012. The future of dry and wet spells in Europe: a comprehensive study based on the ENSEMBLES regional climate models. Int. J. Climatol. 32, 1951–1970. https://doi.org/10.1002/joc.2421.

Hoerling, M., Eischeid, J., Perlwitz, J., Quan, X., Zhang, T., Pegion, P., 2012. On the increased frequency in Mediterranean Drought. J. Clim. 25, 2146–2161. https://doi.org/10.1175/JCLI-D-11-00296.1.

Iglesias, A., Moneo, M., Garrote, R., Flores, F., 2009. Drought and climate risks. In: Garrido, A., Llamas, R.M. (Eds.), Water Policy in Spain. CRC Press, Cambridge, pp. 63–75.
Ilarri, M., Suza, A.T., Dias, E., Antunes, C., 2022. Influence of climate change and extreme weather events on an estuarine fish community. Sci. Total Environ. 827, 154190 https://doi.org/10.1016/j.scitotenv.2022.154190.
Irannezhad, M., Marttila, H., Chen, D., Kløve, B., 2016. Century-long variability and trends in daily precipitation characteristics at three Finnish stations. Adv. Clim. Chang. Res. 7, 54–69. https://doi.org/10.1016/j.accre.2016.04.004.
Jacob, D., Petersen, J., Eggert, B., Alias, A., Christensen, O.B., Bouwer, L.M., Braun, A., Colette, A., Deque, M., Georgievski, G., Georgopoulou, E., Gobiet, A., Menut, L., Nikulin, G., Haensler, A., Hempelmann, N., Jones, C., Keuler, K., Kovats, S., Kroner, N., Kotlarski, S., Kriegsmann, A., Martin, E., van Meijgaard, E., Moseley, C., Pfeifer, S., Preuschmann, S., Radermacher, C., Radtke, K., Rechid, D., Rounsevell, M., Samuelsson, P., Somot, S., Soussana, J.F., Teichmann, C., Valentini, R., Vautard, R., Weber, B., Yiou, P., 2014. EURO-CORDEX: newhigh-resolution climate change projections for European impact research. Reg. Environ. Chang. 14, 563–578. https://doi.org/10.1007/s10113-013-0499-2.
Jenkins, K., Warren, R., 2014. Quantifying the impact of climate change on drought regimes using the standardized precipitation index. Theor. Appl. Climatol. 120, 41–54. https://doi.org/10.1007/s00704-014-1143-x.
Ji, L., Peters, A.J., 2003. Assessing vegetation response to drought in the northern Great Plains using vegetation and drought indices. Remote Sens. Environ. 87, 85–98. https://doi.org/10.1016/S0034-4257(03)00174-3.
Kendall, M.G., 1975. Rank Correlation Methods. Charles Griffin, London.
Keyantash, J., Dracup, J.A., 2002. The quantification of drought: an evaluation of drought indices. Bull. Am. Meteorol. Soc. 83, 1167–1180. https://doi.org/10.1175/1520-0477-83.8.1167.
Li, X., Fang, G., Wen, X., Xu, M., Zhang, Y., 2022. Characteristics analysis of drought at multiple spatiotemporal scale and assessment of CMIP6 performance over the Huaihe River Basin. J. Hydrol. Reg. Stud. 41, 101103 https://doi.org/10.1016/j.ejrh.2022.101103.
Limones, N., Vargas, J., Paneque, P., 2022. Spatiotemporal characterization of meteorological drought: a global approach using the Drought Exceedance Probability Index (DEPI). Clim. Res. 88, 137–154. https://doi.org/10.3354/cr01703.
Lloyd-Hughes, B., Saunders, M.A., 2002. A drought climatology for Europe. Int. J. Climatol. 22, 1571–1592. https://doi.org/10.1002/joc.846.
Lorenzo, M.N., Ramos, A.M., TAboada, J.J., Gimeno, L., 2011. Changes in present and future circulation types frequency in Northwest Iberain Peninsula. PLoS One 6, e16201. https://doi.org/10.1371/journal.pone.0016201.
Lorenzo, M.N., Alvarez, I., 2020. Climate change patterns in precipitation over Spain using CORDEX projections for 2021–2050. Sci. Total Environ. 723, 138024. https://doi.org/10.1016/j.scitotenv.2020.138024.
Lorenzo, M.N., Alvarez, I., Taboada, J.J., 2022. Drought evolution in the NW Iberian Peninsula over a 60 year period (1960-2020). J. Hydrol. 610, 127923 https://doi.org/10.1016/j.jhydrol.2022.127923.
Loukas, A., Vasiliades, L., Tzabiras, J., 2008. Climate change effects on drought severity. Adv. Geosci. 17, 23–29. https://doi.org/10.5194/adgeo-17-23-2008.
Mann, H.B., 1945. Non-parametric test against trend. Econometrika 13, 245–259. https://doi.org/10.2307/1907187.
McKee, T., Doesken, N., Kleist, J., 1993. The relationship of drought frequency and duration times scales. In: 8th Conference on Applied Climatology. Amer. Meteor. Soc, Anaheim, California, pp. 179–184.
Miró, J.J., Estrela, M.J., Olcina-Cantos, J., Martin-Vide, J., 2021. Future projection of precipitation changes in the Júcar and Segura River Basins (Iberian Peninsula) by CMIP5 GCMs local downscaling. Atmosphere 12, 879. https://doi.org/10.3390/atmos12070879.
Mishra, A.K., Singh, V.P., 2010. A review of drought concepts. J. Hydrol. 391, 202–216. https://doi.org/10.1016/j.jhydrol.2010.07.012.
Moemken, J., Pinto, J.G., 2022. Recurrence of drought events over Iberia. Part I: methodology and application for present climate conditions. Tellus A 74, 222–235. https://doi.org/10.16993/tellusa.50.
Moemken, J., Koerner, B., Ehmele, F., Feldmann, H., Pinto, J.G., 2022. Recurrence of drought events over Iberia. Part II: future changes using Regional climate projections. Tellus A 74, 262–279. https://doi.org/10.16993/tellusa.52.
Morales Gil, A., Olcina Cantos, J., Rico Amorós, A.M., 2000. Diferentes percepciones de la sequía en España: adaptación, catastrofismo e intentos de corrección. Investig. Geogr. 23, 5–46. https://doi.org/10.14198/INGEO2000.23.06.
Moreno, M., Bertolin, C., Ortiz, P., Ortiz, R., 2022. Satellite product to map drought and extreme precipitation trend in Andalusia, Spain: a novel method to assess heritage landscapes at risk. Int. J. Appl. Earth Obs. Geoinf. 110, 102810 https://doi.org/10.1016/j.jag.2022.102810.
Moss, R.H., Edmonds, J.A., Hibbard, K.A., Manning, M.R., Rose, S.K., van Vuuren, D.P., Carter, T.R., Emori, S., Kainuma, M., Kram, T., Meehl, G.A., Mitchell, J.F.B., Nakicenovic, N., Riahi, K., Smith, S.J., Stouffer, R.J., Thomson, A.M., Weyant, J.P., Wilbanks, T.J., 2010. The next generation of scenarios for climate change research and assessment. Nature 463, 747–756. https://doi.org/10.1038/nature08823.
Nashwan, M.S., Shahid, S., 2019. Spatial distribution of unidirectional trends in climate and weather extremes in Nile river basin. Theor. Appl. Climatol. 137, 1181–1199. https://doi.org/10.1007/s00704-018-2664-5.
Naumann, G., Spinoni, J., Vogt, J.V., Barbosa, P., 2015. Assessment of drought damages and their uncertainties in Europe. Environ. Res. Lett. 10, 124013 https://doi.org/10.1088/1748-9326/10/12/124013.
Naumann, G., Alfieri, L., Wyser, K., Mentaschi, L., Betts, R.A., Carrao, H., Spinoni, J., Vogt, J., Feyen, L., 2018. Global changes in drought conditions under different levels of warming. Geophys. Res. Lett. 45, 3285–3296. https://doi.org/10.1002/2017GL076521.
Ojha, S.S., Singh, V., Roshni, T., 2021. Comparison of meteorological drought using SPI and SPEI. Civ. Eng. J. 12 https://doi.org/10.28991/cej-2021-03091783.
Olcina Cantos, J., 2001. Tipología de sequías en España. Ería 56, 201–227.
Orlowsky, B., Seneviratne, S.I., 2013. Elusive drought: uncertainty in observed trends and short- and longterm CMIP5 projections. Hydrol. Earth Syst. Sci. 17, 765–781. https://doi.org/10.5194/hess-17-1765-2013.
Páscoa, P., Gouveia, C.M., Russo, A., Trigo, R.M., 2017. Drought Trends in the Iberian Peninsula over the last 112 years. Adv. Meteorol. 4653126 https://doi.org/10.1155/2017/4653126.
Páscoa, P., Russo, A., Gouveia, C.M., Soares, P., Cardos, R.M., Careto, A., Ribeiro, A., 2021. A high-resolution view of the recent drought trends over the Iberian Peninsula. Weather Clim. Extr. 32, 100320 https://doi.org/10.1016/j.wace.2021.100320.
Ribeiro, A.F.S., Russo, A., Gouveia, C.M., Páscoa, P., 2019. Copula-based agricultural drought risk of rainfed cropping systems. Agric. Water Manag. 223, 105689 https://doi.org/10.1016/j.agwat.2019.105689.
Russo, A., Gouveia, C.M., Páscoa, P., DaCamara, C.C., Sousa, P.M., Trigo, R.M., 2017. Assessing the role of drought events on wildfires in the Iberian Peninsula. Agric. For. Meteorol. 237–238, 50–59. https://doi.org/10.1016/j.agrformet.2017.01.021.
Santos, J.A., Belo-Pereira, M., Fraga, H., Pinto, J.G., 2016. Understanding climate change projections for precipitation over western Europe with a weather typing approach. J. Geophys. Res. Atmos. 121, 1170–1189. https://doi.org/10.1002/2015JD024399.
Schaller, N., Sillmann, J., Anstey, J., Fischer, E.M., Grams, C.M., Russo, S., 2018. Influence of blocking on northern European and Western Russian heatwaves in large climate model ensembles. Environ. Res. Lett. 13, 054015 https://doi.org/10.1088/1748-9326/aaba55.
Sousa, P., Trigo, R.M., Aizpurua, P., Nieto, R., Gimeno, L., Garcia-Herrera, R., 2011. Trends and extremes of drought indices throughout the 20th century in the Mediterranean. Nat. Hazards Earth Syst. Sci. 11, 33–51. https://doi.org/10.5194/nhess-11-33-2011.
Spinoni, J., Naumann, G., Vogt, J.V., Barbosa, P., 2015a. The biggest drought events in Europe from 1950 to 2012. J. Hydrol. Reg. Stud. 3, 509–524. https://doi.org/10.1016/j.ejrh.2015.01.001.
Spinoni, J., Naumann, G., Vogt, J.V., Barbosa, P., 2015b. European drought climatologies and trends based on a multi-indicator approach. Glob. Planet. Chang. 127, 50–57. https://doi.org/10.1016/j. gloplacha.2015.01.012.
Spinoni, J., Naumann, G., Vogt, J.V., 2017. Pan-European seasonal trends and recent changes of drought frequency and severity. Glob. Planet. Chang. 148, 113–130. https://doi.org/10.1016/j.gloplacha.2016.11.013.
Spinoni, J., Vogt, J.V., Naumann, G., Barbosa, P., Dossio, A., 2018. Will drought events become more frequent and severe in Europe? Int. J. Climatol. 38, 1718–1736. https://doi.org/10.1002/joc.5291.
Spinoni, J., Barbosa, P., Buchignani, E., Cassano, J., Cavazos, T., Christensen, J.H., Christensen, O.B., Coppola, E., Evans, J., Geyer, B., Giorgi, F., Hadjinicolaou, P., Jacob, D., Katzfey, J., Koenigk, T., Laprise, R., Lennard, C.J., Kurnaz, M.L., Li, D., Llopart, M., McCormick, N., Naumann, G., Nikulin, G., Ozturk, T., Panitz, H.J., Porfirio, R., Rockel, B., Solma, S.A., Syktus, J., Tangang, F., Teichmann, C., Vautard, R., Vogt, J.V., Winger, K., Zittis, G., Dossio, A., 2020. Future global meteorological drought hot spots: a Study based on CORDEX data. J. Clim. 33, 3635–3661. https://doi.org/10.1175/JCLI-D-19-0084.1.
Stagge, J.H., Rizzi, J., Tallaksen, L.M., Stahl, K., 2015. Future Meteorological Drought: Projections of Regional Climate Models for Europe. DROUGHT-R&SPI (Fostering European Drought Research and Science-Policy Interfacing) Technical Report No. 25.
Tadesse, T., Wilhite, D.A., Harms, S.K., Hayes, M.J., Goddard, S., 2004. Drought monitoring using data mining techniques: a case study for Nebraska, USA. Nat. Hazards 33, 137–159. https://doi.org/10.1023/B:NHAZ.0000035020.76733.0b.
Tallaksen, L.M., Van Lanen, H., 2004. Hydrological drought: processes and estimation methods for streamflow and groundwater. In: Developments in Water Science, Vol. 48. Elsevier Science, 579 pg.
Taylor, K.E., Stouffer, R.J., Meehl, G.A., 2012. An overview of Cmip5 and the experiment design. Bull. Am. Meteorol. Soc. 93, 485–498. https://doi.org/10.1175/BAMS-D-11-00094.1.
Tefera, A.S., Ayoade, J.O., Bello, N.J., 2019. Comparative analyses of SPI and SPEI as drought assessment tools in Tigray region, Northern Ethiopia. SN Appl. Sci. 1, 1265. https://doi.org/10.1007/s42452-019-1326-2.
Torres-Vázquez, M.A., Halifa-Marín, A., Montávez, J.P., Turco, M., 2023. High resolution monitoring and probabilistic prediction of meteorological drought in a Mediterranean environment. Weather Clim. Extr. 40, 100558 https://doi.org/10.1016/j.wace.2023.100558.
Tošic, I., Unkaševic, M., 2014. Analysis of wet and dry periods in Serbia. Int. J. Climatol. 34 (1357–1368), 2014. https://doi.org/10.1002/joc.3757.
Touma, D., Ashfaq, M., Nayak, M.A., Kao, S.C., Diffenbaugh, N.S., 2015. A multi-model and multi-index evaluation of drought characteristics in the 21st century. J. Hydrol. 526, 196–207. https://doi.org/10.1016/j.jhydrol.2014.12.011.
Ullmann, A., Fontaine, B., Roucou, P., 2014. Euro-Atlantic weather regimes and Mediterranean rainfall patterns: present-day variability and expected changes under CMIP5 projections. Int. J. Climatol. 34, 2634–2650. https://doi.org/10.1002/joc.3864.
Um, M.J., Kim, Y., Park, D., Kim, J., 2017. Effects of different reference periods on drought index (SPEI) estimations from 1901 to 2014. Hydrol. Earth Syst. Sci. 21, 4989–5007. https://doi.org/10.5194/hess-21-4989-2017.
Vargas, J., Paneque, P., 2019. Challenges for the integration of water resource and drought-risk management in Spain. Sustainability 11, 308. https://doi.org/10.3390/su11020308.

Vicente-Serrano, S.M., 2006a. Spatial and temporal analysis of droughts in the Iberian Peninsula (1910–2000). Hydrol. Sci. J. 51, 83–97. https://doi.org/10.1623/hysj.51.1.83.

Vicente-Serrano, S.M., 2006b. Differences in spatial patterns of drought on different time scales: an analysis of the Iberian Peninsula. Water Resour. Manag. 20, 37–60. https://doi.org/10.1007/s11269-006-2974-8.

Vicente-Serrano, S.M., Gonzalez-Hidalgo, J.C., de Luis, M., Raventos, J., 2004. Drought patterns in the Mediterranean area: the Valencia region (eastern Spain). Clim. Res. 26, 5–15. https://doi.org/10.3354/cr026005.

Vicente-Serrano, S.M., Beguería, S., López-Moreno, J.I., 2011. Comment on "characteristics and trends in various forms of the palmer drought severity index (PDSI) during 1900-2008" by Aiguo Dai. J. Geophys. Res. 116, D19112. https://doi.org/10.1029/2011JD016410.

Vicente-Serrano, S.M., López-Moreno, J.I., Beguería, S., Lorenzo-Lacruz, J., Sanchez-Lorenzo, J.M., 2014. Evidence of increasing drought severity caused by temperature rise in southern Europe. Environ. Res. Lett. 9, 044001 https://doi.org/10.1088/1748-9326/9/4/044001.

Vicente-Serrano, S.M., Dominguez-Castro, F., Reig, F., Beguería, J.I., Tomas-Burguera, M., Latorre, B., Peña-Angulo, D., Noguera, I., Rabanaque, I., Luna, Y., Morta, A., El Kenawy, A., 2022. A near real-time drought monitoring system for Spain using automatic weather station network. Atmos. Res. 271, 106095. https://doi.org/10.1016/j.atmosres.2022.106095.

Vogel, J., Paton, E., Aich, V., Bronstert, A., 2021. Increasing compound warm spells and droughts in the Mediterranean basin. Weather Clim. Extr. 32, 100312 https://doi.org/10.1016/j.wace.2021.100312.

Wilhite, D., 2000. Drought as a natural hazard: concepts and definitions. In: Wilhite, D.A. (Ed.), Droughts: Global Assessment. Routledge, London, pp. 3–18.

Wilhite, D.A., Glantz, M.H., 1985. Understanding the drought phenomenon: the role of definitions. Water Int. 10, 111–120.

Wilhite, D.A., Svoboda, M.D., Hayes, M.J., 2007. Understanding the complex impacts of drought: a key to enhancing drought mitigation and preparedness. Water Resour. Manag. 21, 763–774. https://doi.org/10.1007/s11269-006-9076-5.

World Meteorological Organization, 2012. Standardized Precipitation Index User Guide (M. Svoboda, M. Hayes and D. Wood). (WMO-No. 1090), Geneva.

Wu, H., Hayes, M.J., Wilhite, D.A., Svoboda, M.D., 2005. The effect of the length of record on the standardized precipitation index calculation. Int. J. Climatol. 25, 505–520. https://doi.org/10.1002/joc.1142.

Zarch, M., Sivakumar, B., Sharma, A., 2015. Droughts in a warming climate: a global assessment of Standardized precipitation index (SPI) and Reconnaissance drought index (RDI). J. Hydrol. 526, 183–195. https://doi.org/10.1016/j.jhydrol.2014.09.071.

Zargar, A., Sadiq, R., Naser, B., Khan, F.I., 2011. A review of drought indices. Environ. Rev. 19, 333–349. https://doi.org/10.1139/a11-01.

Zhao, T., Dai, A., 2017. Uncertainties in historical changes and future projections of drought. Part II: model-simulated historical and future drought changes. Clim. Chang. 144, 535–548. https://doi.org/10.1007/s10584-016-1742-x.